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HAND–ARM FREQUENCY-WEIGHTED VIBRATION EFFECTS ON TACTILITY *

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ABSTRACT

This study reports results of an investigation into the short-term effects of power hand tool vibration on deep sense tactile sensitivity. Five subjects operated a simulated hand tool using a 30 s / 30 s work / rest duty cycle. The handle vibrated at ISO 5349 weighted acceleration of 8 m / s^2, for frequencies of 20 Hz, 80 Hz, and 160 Hz, in three orthognal directions. A no-vibration condition was also included for a control. Tactile sensitivity of the distal index finger was measured after 30 minutes using a ridge detection threshold detection task. The average falling ridge threshold increased five times from 0.01 mm for the no-vibration condition to 0.05 mm at 160 Hz, however no rising ridge threshold shifts were observed. Implications for job design and work practices are discussed.

RELEVANCE TO INDUSTRY

Power hand tool vibration effects on tactility should be considered when performing tactile inspection tasks such as sanding operations and inspecting for rough edges or smoothness. Loss of tactile sensitivity may result in reduced quality and work performance.

KEYWORDS

Depth sensation, hand and arm vibration, power hand tools, ridge aesthesiometer, tactility temporary treshold shift.

INTRODUCTION

The use of power hand tools such as grinders, sanders, polishers, and nutrunners is limited by

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human motor and sensory skills, and hence quality and productivity may be impaired by physical stressors that affect operator performance. Workers utilize skeletal muscles accompanied by proprioceptors, mechanoreceptors, and feedback from other sensory modalities for positioning, holding, and operating hand tools. Power hand tool vibration may introduce disturbances in motor control and sensory feedback mechanisms. Consequently, vibration can diminish performance in precision tasks requiring a high degree of tactile sensation and motor control.

At present there are no hand and arm vibration (HAV) exposure guidelines for controlling short-term manual performance deficits. Current international HAV exposure standards (ISO, 1986) are primarily concerned with protecting workers from incurring vibration white finger (VWF) or hand–arm vibration syndrome, rather than preventing reduced manual proficiency or temporary sensory deficits. The International Organization for Standardization (ISO) draft consensus standard on HAV introduced in 1980 (ISO, 1980) was based on data from practical experience and laboratory experimentation, derived mostly from subjective human responses to hand-transmitted vibration and mechanical behavior of the hand–arm system. Weighted acceleration levels that are now used in the present standard are derived from the draft standard and they are intended for recommending acceptable HAV exposure in terms of VWF onset latencies, or the number of years before onset of vascular symptoms.

The ISO whole-body vibration standards (ISO, 1978) differ from the HAV standards in the following respect. The whole-body vibration exposure standard contains three distinct criteria for establishing exposure limits. These are (1) health and safety, (2) discomfort, and (3) fatigue and performance proficiency. The HAV guidelines do not make these distinctions. Manual performance, fatigue and neuromuscular aspects of HAV may have been overlooked in the HAV standards since the early symptoms of VWF include intermittent neurological symptoms such as tingling and numbness of the fingers. Temporary tingling or numbness during, or soon after use of a vibrating hand tool however, is not usually considered as vibration syndrome. Nevertheless, these temporary symptoms may affect manual performance and should be considered in power tool selection and job design.

Previous studies have shown that tactility, as measured using pressure sensation (Streeter, 1970) and surface roughness (Kume et al., 1984) generally diminish with increasing vibration amplitude. Haines et al. (1988) measured temporary depth sense and two-point discrimination threshold shifts in workers after operating jeckleg drills. In addition to reports of numbness, vibrating hand tool operators often complain of fatigue and discomfort.

This investigation was undertaken to evaluate the short-term effects of vibration on tactility when using the ISO 5349 international standard for HAV exposure. The operating hypothesis was that frequency-weighted acceleration has the same effect on tactile sensitivity over a range of frequencies representative of vibrating hand tools used for sanding and surface grinding.

METHODS

In order to study the effects on tactility, tactile sensitivity was measured after subjects were exposed to HAV at different frequencies. Experimental conditions were selected that represented generalized properties of industrial hand tools used in manufacturing. Vibration frequency and handle direction was controlled in a $3 \times 3 + 1$ (Frequency × Direction + No-vibration) factorial experimental design. Subjects were exposed to hand transmitted vibration at fixed ISO weighted acceleration (ISO, 1986) of 8 m/s^2 (see Table 1), three vibration frequencies including 20 Hz, 80 Hz, and 160 Hz in three orthognal directions. A control condition of no-vibration was also included. The load weight was fixed at 1.5 kg.

An apparatus consisting of an electrodynamic vibrator was constructed for simulating vibrating

TABLE 1

Equal ISO frequency weighted acceleration conditions

Frequency (Hz)	RMS amplitude (m/s^2)
20	10
80	40
160	80

power hand tool use while controlling vibration frequency, magnitude, direction, posture, and load weight (Radwin, 1986; Radwin et al., 1987). A cylindrical handle was attached to the vibrator which was suspended using a pneumatic balancer. Standing subjects were instructed to hold the handle using a power grip with the dominant hand. The ISO 5349 basicentric coordinate system was used to indicate direction. The simulator handle was held at a 90 deg elbow angle, measured using a goniometer, with the upper arm parallel to the torso.

An automated ridge aesthesiometer was designed and constructed, based on the manual aesthesiometer used by Renfrew and modified by Corlett (Renfrew, 1960, 1969; Corlett et al., 1981) for quickly determining depth sensation tactile sensitivity. A nylon disc was constructed having a 9.0 cm diameter and 2.5 cm width (see Fig. 1). The 2.0 mm wide ridge along the disc's periphery was machined by eccentrically milling the disc edges producing a ridge rising from a minimum height of 0.0 mm to a maximum height of 1.2 mm over 97% of the total disc circumference. The remaining 3% of the disc circumference was a blank zone having no ridge. Subjects placed the right index finger against a rotating disc and indicated when they detected a ridge.

Disc rotation was driven by a timing belt from a variable speed gear head DC motor (see Fig. 2). A DC voltage across a continuous turn 10.21 K Ω potentiometer, rotating along with the motor, was measured using an 8-bit analog-digital converter and microcomputer to indicate ridge height. Rather than allowing subjects to rotate the disc at their own pace, as in the original apparatus (Corlett et al., 1981), this paradigm forced subjects to respond within a fixed time window by controlling the rotation speed range. The disc rotation speed was randomly set in ten equal steps between 2.5 rpm and 5.0 rpm.

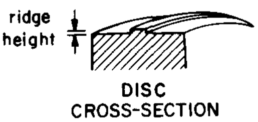

Fig. 1. A ridge was machined along the periphery of a Teflon disc and tapered from a height of 1.2 mm to 0.0 mm.

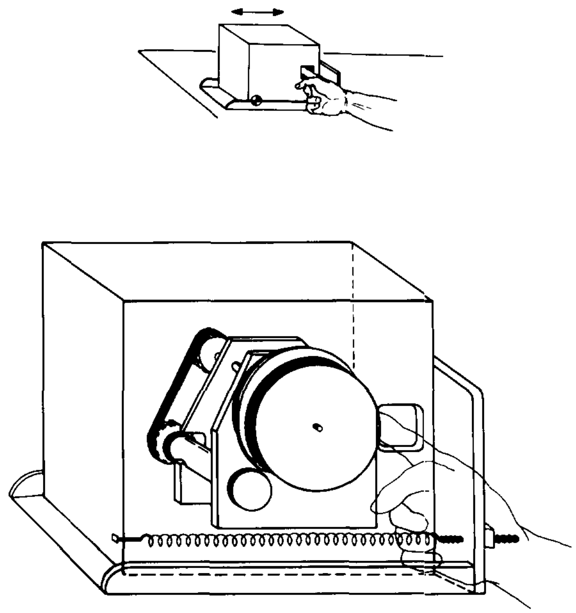

Fig. 2. Subjects placed the distal index finger pad against the rotating disc to measure their ridge detection threshold. The ridge aesthesiometer was pushed along tracks when a subject inserted their index finger against the disc displacing a spring the distance indicated by a target to control the pressure against the finger pad.

Subjects inserted the right index finger against the disc through a square cutout in the Plexiglass housing. The housing assembly was seated on a cart that glided along a track (see Fig. 2). By pushing against the disc, a spring attached to the box was stretched which increased the force exerted against the finger. Subjects were instructed to push against the disc and align a mark on the box with a target on the track to maintain finger pressure against the disc at 75 g. Glycerine was applied to the finger tip using a cotton swab to lubricate the surface between the finger and the disc and prevent abrasion.

Subjects were required to decide whether or not they initially felt the ridge. A response push button held in the left hand was pressed if the ridge was felt and released when no ridge was felt. They continued to respond by pressing the button when the ridge became sufficiently high to be perceived and releasing the button when the ridge height was too low to detect. The disc continually rotated clockwise throughout the procedure.

A trial consisted of an initial response followed by a pair of rising and falling ridge threshold determinations. The order of rising and falling ridge presentations depended upon the initial condition which was randomly presented. The three threshold sets were averaged producing one average rising and falling threshold. Baseline thresholds were obtained from each subject prior to every experimental session in order to test for daily threshold variations. Finger temperatures were measured prior to each experimental session and also following vibration exposure using a thermocouple.

Exposures consisted of one-half hour of 30 s vibration separated by 30 s rest periods, representing a 50 percent duty cycle. This equaled a total vibration exposure of 15 min. Individual subjects experienced all 10 conditions, serving as their own controls. Experimental conditions were randomized, presenting one condition to each subject per session. Consecutive sessions were separated by at least 12 h.

Prior to the experiment, subjects were trained to perform the ridge task during a one week period and were required to achieve apriori performance levels. Ridge detection performance criteria included rising threshold standard deviation of less than or equal to 0.02 mm, and falling threshold standard deviation of less than of equal to 0.05 mm, in ten consecutive determinations.

All subjects were volunteers who reported they were healthy young adults, having no history of neuromuscular or vascular disorders, and who had not suffered any injuries of the upper extremities. No subjects had prior occupational experience operating power hand tools. Five subjects participated in the experiment and were paid for their participation on an hourly basis. All were right handed. Hand length and hand breadth was measured for the dominant hand using a caliper (Garrett, 1970). Table 2 summarizes subject strength and anthropometry.

Statistical analysis included repeated measures analysis of variance using subjects as a random effects blocking variable. The regression approach to analysis of variance was utilized, incorporating orthognal indicator variables, in order to account for the design asymmetry presented by the absence of directionality associated with the no-vibration experimental condition.

RESULTS

Average falling ridge thresholds are presented in Fig. 3. The falling ridge thresholds clearly increased for increasing frequency between 0 Hz and 160 Hz. The average threshold increased from 0.01 mm for no-vibration to 0.05 mm at 160 Hz vibration. This represented a 0.04 mm shift in the falling threshold, or a five times increase in the falling ridge threshold between the no-vibration condition and vibration at 160 Hz. The frequency effect was statistically significant ($F(3, 12) = 4.01$, $p = 0.037$), however no significant effect was observed for direction ($F(2, 8) = 0.39$, $p > 0.5$).

Average rising ridge threshold shifts are plotted in Fig. 4. No significant effect was observed in the rising ridge thresholds for the effect of frequency ($F(3, 12) = 1.71$, $p > 0.25$), or for the effect of direction ($F(2, 8) = 1.46$, $p > 0.4$).

Average rising ridge thresholds ($M = 0.20$, s.d. = 0.05 mm) were consistently greater than falling ridge thresholds ($M = 0.02$, s.d. = 0.01 mm) and were more variable. Hence, rising ridge thresholds were less reliable than falling ridge thresholds. Baseline rising ridge thresholds measured prior to each experimental session varied

TABLE 2

Subject anthropometry and strength data

Subject	Sex	Age (years)	Stature (cm)	Weight (kg)	Hand length (cm)	Hand breadth (cm)	Grip strength (N)
1	M	35	175	79	18.7	8.6	422
2	M	23	188	74	21.5	9.0	470
3	M	22	188	82	19.4	8.8	539
4	F	21	160	61	16.4	7.1	240
5	F	25	150	53	15.6	7.6	289

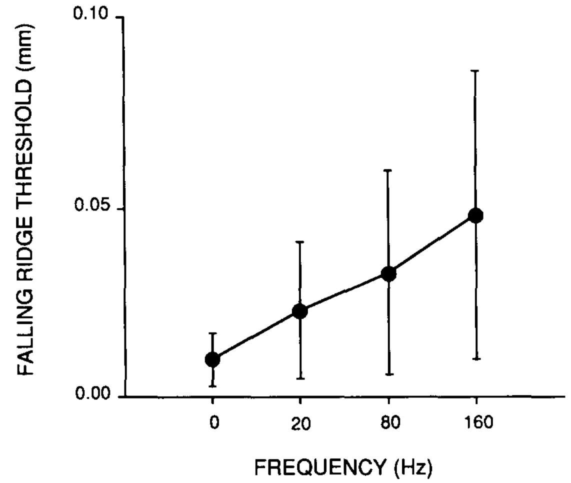

Fig. 3. Falling ridge threshold plotted against frequency (5 subjects). Error bars indicate the standard deviation between subjects.

significantly between subjects, ranging from 0.16 mm to 0.22 mm ($F(4, 45) = 3.45$, $p = 0.015$). Falling ridge baseline thresholds also were significantly different between subjects ranging between 0.01 mm to 0.03 mm ($F(4, 45) = 4.66$, $p = 0.003$). No significant differences between the 10 experimental sessions were found for the rising ridge baseline thresholds ($F(9, 4) = 0.19$, $p > 0.5$) or for the falling ridge baseline thresholds ($F(9, 4) = 0.30$, $p > 0.5$).

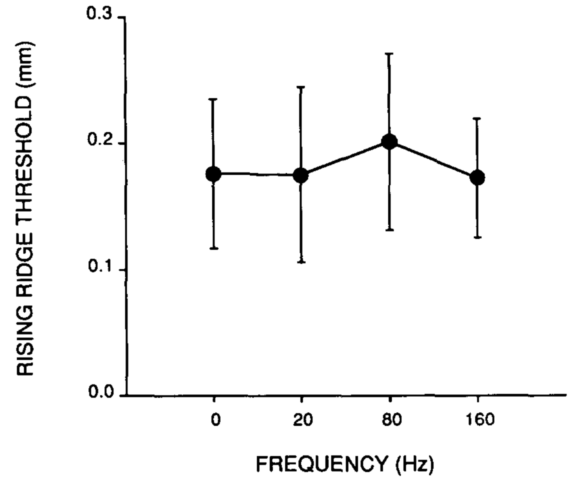

Fig 4. Rising ridge threshold plotted against frequency (5 subjects). Error bars indicate the standard deviation between subjects.

The average finger temperature measured before and after each trial increased 0.02°C (s.d. = 1.5°C). No significant finger temperature differences were found between subjects ($F(4, 12) = 0.43$, $p > 0.5$) or for the effect of vibration frequency ($F(3, 4) = 1.59$, $p > 0.3$). This suggested that finger temperatures were relatively stable during the course of the experiment and it was unlikely that temperature changes affected tactility.

DISCUSSION

The results indicated that HAV exposure using equal ISO 5349 frequency-weighted acceleration of 8 m/s^2, and vibration frequencies at 20 Hz, 80 Hz and 160 Hz produced short-term tactility effects. Falling ridge thresholds (see Fig. 3) increased with increasing frequency for equivalent frequency-weighted acceleration amplitudes. When vibration amplitude was fixed at constant ISO weighted acceleration the vibration effects on tactile sensitivity should have remained constant across frequency if the weighting system was effective at preventing tactile performance deficits. These results indicated that the HAV frequency weightings did not account for the short-term effects of hand tool vibration on tactility.

The results in this study agreed with the vibration effects on tactility threshold shifts previously reported by Streeter (1970) who found after three minutes of continuous vibration exposure, mean pressure sense loss similarly had a direct relationship to increasing frequency. Streeter reported that pressure sensitivity decreased approximately 7 times the no-vibration baseline at 60 Hz, 10 times the no-vibration sensitivity at 80 Hz and 13 times the no-vibration sensitivity at 100 Hz. That investigation used constant displacement amplitudes, however, and did not directly control the vibration stimulus magnitude, as in this study, but controlled the power input to the vibrator.

Baseline ridge detection thresholds were similar to the threshold values reported by Corlett et al. (1981) for normal young adults. Average rising ridge thresholds measured by Corlett and associates for 25 students were 0.13 mm (s.d. = 0.05 mm) using the right index finger, and 0.11 mm (s.d. = 0.05 mm) using the left index finger, compared to 0.20 mm (s.d. = 0.05 mm) in this study. Hence, average rising threshold values for the right index finger of the five subjects in this investigation were 0.07 mm greater than Corlett's.

One difference between Corlett's aesthesiometer and the one used in this investigation is that this apparatus was motorized. That insured the stimulus rate was not under direct subject control, as in the original device. Much of the difference between results of this study and Corlett et al. may be accounted for by considering response reaction time. The disc speed was randomized between 2.5 rpm and 5.0 rpm. Since the ridge height increased from 0.00 mm to 1.20 mm over half the disc circumference, the rate of change in ridge height was approximately 2.40 mm per revolution. The rate of ridge height change was 0.10 mm per second for the 2.5 rpm minimum speed and 0.20 mm per second for the 5.0 rpm maximum disc speed. Therefore a longer reaction time will produce a larger threshold. A fast reaction time of 250 ms will result in an average threshold increase of 0.04 mm. Hence reaction time accounts for much of the 0.07 mm difference between Corlett et al. and the data obtained in this investigation.

Corlett and his colleagues observed a number of falling ridge thresholds for normal subjects were below the measurement resolution of the apparatus. They suggested improving the design by increasing the maximum ridge height and the area with no ridge. These recommendations were incorporated into the apparatus used for this study (see Methods) raising the average falling ridge threshold to 0.02 mm (s.d. = 0.01 mm). The gap between rising and falling ridge thresholds may be due to persistent sensations lasting after the stimulus has ended during the falling ridge presentations. When subjects respond that the ridge has fallen below the perceived threshold, the disc has rotated to a lower ridge height. Another theory to consider is that the rising ridge and falling ridge stimuli are different and are perceived using different sensory mechanisms.

A previous study by Radwin et al. (1987) had demonstrated that hand tool vibration can introduce disturbances in neuromuscular control resulting in excessive grip force when holding a vibrating handle. These effects were attributed to either a tonic vibration reflex response in the forearm muscles or impaired hand tactility. The findings in this study indicate that the increased grip force was probably not due to changes in hand tactility but more likely mediated through the tonic vibration reflex. These results strengthen that conclusion because the tactility deficits observed in this study increased with increasing frequency. The inverse effect occurred in the grip force study. Grip force effects were lowest at 160 Hz vibration, where the greatest effects on tactile sensitivity were observed.

The effects measured in this study were acquired after removing the hand from the vibration stimulus rather than during actual treatment with HAV. Although unavoidable, the delays may have diminished the magnitude of the tactility effects. Since subjects were only exposed to vibration for a total of 15 minutes, larger effects are expected for longer periods of exposure. Kume et al. (1984) found tactile sensitivity had not completely recovered after twenty minutes from the time of vibration exposure.

It is important to emphasize that the task performed in this study was performed for a relatively short duration of 30 min. Tasks performed occupationally may involve far longer durations and greater grip exertions. Interactions between forceful exertions and segmental vibration needs to be studied in future investigations. This study did not examine long-term effects which may lead to increased risk of incurring cumulative trauma disorders.

The subjects participating in this study were all young, healthy adults, ranging in age between 21 and 35 years old. Consequently the effects of age is not included in these results and should be addressed in a future study. Haines et al. (1988), however, did not observe any age effects when testing depth sense thresholds for 91 workers having a mean age of 41 years.

This study was not intended to provide data for supplementing vibration exposure guidelines, but was conducted as a preliminary investigation for exploring the existence of these manual performance effects when using the frequency-weighted vibration standards. Results of this work suggests that HAV the ISO 5349 frequency weighted acceleration does not necessarily control for these short-term tactility effects. Exposure guidelines should be therefore developed for controlling performance aspects of hand transmitted vibration as well as health and safety exposure limits. This would involve a much larger population of subjects spanning a range of ages commensurate with the working population and studying a greater bandwidth of vibration frequencies. Since the effects increased for increasing frequency between 0 Hz and 160 Hz, a frequency weighting network that further de-emphasizes the high frequencies would likely be more appropriate for controlling these effects.

Results of this study provide additional guidelines for design and selection of hand tools, and should also be considered in task design. When tactile sensitivity is required for performing a task, avoid using tools vibrating in the frequency range of 160 Hz and acceleration magnitudes greater than or equal to 80 m/s^2 (unweighted). These factors should be particularly considered for tasks requiring tactile inspection when operating a vibrating hand tool, such as a sanding operation and inspecting for rough edges or smoothness. If tools having lower frequency vibration than 160 Hz are selected, acceleration amplitudes should be also lowered in order to avoid undesirable effects of increased grip force at lower vibration frequencies (Radwin et al., 1987).

Recommendations to help reduce vibration amplitude and exposure such as engineering controls, medical surveillance, work practices, and personal protective equipment have been proposed (Reynolds, 1977; Wasserman, 1985). They include: (1) use of engineering controls to minimize the need for vibrating tools, (2) redesigning tools, (3) careful maintenance of tools, (4) operating vibrating tools only when necessary, (5) use of anti-vibration tools and work apparel to reduce vibration levels, (6) rebalancing operations and introducing work breaks, (7) grasping tools as lightly as possible, consistent with safe work practices to minimize coupling, and (8) resting the tool on a support or work piece as much as possible.

CONCLUSIONS

Hand tool vibration exposure guidelines have mostly considered vascular disorders such as VWF. This investigation has demonstrated that hand tool vibration may have a short term effect on tactility and should be considered in future vibration exposure guidelines. Tactile sensitivity decreased with increasing frequency after operating a simulated hand tool for 30 min using a 50% duty cycle and 8 m/s^2 weighted acceleration, indicated by falling ridge threshold shifts. No shift was observed for rising ridge thresholds. Since tactile sensitivity decreased with increasing frequency between 0 Hz and 160 Hz, it was concluded that loss of tactility was not likely the cause of increased grip force, as shown in a previous study, since grip force effects were lowest at 160 Hz vibration where tactility loss was greatest.

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