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Evaluation of psychometric estimates of vibratory hand-tool grip and push forces

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Abstract

Tool grip and push forces are important determinants of health risk associated with operation of powered hand tools. In the field, use of sophisticated hand-force instrumentation can be impractical. This study investigated the potential for using psychophysical force recall methods to estimate grip and push forces when operating vibratory hand tools. This study examined various combinations of handle vibration and grip and push force exposures upon one's ability to recall those forces using psychophysical methods. Twelve male subjects grasped and pushed an instrumented handle for 45 s at one of three levels of force while it vibrated sinusoidally at one of five frequencies (0, 12.5, 40, 125, or 250 Hz). We examined the effects of post-exertion rest periods of 10 and 20 s upon force recall performance, and day-to-day test-retest reliability. Results showed vibration frequency and force level differentially influenced grip and push force recall accuracy. Subjects characteristically overestimated grip and push forces; especially during vibration exposures of 40 and 125 Hz. The magnitude of the overestimations increased as target force levels decreased. Test–retest correlations were reasonably strong.

Relevance to industry

Operators of powered hand tools are at risk of developing health problems associated with repeated forceful actions and exposure to intense hand-transmitted vibration. To better assess health risks, hand-tool coupling forces should be quantified. Psychophysical force recall techniques may permit assessment of these forces without the need for expensive or fragile instrumentation. An understanding of the effects of vibration and force level upon force recall accuracy and reliability must first be explored before such methods are proposed for research or field assessments.

Keywords: Force matching; Force recall; Coupling force; Hand-arm vibration; Psychophysics

1. Introduction

The operation of powered hand tools such as grinders, chain saws, chipping hammers, and drills exposes workers to hand-arm vibration. A tight hand-tool coupling not only imposes higher stresses on the anatomical structures of the hand-arm system and impedes peripheral circulation, but it also increases the transmissibility of vibration to the hand and arm (Riedel, 1995; Kaulbars, 1996; Wasserman, 1998). The use of vibratory tools in combination with forceful and repetitive hand motions may also result in a greater incidence of other forms of cumulative trauma disorders such as carpal tunnel syndrome (see Chapter 5 of NIOSH, 1997; Armstrong et al., 2002).

The need for hand-force measurement has been widely recognized (ISO, 2001), and an ISO standard addressing coupling-force measurement has been drafted (ISO, 2004). However, consensus as to how to best measure those forces has yet to be achieved.

Several methods have been used to measure the hand forces applied to tool handles. One is to instrument the tool

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grip surfaces with strain gauges or force transducers (Radwin, 1999; McGorry, 2001 are examples). However, the application of instrumentation to tool handles must inevitably be customized for each tool's unique hand grip geometry and other properties. This approach is expensive, time consuming, and could alter the true grip posture and dynamics when operating the tool if not properly configured. Some instrumentation manufacturers have dealt with these problems by developing wafer-thin, flexible force sensors that can be applied to tool handles or incorporated into a work glove (Wasserman et al., 2001; Nikonovas et al., 2004; Welcome et al., 2004). So far, such instrumentation methods have been expensive and are often too fragile for many hand-tool exposure assessments in field environments.

An alternative to direct force measurement is the use of psychophysical force magnitude estimation methods. Psychophysical methods are well-documented to demonstrate lawful behaviors (Stevens and Mack, 1959; Stevens, 1960; Eisler, 1962). Psychophysical methods are widely used in ergonomics for a variety of applications including exertion ratings (Borg, 1982), lifting task evaluations (Garg et al., 1980), posture studies (Wiker et al., 1989a), and for cross-modal matching of a wide variety of perceptual phenomena (Stevens, 1957). Perception of exertion levels has demonstrated repeatability within a variety of work postures (Wangenheim et al., 1986) and in post-exertion force-recall protocols (Hammarskjöld et al., 1990). Subjects have also shown remarkable abilities to correctly rank weights and forces (Karwowski et al., 1992; Kumar and Simmonds, 1994; Wiktorin et al., 1996).

Several investigators have studied the reliability and accuracy of psychophysical force recall techniques (Lowe, 1995; Wiktorin et al., 1996; Bao and Silverstein, 2005). This type of measurement is carried out by asking a test subject to reproduce his/her hand force with a similar type of hand-handle coupling action (e.g. push, power grip, or pinch grip) on a dynamometer, grip strength meter, or pinching strength meter. These studies demonstrated that the subjects could reproduce familiar forces reasonably well; and the force recall method could be considered reliable within certain force ranges. However, these studies were performed with manual tasks or simulated labor in the absence of hand-transmitted vibration exposure. The accuracy and reliability of the force recall method under exposure to hand-transmitted vibration have not been reported.

Force-recall accuracy may degrade during or immediately following exposure to vibrating tools. Several factors may contribute to force-recall degradation. First, several investigators have found motor-sensory illusions and loss of position sense with exposure to muscle or tendon vibration (Goodwin et al., 1972; Feldman and Latash, 1982; Miall et al., 2000). Nowak et al. (2004) suggested that vibration may impair a subject's memory of forces used in lifting tasks causing them to overestimate forces during task replication. Second, vibration-induced involuntary muscle contraction, known as the tonic vibration reflex (TVR), has been associated with over-gripping of tools (Goodwin et al., 1972; Radwin et al., 1987). Third, cutaneous perception of pressure and vibratory stimuli is differentially affected by various vibration frequencies and acceleration characteristics and is susceptible to vibration-induced paraesthesia (Verrillo, 1975).

The human hand-arm system has been regarded as a biomechanical system consisting of rigid elements that are coupled to springs and viscous damping elements. This system responds differently to various vibration exposures and with different levels of hand-tool coupling stiffness (i.e., grip force) for any given vibration frequency. Common terms used to describe these biodynamic responses to vibration include dissipated power, vibration transmissibility (expressed as a transfer function), and apparent mass. However, the biodynamic response has usually been expressed in terms of mechanical impedance (Lundström, 1984; ISO, 1998; Dong et al., 2004b). A high mechanical impedance value indicates that the system is more responsive to vibration stimuli. Mechanical systems, including the hand-arm system, exhibit particularly high impedance values at certain vibration frequencies. The frequency at which the system exhibits its highest mechanical impedance is referred to as the system's natural frequency or resonance point. It is speculated that vibration-induced disruptions in force perception may be particularly pronounced at the resonance frequency.

While there are several findings that indicate that subjects can reliably recall and reproduce forces over a wide range of postures and force levels (Wiktorin et al., 1996), the accuracy of force-recall data may be affected by changes in the force level. In his book, Stevens (1986, pp. 271–279) described a phenomenon that commonly occurs in psychophysical matching experiments. This phenomenon exhibits itself as a tendency for the subject to shorten the range of his/her responses. In other words, the subject tends to err in the direction of the center of the scale. Stevens referred to this consequence as the "regression effect" where subjects tend to regress towards the mean. This phenomenon appeared in several studies where subjects tended to over-force low-force targets and under-force high-force targets (e.g., Kumar and Simmonds, 1994). Likewise, in Wiker et al.'s (1989b) study, psychophysical functions for grip and pinch force pivoted; producing over-forcing of low-force grips; under-forcing high-force grips; and maintaining accuracy at the midpoint at 50% maximum voluntary effort grips.

There is likely an interaction between force level and the biodynamic response to vibration. Studies have shown that increased muscle force increases the biodynamic system stiffness which, in turn, increases its mechanical impedance and its resonance frequency (Lundström, 1984; Kihlberg, 1995; Dong et al., 2004b). Thus, increased or decreased grip and push forces might influence the resonance effect and the vibration-induced sensorineural disturbances at certain frequencies. Increased force levels may also

Table 1
Anthropometric descriptors of subjects participating in this study

Subject	Age (yr)	Stature (m)	Weight (kg)	Hand[a] breadth (mm)	Hand[b] length (mm)	Hand[c] circum. (mm)	Hand[d] volume (mm)	Forearm[e] volume (mm)
1	27	1.80	86.2	91	188	220	400	1820
2	24	1.80	81.7	84	180	220	360	1500
3	22	1.91	90.7	85	191	211	420	1700
4	27	1.73	97.7	95	206	233	520	1970
5	24	1.77	115.8	88	197	219	460	2320
6	18	1.73	63.5	87	184	213	350	1340
7	25	1.91	104.3	98	200	242	500	2080
8	19	1.78	90.7	89	196	215	420	1780
9	23	1.85	86.2	89	194	222	450	1760
10	23	1.82	83.9	82	193	210	430	1660
11	28	1.80	72.8	87	195	210	395	1460
12	20	1.83	74.8	77	187	203	400	1680
Mean	23	1.81	87.4	88	193	218	425	1756
SD	3	0.06	14.2	6	7	11	51	273

[a]At metacarpals.
[b]From tip of third finger to crease at wrist.
[c]At metacarpals.
[d]Water displaced by hand submerged to crease at wrist.
[e]Water displaced by hand and arm submerged to crease at elbow.

facilitate fatigue effects, and in turn, affect a subject's force perception and recall ability.

The force recall method requires minimum instrumentation and is convenient, inexpensive, and versatile for a variety of combinations for hand tools and work environments. However, the validity, reliability, and quantitative effects of vibration and grip force on post-exposure force-recall accuracy have yet to be determined. This study was designed to evaluate the impact of vibration, hand force level, and post-exposure delay on the accuracy of the force recall technique. The selected vibration frequencies, force levels, and delays were based on conditions that could be anticipated during actual field use of typical vibratory tools. The objectives of this study were to: (a) gauge the impact of sinusoidal vibration exposure, at various operationally-relevant levels of grip and push force, on a subject's ability to recall grip and push forces, (b) explore the impact of delays between vibration exposures and subsequent psychophysical assessments, and (c) evaluate test–retest reliability of the method.

2. Methods

2.1. Subjects

Twelve volunteer subjects were recruited from a local university and participated in the study on a paid and informed-consent basis. See Table 1 for relevant anthropometric descriptors of the study participants.

2.2. Instrumentation

A vibration test system (Unholtz-Dickie, TA250-S032-PB) was assembled and programmed to deliver sinusoidal vibration to an instrumented handle that was fixed upon a shaker. Single-axis sinusoidal vibrations were presented to the handle along the axis of the forearm at amplitudes for given exposure frequencies that met the ANSI S3.34 Standard (ANSI, 1986) <0.5-h exposure limits. Table 2 provides the handle frequency and acceleration characteristics for vibration exposures.

Table 2
Single-axis sinusoidal vibration exposures

Frequency (Hz)	Acceleration (m/s^2 peak)
0	—
12.5	11.3
40	28.4
125	89.9
250	179.4

Signals from two calibrated strain gauge sensors (Interface, SML-50) were amplified, averaged, and passed into a data acquisition module (National Instruments, PCI-6036E) to record handle grip force. Handle push forces were estimated by recording horizontal foot ground-reaction forces on a force plate (Kistler, 9286AA). To provide visual feedback of the applied grip and push forces, a custom graphical display was developed in-house using LabVIEW™ software (National Instruments, version 6.1). Grip and push forces were simultaneously displayed in front of the subjects on a computer monitor as unnumbered dial gauges. The top of each dial gauge had an index mark to indicate the target force. The grip force dial was programmed to display a range of target force ± 15 N, and the push force dial was set at target force ± 25 N. Regardless of the values of the target forces, the goal was

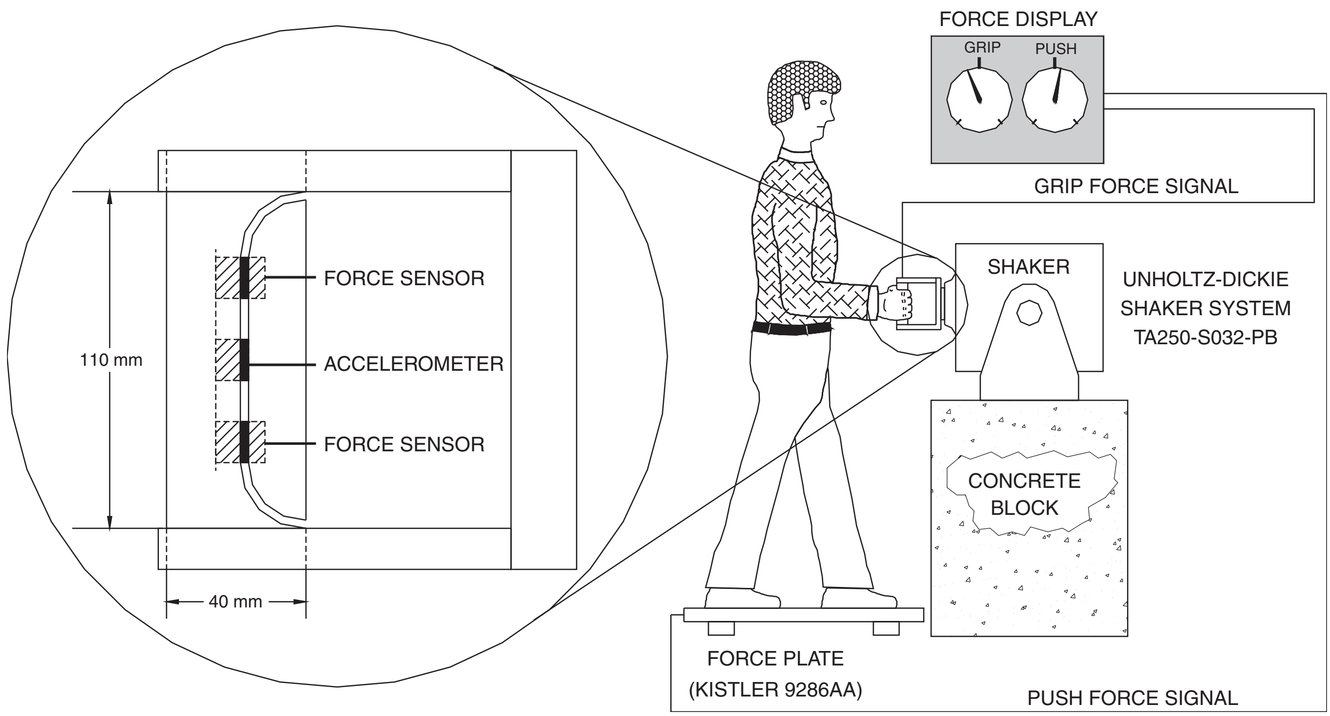

Fig. 1. View of experimental apparatus used to present controlled vibration exposures to the hand and to measure grip and push forces.

to orient the needles vertically. The grip and push force signals were sampled at 1000 Hz, and the video display was refreshed at a rate of 4 Hz. Fig. 1 shows the experimental setup.

2.3. Procedure

Prior to participation, the study procedure was explained to each subject. Following the briefing, each subject read and signed a consent form. The study protocol was reviewed and approved by the National Institute for Occupational Safety and Health (NIOSH) Human Subjects Review Board.

During the experiment, each subject stood upright on the calibrated force plate mounted on a platform. The subject posture and hand force levels were based on those presented in the ISO standard for the measurement of anti-vibration glove transmissibility (ISO 10819, 1996). The height of the platform was adjusted so that the subject could apply a power grip to the instrumented cylindrical handle at its midpoint while keeping his forearm parallel to the floor. With the elbow angled at 90°, the subject applied specified hand forces (grip and push) to the vibrating handle. Three levels of hand force were studied; (a) 15-N grip/25-N push, (b) 30-N grip/50-N push, and (c) 45-N grip/75-N push. Each subject was provided with visual feedback of his grip and push forces while he attempted to "memorize" his applied forces. At the conclusion of a 45-s force production/memorization period, subjects were instructed to release the handle which initiated a short, controlled rest period of either 10 or 20 s. During the rest period, the shaker was turned off, and the force dials were blanked from the monitor. At the end of the rest period, the subject was instructed to re-grip the now-idle handle and attempt to reproduce the grip and push forces without the aid of visual feedback. The subject was asked to nod his head once he believed he had matched the grip and push forces produced during exposure and to maintain the matched forces for 10 s. At the nod of the subject's head, the investigator mouse-clicked an icon on the feedback monitor to flag the data and initiate the force recall measurement period. After the 10-s grip and push force recall period, subjects were instructed to release the handle, step off the platform, and to rest for 90 s. During the last 10 s of the rest period, vibration was re-applied to the handle. Subjects were then asked to step back on the platform, re-assume the correct posture, and prepare for the next trial. The timeline of a complete force production, recall, and rest sequence is depicted in Fig. 2.

Each subject completed three practice trials at the beginning of each test session. Following practice, subjects completed a 30-trial matrix that consisted of each combination of frequency (five levels), force (three levels), and rest period (two levels). The 30-trial sequence was completely randomized for each subject. At no time were the subjects given information regarding the vibration frequency, hand-force levels, or duration of the rest period. After the 12th and 24th trials, subjects were given 5-min rest breaks. Including time for procedure explanation and consent form signing, a test session lasted about $2\frac{1}{2}$ h. In order to examine repeatability, each of the 12 subjects returned for a second session of testing. There was a minimum of 1 day and a maximum of 7 days between the two sessions. The same vibration frequency, force level,

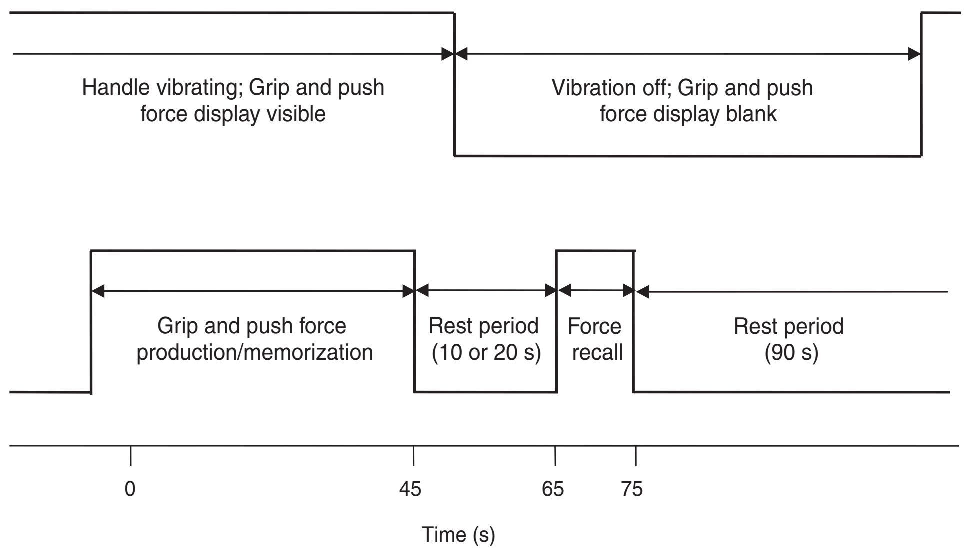

Fig. 2. Timeline of events during a force production and recall trial.

and rest period combinations were completed, but with a different independently randomized trial sequence. Hence, by the end of the study, each of the 12 subjects had twice completed the 30-trial matrix.

2.4. Analyses

Grip and push forces were averaged over the 45-s force production/memorization period. These averages became the values to which the averaged force recall values were compared. It was observed that the recall forces produced by some of the subjects began to decay about midway through each force recall attempt. Therefore, only the first 3 s of the force recall attempt were used during data analysis. Force recall accuracy was quantified in terms of error. The force recall error was computed for each trial from

$$E = F_p - F_r, \quad (1)$$

where E is the error between the average force produced during the 45-s vibration production/memorization period (F_p) and the 3-s force-recall average (F_r). The error values were expressed in Newtons.

A fixed-effects Analysis of Variance (ANOVA) model was used to test the effects of force type (grip, push), vibration frequency level, force level, rest period between force production and recall trials, and inter-day sessions upon grip and push forces as separate dependent metrics. Tukey tests were used for post-hoc analysis of significant effects ($p \leqslant 0.05$) using 95% confidence intervals. Test–retest reliabilities of replicated trials were computed using Pearson product-moment correlations.

3. Results

Means and standard deviations of grip and push force recall errors for the experimental conditions tested are provided in Table 3. Table 4 presents the ANOVA findings for grip and push errors.

Fig. 3 shows the relationship between force level and force recall accuracy. As shown in the figure, accuracy of grip or push force recall improved as force level increased. Tukey pair-wise comparisons showed that force recall errors were different among all target levels of grip or push force ($p < 0.01$).

The impacts of vibration frequency and force magnitude upon grip and push force recall errors are depicted in Fig. 4. There were consistent outcomes: (1) vibration frequency effects were quadratic in nature with greatest errors produced at 40 Hz, and (2) recall errors in grip or push force at any given frequency of vibration generally decreased as the forces to be recalled were increased in magnitude.

Tukey pair-wise tests showed that grip and push force recall errors were different between 40-Hz exposures and all other vibration exposures except 125 Hz ($p < 0.01$). The 12.5- and 250-Hz exposures were not significantly different than the no vibration condition nor to one another ($p > 0.05$). These findings did not change with length of rest periods between force production and recall trials, or between trial replicates across test days ($p > 0.10$).

Overall, grip and push force recall errors were statistically equivalent without regard to the rest time period between force production and recall trials. This finding held for grip force production regardless of the time period between exposure and recall trials. However, errors in push force recall declined when subjects increased rest periods between force production and recall trials. See Fig. 5.

The ANOVA revealed no difference in performance between test days ($p > 0.10$). To further examine reliability, the actual grip and push recall forces produced in Day 1 were compared with those of Day 2. The Pearson product-

Table 3
Means and standard deviations of grip and push force recall errors for given vibration, force and rest period between force production and recall trials

Parameter		Grip error (N)		Push error (N)	
		Mean	SD	Mean	SD
Vibration freq. (Hz)	0	3.2	9.3	2.2	10.9
	12.5	1.8	10.3	2.7	12.6
	40	8.9	11.8	8.2	13.9
	125	7.1	10.2	7.7	14.3
	250	4.7	11.0	5.3	12.5
Grip/push force level (N)	15/25	7.0	8.2	8.8	10.4
	30/50	5.4	11.4	4.7	12.1
	45/75	3.0	12.1	2.2	15.5
Rest period (s)	10	4.9	10.9	6.6	12.9
	20	5.4	10.8	3.8	13.2

Table 4
ANOVA of grip and push force recall error

SOURCE	SS	DF	MS	*F*	*P*<
Type of exertion (*T*)	2.6	1	2.6	0.0	0.89
Frequency (HZ)	8,948.3	4	2237.1	16.3	**0.01**
Force (*F*)	6,901.5	2	3450.8	25.1	**0.01**
Rest period (*R*)	500.1	1	500.1	3.6	0.06
Day (*D*)	66.7	1	66.7	0.5	0.49
*T**HZ	196.1	4	49.0	0.4	0.84
*T***F*	525.1	2	262.6	1.9	0.15
HZ**F*	979.1	8	122.4	0.9	0.52
*T**HZ**F*	726.3	8	90.8	0.7	0.73
*T***R*	948.0	1	948.0	6.9	**0.01**
HZ**R*	216.3	4	54.1	0.4	0.81
*T**HZ**R*	390.9	4	97.7	0.7	0.58
*F***R*	603.4	2	301.7	2.2	0.11
*T***F***R*	204.3	2	102.1	0.7	0.48
*F**HZ**R*	1,008.7	8	126.1	0.9	0.50
*T**HZ**F***R*	593.3	8	74.2	0.5	0.83
*T***D*	313.2	1	313.2	2.3	0.13
HZ**D*	255.1	4	63.8	0.5	0.76
*T**HZ**D*	92.2	4	23.1	0.2	0.95
*F***D*	479.7	2	239.8	1.7	0.17
*T***F***D*	58.4	2	29.2	0.2	0.81
HZ**F***D*	408.0	8	51.0	0.4	0.94
*T**HZ**F***D*	519.9	8	65.0	0.5	0.88
*R***D*	20.3	1	20.3	0.1	0.70
*T***R***D*	3.1	1	3.1	0.0	0.88
HZ**R***D*	282.7	4	70.7	0.5	0.72
*T**HZ**R***D*	222.6	4	55.7	0.4	0.80
*F***R***D*	24.7	2	12.4	0.1	0.91
*T***F***R***D*	184.9	2	92.5	0.7	0.51
*F**HZ**R***D*	714.0	8	89.3	0.7	0.74
*T**HZ**F***R***D*	313.7	8	39.2	0.3	0.97
Error	181,147.0	1320	137.2		
Total	246,773.4	1440			

moment correlations for each subject and for the group are contained in Table 5. The results indicate strong test–retest reliability as correlations for each subject were found to be significant ($p<0.01$) for both grip and push recall forces.

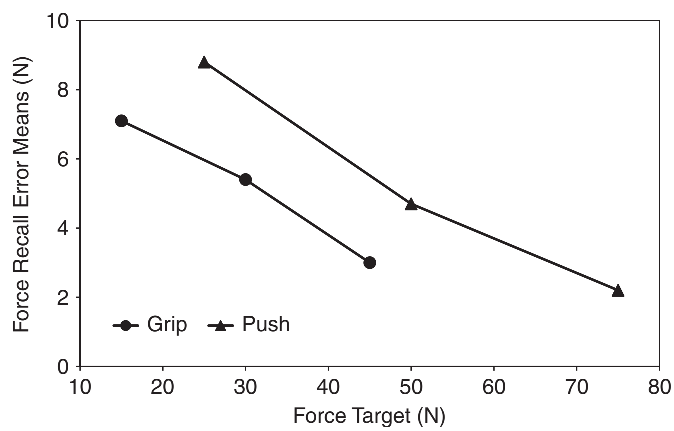

Fig. 3. Force recall accuracy versus grip and push force targets across all frequencies of vibration.

4. Discussion

Hand-arm vibration has previously demonstrated a capacity to alter sensorineural information generated within the dermis, the muscle–tendon complex, or mediated by the central nervous system (McCloskey, 1981; Nowak et al., 2003). McCloskey (1981) demonstrated that in addition to sensory feedback, motor cortex outflow is simultaneously transmitted to the sensory cortex in a feed-forward mechanism. This mechanism, referred to as "corollary discharge" or "efference copy," appears to influence a subject's perception of how much an object weighs or the amount of effort that is required to complete a motor task (Lacourse and Morris, 1991; Burgess and Jones, 1997).

Studies have shown that vibration may disrupt this sensory mechanism. For instance, Nowak et al. (2004) found that vibration induced overestimation of grip forces. The results of their study indicated that the subjects could quickly memorize the grip forces necessary to perform lifting lifts; and the subjects were able to appropriately

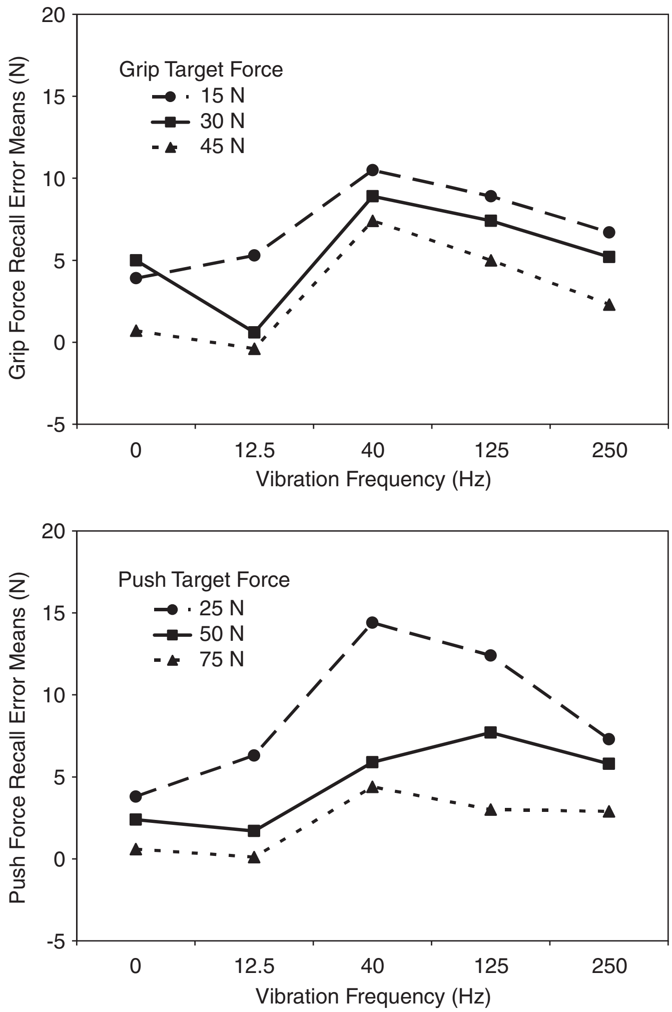

Fig. 4. Grip and push force recall error means plotted against vibration frequency.

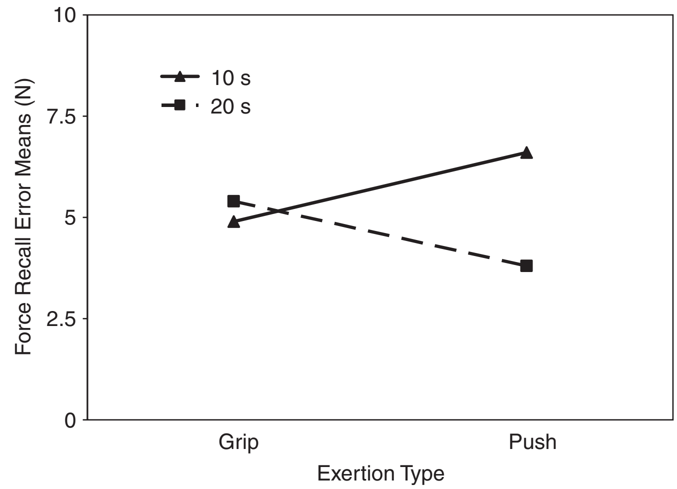

Fig. 5. Error in force recall as a function of exertion and rest period between force production and recall trials.

Table 5
Test–retest correlations across all experimental conditions ($N = 30$) for each subject

Subject	Grip	Push
1	0.63	0.76
2	0.74	0.90
3	0.69	0.75
4	0.55	0.85
5	0.65	0.82
6	0.66	0.87
7	0.78	0.88
8	0.66	0.74
9	0.88	0.94
10	0.65	0.77
11	0.71	0.75
12	0.54	0.84
Mean	0.68	0.82
Min	0.54	0.74
Max	0.88	0.94

scale their grip forces in subsequent lifts. The results were similar when the subjects used one hand during memorization and the opposite hand to perform subsequent lifts. When muscles were vibrated during the rest period, subjects' grip force rates increased and grip force peaks were higher as compared to non-vibration trials. The researchers suggested that vibration exposure may impair the memory processes involved in grip force scaling. Moreover, they concluded that since the vibration effect also transferred to the non-vibrated hand, vibration must have affected the efferent components involved in the grip force memory process. While the vibration exposure conditions in the present study were different, this efferent perturbation might explain, at least in part, the push and grip force overestimations observed here.

The notion that vibration affects the perception of static force sensation is supported by the results of several studies (Cafarelli and Kostka, 1981; Miall et al., 2000). Researchers have shown that vibration can excite muscle spindle primary endings, and to a lesser extent, spindle secondary endings, Golgi tendon organs, and Pacinian corpuscles (i.e. Burke et al., 1976; Cafarelli and Kostka, 1981). It has been suggested that vibration-induced afferent stimulation will lead to the perception of increased intensity of intramuscular tension (Cafarelli and Kostka, 1981). Similarly, the force recall overestimations realized in this study may have been influenced by vibration-induced disruptions in the muscle afferent flow.

It has also been established that peripheral afferent components play a significant role in force production perception (Goodwin et al., 1972; Lafargue et al., 2003). It has been estimated that the afferent contributions account for about 30% of the overall sensation of intramuscular tension (Cafarelli and Bigland-Ritchie, 1979). Depending upon the magnitude of grip forces required, differential weighting may be applied to cutaneous contact or pressure and muscle tension afferents (Ebied et al., 2004). Henningsen et al. (1995) demonstrated that changes in either efferent or afferent behavior in grip force production can influence perception that is dependent upon the other.

Several researchers in the 1960s discovered that when a moderately active muscle was stimulated by vibration, the activity in that muscle increased while the activity in the antagonist muscles decreased (Hagbarth and Eklund, 1965; de Gail et al., 1966). As discussed before, this phenomenon, known as the TVR, may have played a role in this study. However, Hagbarth and Eklund (1965) observed that TVR action was not normally induced unless the vibration was directly applied to the muscle tendons, and that any reflex action was limited to the muscles whose tendons were stimulated. Furthermore, subjects have demonstrated an ability to counteract or prevent TVR if visual feedback of limb position or muscle force is available (Hagbarth and Eklund, 1965; de Gail et al., 1966). Radwin et al. (1987) reported, using a comparable stimulus methodology, that estimated TVR response was greatest at 40 Hz; the frequency which demonstrated the greatest error in our force recall trials. Given that our greatest force recall error occurred at 40 Hz, and because we did not design the experiment to rule out the contribution of TVR, we are not dismissing its potential contribution to force recall errors in this study.

Another plausible contributor to the significant vibration effects is the disruption of the skin and subcutaneous afferents. There are several nerve fibers in the skin and subcutaneous tissues responsible for mechanoreceptive afferent flow. (For a review of these mechanoreceptive units, see Johansson and Vallbo (1983)). Briefly, the units are classified as either fast adapting (FA) or slow adapting (SA) and are divided into two types according to size and shape. Group I units are smaller and have sharp borders, while Group II units are larger and have relatively obscure borders. All of these units are sensitive to vibration in varying degrees. Of these units, the FA II units (Pacinian corpuscles and Golgi-Mazzoni bodies) are the most sensitive to vibration (Lundström and Johansson, 1986). Further, Verrillo (1975) identified the Pacinian corpuscle as the primary receptor for vibration perception. The FA II units are most sensitive when exposed to vibrations between 100 and 300 Hz (Johansson and Vallbo, 1983). Therefore, it is reasonable to presume that vibration-induced disturbances to the FA II unit outflow may have played a role in this study's force recall overestimations, particularly at 125 and 250 Hz.

The biodynamic responses of the fingers-hand-arm system may also influence force perception. In the present study, the largest grip and push force recall errors occurred at 40 Hz; regardless of the grip or push force magnitudes. This frequency falls within the range of reported hand-arm system resonance (25–63 Hz) (Kihlberg, 1995; ISO, 1998; Dong et al., 2004a). Grip and push force errors were also significant at 125 Hz. Human fingers have displayed resonance in the range of 100–250 Hz (Dong et al., 2004b). These results support the notion that vibration-induced disruptions in force perception and recall process may be particularly pronounced at the resonance frequency. Resonance may also affect afferent sensory processes.

Aside from purely mechanical changes increasing physical perturbation of efferent/afferent feedback, response changes observed in this study could be explained by sensory and perceptual phenomena. Nearly all grip and push force recall trials produced over-force errors. This observation is consistent with several early psychophysical studies that demonstrated that force recall accuracy depends on stimulus intensity (Stevens and Mack, 1959; Stevens, 1960). In the Stevens and Mack's (1959) study, the researchers found that the perception of apparent grip force approximates a power function with an exponent of 1.7.

In the present study, force-recall accuracy increased as the force target increased. This finding is consistent with an earlier study by Lowe (1995). Lowe's subjects were asked to match four levels of target grip force (20%, 35%, 50%, and 65% MVC). These subjects were more accurate when attempting to match the two higher force targets than with the two lower force targets. This phenomenon may be attributed to diminished cutaneous feedback in hypoxic dermis, resulting in greater reliance in muscle–tendon feedback for gauging force (Wiker et al., 1989b). Transitioning from cutaneous pressure cues to greater reliance upon deep muscle-tendon cues to gauge grip or push force level leads to the production of greater forces to achieve just noticeable differences in low-level grip forces. This error may diminish when subjects are asked to produce greater levels of perceived grip force in which cutaneous cues or shaping perceptions would be mitigated or eliminated (Wiker et al., 1989b).

5. Conclusions

The major objectives of this study were to explore the effects of vibration and force level on the accuracy of a force recall technique. Vibration frequency and force level were found to be significant influences on force recall accuracy. Subjects tended to overestimate grip and push forces. These overestimations were especially pronounced during vibration exposures of 40 and 125 Hz. Because those frequencies fall within the resonance frequency ranges for the hand-arm system (25–63 Hz) and the fingers (125–160 Hz), respectively, there appears to be a relationship between force recall accuracy and the biodynamic response of the hand-arm system to vibration. Vibration may also effect efferent and/or afferent contributions to the force memory process. Force recall errors were smaller at higher grip and push force levels than they were at lower force levels.

Applying instrumentation to tool handles to measure coupling forces can be expensive and impractical. As an alternative, a force matching or recall technique may be used. Based on this experiment, the force recall technique shows promise as errors were small throughout the range of operationally-relevant vibration and grip force conditions of this study.

Various powered hand tools generate unique vibration spectra with different dominant frequencies. Knowledge of the effects of the vibration at different dominant frequencies on force recall methods can be used to determine the reliability of this technique under vibration conditions. Moreover, knowledge of vibration effects and the effects of hand–handle coupling characteristics may foster the development of weighting factors for improving force recall applications.

Disclaimer

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

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