Effects of vibration on grip and push force-recall performance

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Abstract

Comprehensive assessments of health risks associated with the operation of vibratory tools should include evaluations of hand–tool coupling forces. The use of hand-force instrumentation in field applications can be difficult and expensive. A previous study (McDowell, T.W., Wiker, S.F., Dong, R.G., Welcome, D.E., Schopper, A.W., 2006. Evaluation of psychometric estimates of vibratory hand–tool grip and push forces. International Journal of Industrial Ergonomics 36(2), 119–128.) examined various combinations of handle vibration frequencies and grip and push force levels upon one's ability to recall those forces using psychophysical methods. The results of that study were promising. The present study is a follow-up experiment that further investigated the potential for using psychophysical force-recall methods to estimate grip and push forces when operating powered hand tools. In this experiment, 20 subjects (10 male, 10 female) grasped and pushed an instrumented handle for 45 s at one of three force levels while it vibrated sinusoidally at one of four frequencies (16, 31.5, 63, or 125 Hz) or with no vibration. Unlike the first study, two levels of vibration magnitude were examined along with gender differences. This study further clarifies relationships between vibration exposure characteristics and their effects on grip and push force-recall performance. Vibration exposure conditions and other influential factors can be accounted for in enhanced force-recall methodologies that can be incorporated into a variety of workplace exposure assessment applications.

Relevance to industry

Workers who are repeatedly exposed to intense hand-transmitted vibration are at risk of developing health problems. To better assess these health risks, hand–tool coupling forces should be evaluated. A refined psychophysical force-recall technique may be a practical alternative to expensive or fragile instrumentation. Before such a method is proposed for laboratory or field applications, an understanding of vibration effects upon force-recall performance must first be explored.
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1. Introduction

Workers who apply repeated forceful gripping and pushing forces to the handles of vibratory tools can be at risk of developing circulatory, neurological, or musculoskeletal disorders (NIOSH, 1997; Griffin and Bovenzi, 2001). These disorders have been collectively grouped as hand–arm vibration syndrome (HAVS) (Gemne and Taylor, 1983). The need for assessing HAVS risks associated with exposures to hand-transmitted vibration is well established. It is also well known that the amount of vibration actually transmitted to the hand–arm system is dependent on the coupling forces at the hand–handle interface (Taylor and Brammer, 1982; Riedel, 1995; Kaulbars, 1996). The international standard for assessing exposure to hand-transmitted vibration, ISO 5349-1 (2001), indicates that hand coupling forces influence the vibration energy transmitted to the hand. The need to quantify the forces acting at the hand–handle interface has been further emphasized in a recent draft international standard (ISO/DIS 15230, 2005). While the draft standard attempts to

establish definitions and standardize terminology, it contains no specific guideline or methodology for hand force measurement. Likewise, neither the current National Institute for Occupational Safety and Health (NIOSH) recommendations (NIOSH, 1989) nor the American National Standards Institute (ANSI) standard (ANSI S2.70, 2006) for assessing hand–arm vibration exposure provide specific guidance for hand force quantification.

An understanding of the nature of hand forces applied to tools is essential for developing appropriate strategies and working procedures geared to minimize stress and transmitted vibration. Unfortunately, there has been no consensus as to how to best measure those forces. Correction factors have been proposed for improved application of the ISO standard (Riedel, 1995; Kaulbars, 1996). However, these correction factors do not provide adequate estimates of hand contact forces (Welcome et al., 2004).

While hand forces can be effectively and accurately measured with dynamometers and handgrip and pinch strength meters, it remains a formidable task to quantify hand forces applied to vibratory tools in the workplace. Several methodologies have been utilized for measuring hand coupling forces on tool handles. One way is to affix strain gauges or force transducers to tool handles (Radwin and Yen, 1999; McGorry, 2001). However, the application of tool handle instrumentation may alter the hand postures and contact areas on the handle surface such that the measured forces may not offer an accurate account of the coupling forces actually utilized by workers. Thin, flexible force sensors that can be wrapped around the tool handle or incorporated into a work glove may overcome these difficulties (Gurram et al., 1995; Wasserman et al., 2001; Welcome et al., 2004). Unfortunately, such instrumentation installations can be expensive and too fragile for many workplace environments. Therefore, alternative methods for coupling force quantification need to be developed.

One promising force measurement alternative involves the psychophysical method of force recall. With this type of measurement, a subject applies hand forces to a tool handle while performing a real or simulated work task; then they are asked to recall and reproduce the hand forces with a similar posture and coupling action on a grip strength meter or handle dynamometer. Several investigators (Lowe, 1995; Wiktorin et al., 1996; Bao and Silverstein, 2005) have studied the reliability and accuracy of this method. Test subjects demonstrated that they could reliably reproduce forces within certain ranges; though these studies were performed with manual tasks or simulated labor with no exposures to hand-transmitted vibration. The effects of hand-transmitted vibration exposure on force-recall performance are not well known.

Exposure to hand-transmitted vibration may lead to a decline in force-recall performance. Several vibration-related factors may contribute to force-recall deterioration. Investigators have observed that exposure to muscle or tendon vibration can cause motor–sensory illusions and loss of position sense (Feldman and Latash, 1982; Miall et al., 2000). Nowak et al. (2004) found that vibration may impair a subject's memory of hand forces applied during lifting tasks. This interference can lead to the overestimation of those forces during task replication attempts. Additionally, variations in vibration frequency and/or magnitude can differentially-affect mechanoreceptive responses to stresses and vibratory stimuli (Verrillo, 1975).

Like any biomechanical system, the human hand–arm system will respond differently to various vibration exposures. The specific biodynamic response of any individual's hand and arm system depends on its mechanical properties (Dong et al., 2004a). The frequency at which any system exhibits its greatest response is commonly referred to as the system's natural frequency or resonance point. At or near resonance, the aforementioned vibration-induced disruptions are likely to be particularly pronounced. However, a system's resonance point will change with variations in the system's dynamic stiffness (Lundström, 1984; Kihlberg, 1995; Dong et al., 2004b). As the forces acting at the hand–handle interface change, the system stiffness will change along with system and subsystem resonance. Thus, the overall response of the hand–arm system to vibration results from a complex interaction of the system's physical properties, the vibration exposure characteristics, and the changing stiffness of the system as applied forces vary.

A previous experiment was conducted at our NIOSH laboratory to explore the effects of various vibration frequencies and other factors on force-recall performance (McDowell et al., 2006). The test apparatus and subject postures employed in that study were identical to those described below for the present study. Results showed that on average the subjects characteristically overestimated grip and push forces. Force-recall errors were significantly higher following 40 and 125 Hz vibration exposures as compared to the other exposure conditions. Force-recall errors decreased as target force levels increased. No significant difference was found between the two levels of rest period duration. Test–retest correlations were strong.

Overall, the results of the previous force-recall experiment showed promise as errors were small throughout the range of the study's vibration and grip force conditions. Encouraged by those results, we elected to conduct this follow-up study to further explore force-recall performance under vibration conditions. The major differences between the present study and the previous one include:

(a) a new and larger set of test subjects,
(b) the participation of both genders,
(c) a different set of vibration frequencies,
(d) a single level of rest period duration (as opposed to two levels), and
(e) the introduction of a second level of vibration magnitude.

The objectives of the present study are to evaluate the impact of (a) vibration frequency, (b) vibration magnitude, (c) grip and push force level, and (d) gender on a subject's ability to recall grip and push forces. The selected vibration and hand force conditions are based on those that could be anticipated during actual field use of typical vibratory tools.

2. Methods

2.1. Subjects

For the present study, 20 participants (10 male, 10 female) were recruited via notices posted at a local university and other area public facilities. The subjects participated on a paid and informed-consent basis. Table 1 contains anthropometric descriptors of the study participants.

2.2. Equipment and instrumentation

An electrodynamic vibration test system (Unholtz-Dickie, TA250-S032-PB) delivered sinusoidal vibration to an instrumented handle that was affixed to a shaker. Fig. 1 shows the experimental setup and depicts the subject

posture. Single-axis sinusoidal vibrations were presented to the handle along the axis of the subject's forearm.

Nine specific vibration exposure conditions were presented to the subjects; four vibration frequencies and two levels of vibration magnitude were examined along with the 0 Hz (no vibration) condition. Table 2 provides details of the nine vibration exposure conditions. The two vibration magnitude levels were based on the frequency-dependent acceleration values corresponding to the ANSI S3.34 Standard (ANSI S3.34, 1986) 4–8-h (referred to as low magnitude in this study) and <0.5-h (referred to as high magnitude) exposure limits.

To measure the applied grip forces, a two-piece cylindrical handle (40 mm diameter) comprised two calibrated strain gauge sensors (Interface, SML-50). The force sensors were sandwiched between the two handle pieces. The signals from the grip force sensors were amplified, averaged, and passed into a data acquisition module (National Instruments, PCI-6036E). Push forces applied to the handle were quantified by recording horizontal or shear forces at the subjects' feet while they stood upon a force plate (Kistler, 9286AA).

A custom graphical display was developed in-house, using National Instruments LabVIEW™ software (version 6.1), to present and record the applied grip and push

Table 1
Anthropometric descriptors of subjects participating in this study

Subject	Age (yrs)	Stature (m)	Weight (kg)	Hand breadth (mm)[a]	Hand length (mm)[b]	Hand circum. (mm)[c]	Hand volume (ml)[d]	Forearm volume (ml)[e]
F1	18	1.70	63.2	74	174	178	245	965
F2	33	1.73	67.0	83	184	198	285	1000
F3	26	1.61	57.2	82	177	195	260	940
F4	27	1.63	52.0	73	180	183	250	910
F5	22	1.57	64.0	76	171	187	258	1095
F6	45	1.65	71.8	76	178	187	275	1200
F7	27	1.68	62.0	75	170	180	263	1075
F8	35	1.52	46.4	70	158	171	195	611
F9	24	1.61	54.4	71	176	178	235	950
F10	29	1.63	75.2	74	181	180	313	1205
M1	28	1.75	75.4	87	181	210	313	1700
M2	22	1.78	81.6	94	188	221	400	1675
M3	27	1.88	90.8	88	198	207	380	1675
M4	29	1.78	72.6	90	192	202	383	1450
M5	33	1.78	65.9	85	183	208	370	1490
M6	28	1.78	87.4	88	193	212	428	1700
M7	27	1.91	112.8	80	188	200	345	1570
M8	21	1.73	102.2	89	186	223	432	1800
M9	19	1.98	102.2	100	203	238	500	1980
M10	19	1.73	63.5	87	184	213	350	1340
Mean	27	1.72	73.4	82	182	199	324	1317
Min	18	1.52	46.4	70	158	171	195	611
Max	45	1.98	12.8	100	203	238	500	1980
SD	6.4	0.11	17.9	8.3	10.3	18.0	80.0	372.3

[a]At metacarpals.
[b]From tip of 3rd finger to crease at wrist.
[c]At metacarpals.
[d]Water displaced by hand submerged to crease at wrist.
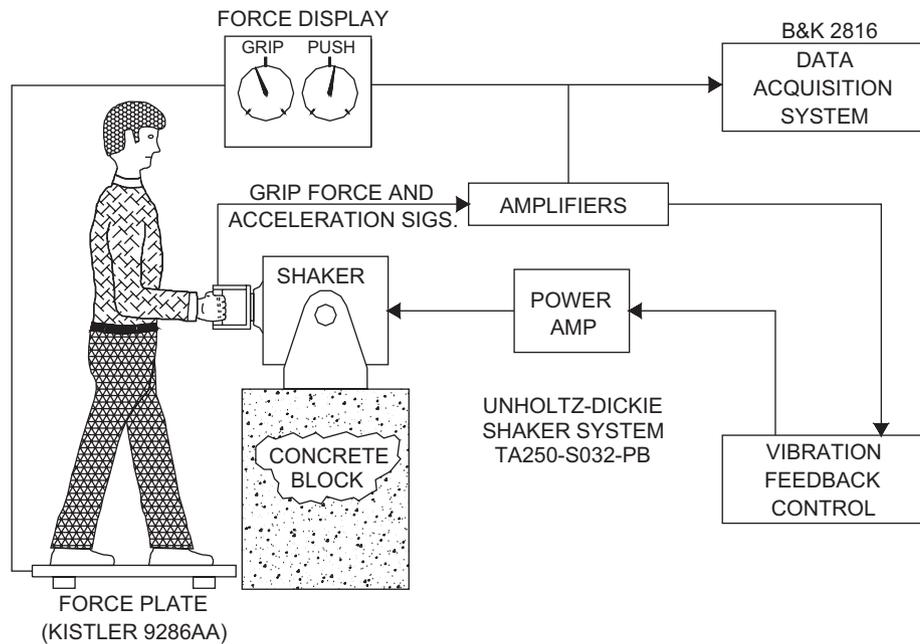[e]Water displaced by hand and arm submerged to crease at elbow.

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

Table 2
The nine vibration conditions presented to the subjects in the present study

Frequency (Hz)	Low magnitude (m/s^2 peak)	High magnitude (m/s^2 peak)
0.0	—	—
16.0	2.8	11.3
31.5	5.6	22.6
63.0	11.3	45.1
125.0	22.5	89.9

The no-vibration condition is indicated as 0 Hz. Low magnitude = 4–8-hour limits established by the ANSI S3.34 standard; High magnitude = <0.5-hour limits (ANSI S3.34, 1986).

forces. A computer monitor simultaneously displayed the grip and push forces as unnumbered dial gauges. The top of each dial gauge featured an index mark to indicate the target force. The grip force dial gauge was configured to display a range of target force ±15 N; the push force dial gauge was set at target force ±25 N. (See McDowell (2006) for additional details regarding the instrumented handle, graphical display, and monitor placement.) Regardless of the values of the target grip and push forces, the goal was to vertically-align the gauge needles with the index marks. The grip and push force signals were sampled at 1000 Hz; the video display was refreshed at a rate of 4 Hz.

2.3. Procedure

The study protocol and subject consent form were reviewed and approved by the NIOSH Human Subjects Review Board and West Virginia University's Institutional Review Board. Prior to participation, the study procedure

was explained to each subject. Following the briefing, each subject read and signed the consent form.

As depicted in Fig. 1, each subject stood upright on the calibrated force plate mounted on a platform. The height of the platform was adjusted so that the test participant could apply specified hand forces (grip and push) to the instrumented handle at its midpoint while maintaining an elbow angle of 90° with the forearm parallel to the floor. The subject posture and grip and push force levels were based on those presented in the ISO standard for the measurement of anti-vibration glove transmissibility (ISO 10819, 1996). As in the previous study, three levels of hand force were examined; (a) 15 N grip, 25 N push, (b) 30 N grip, 50 N push, and (c) 45 N grip, 75 N push.

The timeline for a force memorization and recall trial for the present experiment is similar to that described in the previous experiment (McDowell et al., 2006) and is depicted in Fig. 2. In summary, each participant was provided with visual feedback of their grip and push forces while they attempted to "memorize" the applied forces. At the conclusion of a 45-second force-memorization period, the participant released the handle which initiated a short, controlled rest period of 20 s. During the rest period, the shaker was turned off, and the grip and push force dials were blanked from the monitor. At the end of the rest period, the study participant re-gripped the now-idle handle and attempted to reproduce the grip and push forces without visual feedback. The subject was asked to nod their head once they believed they had matched the grip and push forces they applied during vibration exposure and to maintain the recalled forces for 5 s. The investigator mouse-clicked an icon on the feedback monitor at the nod of the participant's head. This action
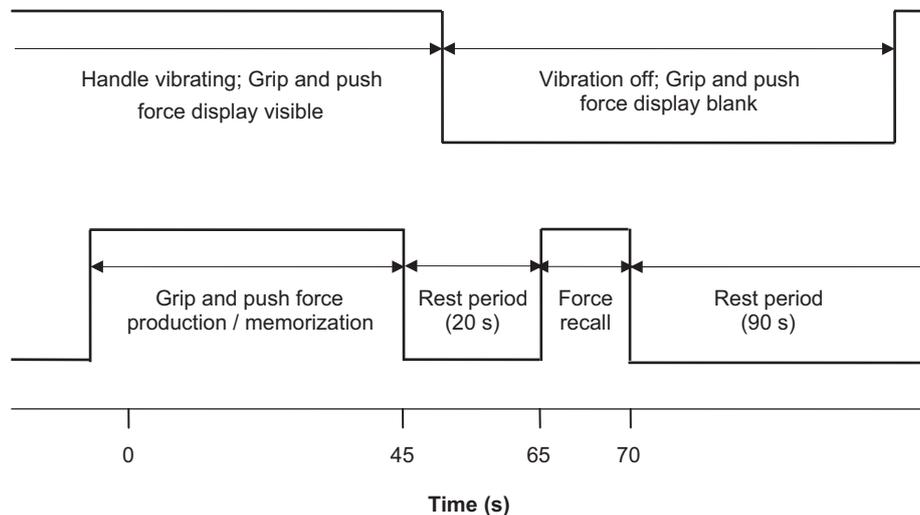
Fig. 2. Timeline of events during a force memorization and recall trial.

initiated the force-recall measurement period. After the five-second grip and push force-recall period, the participant released the handle, stepped off the platform, and rested for 90 s while the investigators prepared for the next trial. Participants then stepped back on the platform, re-assumed the correct posture, and began the next trial.

Each study participant completed three practice trials at the beginning of each test session. Following the three practice trials, participants completed a 27-trial matrix that consisted of each combination of vibration exposure condition (nine levels) and applied hand force (three levels). Except for the practice runs, the sequence was completely randomized for each subject. At no time were the subjects provided with information regarding the hand-force levels or vibration characteristics. Participants were given five-minute rest breaks after the 10th and 20th trials. Including time for procedure explanation and consent form signing, a test session lasted about $2\frac{1}{2}$ h. In order to examine repeatability of subject performance, each of the 20 subjects returned on another day for a second session of testing. The same vibration condition and force level combinations were completed, but with a different independently-randomized trial sequence. Thus, by the end of the study, each of the 20 subjects had twice completed the full matrix.

2.4. Analyses

Grip and push forces were separately-averaged over the 45-second force-memorization period. These averages became the values to which the force-recall values were compared. Force-recall performance was quantified in terms of error. The force-recall error was computed for each trial from

$$E = F_r - F_m,$$ (1)

where E is the error, in Newtons, F_m the average force produced during a 45 s vibration exposure/force memor-

ization period, F_r the average force produced during the subsequent force-recall period.

Separate ANOVAs were conducted for grip error and push error to identify influential factors and any significant interactions. Because the factors were not fully crossed (i.e., low and high magnitudes do not exist for the no-vibration condition), the 0 Hz results were excluded from the initial analyses. A mixed within-subjects (split-plot) factorial design with repeated measures on test session was used with gender serving as the whole plot with vibration frequency (four levels), applied force (three levels), vibration magnitude (two levels), and test session (Day 1 or Day 2) as sub-plot factors. Test–retest reliabilities of replicated trials were computed using Pearson product–moment correlations.

To further explore the vibration effect, a follow-up set of mixed within-subjects factorial ANOVAs was conducted to include the 0 Hz condition. Once again, a gender-based split-plot design was used with vibration condition (nine levels), force level (three levels), and test session (two levels) as sub-plot factors. Fisher's least significant difference (LSD) tests were used for post hoc pairwise comparisons.

3. Results

3.1. Summary of results

Table 3 contains the grip and push force-recall error means, standard deviations, and 95% confidence intervals for each vibration condition, force level, gender, and test day.

To evaluate the normality assumption for the ANOVAs, normal probability plots of residuals were examined. The assessments proved to be satisfactory; no troubling departures from normality were revealed. The ANOVA results indicate that the interaction between vibration frequency and vibration magnitude is statistically significant for both grip force recall ($F_{3,54} = 4.36$, $p < 0.01$) and

Table 3
Force-recall error means, standard deviations, and 95% confidence intervals for given vibration condition, force level, gender, and test session evaluated in the present study

Parameter	Level	Grip				Push			
		Recall error		95% C.I.		Recall error		95% C.I.	
		Mean	SD	Lower bound	Upper bound	Mean	SD	Lower bound	Upper bound
Vibration condition	No vibration	4.4	13.9	1.9	6.9	2.3	10.5	−0.1	4.7
	16 Hz/Low mag	4.6	12.2	2.4	6.8	3.2	10.5	1.3	5.1
	16 Hz/High mag	5.9	14.9	3.2	8.6	5.3	13.1	2.9	7.7
	31.5 Hz/Low mag	5.5	16.1	2.6	8.5	4.0	12.4	1.8	6.3
	31.5 Hz/High mag	11.3	18.2	8.0	14.6	11.1	15.1	8.3	13.8
	63 Hz/Low mag	6.4	13.8	3.9	8.9	4.0	13.9	1.5	6.5
	63 Hz/High mag	10.2	16.6	7.2	13.2	14.5	17.6	11.3	17.7
	125 Hz/Low mag	6.8	14.9	4.1	9.5	4.4	12.7	2.1	6.6
	125 Hz/High mag	6.4	16.7	3.4	9.5	8.5	15.4	5.7	11.2
Force level	Low	6.8	10.3	5.7	7.8	5.2	9.7	4.2	6.2
	Medium	6.9	15.9	5.2	8.5	5.4	13.4	4.1	6.8
	High	6.9	19.0	4.9	8.9	8.4	18.5	6.5	10.3
Gender	Female	5.9	18.2	4.3	7.4	3.9	13.9	2.8	5.1
	Male	7.8	12.0	6.8	8.8	8.8	14.5	7.6	10.0
Test session	Day 1	7.6	17.1	6.1	9.0	7.2	14.6	6.0	8.4
	Day 2	6.1	13.6	5.0	7.3	5.5	14.1	4.3	6.7

All values are in Newtons.

push force recall ($F_{3,54} = 6.54$, $p < 0.001$). Test session was also revealed as a statistically significant factor as the error means for Day 1 test sessions were found to be significantly higher than those for Day 2 for both grip ($F_{1,18} = 5.92$, $p < 0.05$) and push ($F_{1,18} = 6.15$, $p < 0.05$). Force level was a statistically significant influence on push force-recall error ($F_{2,36} = 9.10$, $p < 0.001$); but force level was not found to be significant for grip. No other main effects or interactions approached statistical significance for either grip or push ($p > 0.15$ for all other effects).

3.2. The effect of vibration

As noted above, the ANOVA results revealed that exposure to vibration significantly influences force-recall performance. The vibration effect is illustrated in Fig. 3.

As shown in Fig. 3(a), the pairwise comparisons of grip force-recall error means for the nine vibration conditions indicated that errors during trials with exposures to 31.5 Hz/high magnitude and 63 Hz/high magnitude vibrations were significantly higher ($p < 0.01$) than each of the other seven vibration conditions; the error means for these two conditions were not statistically different from each other. No significant differences were found among the other vibration conditions for grip force recall. The pairwise comparison results for push force recall are illustrated in Fig. 3(b). As indicated, the 63 Hz/high magnitude condition produced significantly higher errors than all other vibration conditions ($p < 0.01$). The 31.5 Hz/ high magnitude push force-recall error mean was signifi-

cantly higher ($p < 0.01$) than all conditions except for the 63 Hz/high magnitude and 125 Hz/high magnitude conditions. The 125 Hz/high magnitude errors were higher ($p < 0.05$) than all conditions except 31.5 Hz/high magnitude and 63 Hz/high magnitude. The 16 Hz/high magnitude mean was significantly higher than the 0 Hz (no vibration) condition at the $p < 0.05$ level; it was not significantly higher than any of the low magnitude vibration conditions. No significant differences were found among the no-vibration condition and the four low magnitude vibration condition comparisons.

3.3. Test session effect

As outlined in Section 2, after completing randomized trials for each combination of vibration frequency, vibration magnitude, and force level, each participant returned on another day to complete the entire test matrix in a newly-randomized order. The ANOVA results provided evidence of a practice effect as the force-recall error means for Day 1 test sessions were significantly higher than those for Day 2 for both grip and push (see Table 3). To further examine test–retest reliability, Pearson product–moment correlations (r) were calculated for each subject's recalled grip and push forces across all test variable combinations ($N = 27$). These results, presented in Table 4, indicate strong test–retest reliability for both grip and push force recall as correlations for all but one participant were found to be significant.
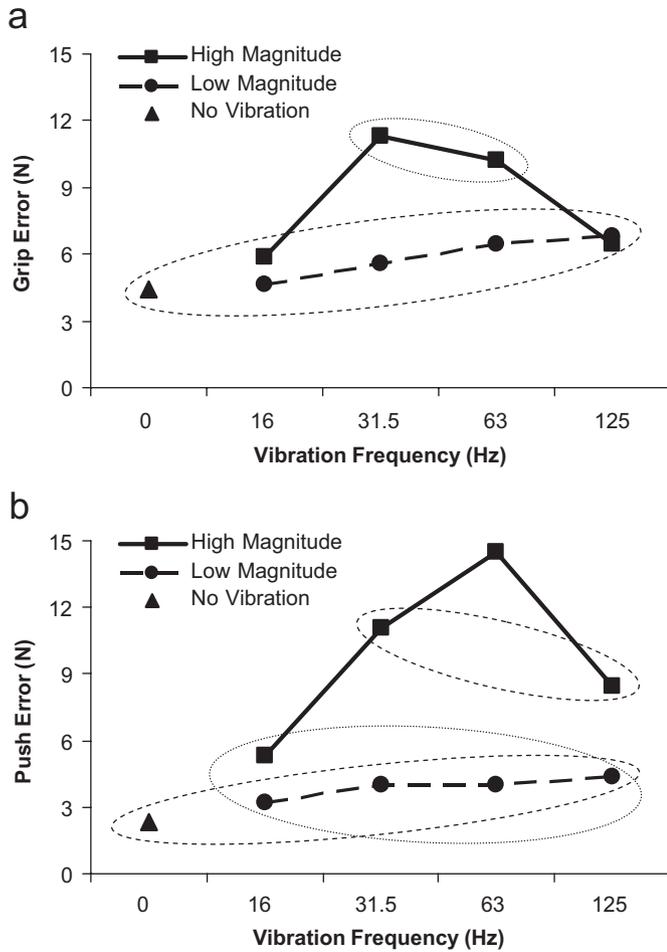
Fig. 3. Force-recall error means for grip 3(a) and push 3(b) at each of the nine vibration exposure conditions. The ellipses indicate the results of the pairwise comparisons; means within a given ellipse are not significantly different at the $p < 0.05$ level.

Table 4
Test–retest correlations across all experimental conditions ($N = 27$) for each of the 20 subjects

Subject	Grip	Push	Days between sessions
M8	0.30	0.86**	37
M9	0.45*	0.61**	17
M7	0.51**	0.63**	1
M1	0.54**	0.86**	14
F6	0.58**	0.83**	2
M2	0.64**	0.90**	1
M3	0.64**	0.92**	1
F5	0.65**	0.83**	1
F7	0.69**	0.92**	32
F9	0.69**	0.94**	7
F8	0.71**	0.91**	7
F2	0.73**	0.81**	1
M5	0.74**	0.85**	6
F3	0.76**	0.78**	1
F1	0.77**	0.93**	14
M10	0.79**	0.90**	6
F10	0.83**	0.91**	1
F4	0.88**	0.94**	7
M4	0.91**	0.92**	1
M6	0.95**	0.93**	30
Mean	0.69	0.86	9
SD	0.16	0.09	11
Min	0.30	0.61	1
Max	0.95	0.94	37

The subject data are sorted from worst to best by grip. Days between the two test sessions for each subject are also indicated.
*Sig. at 0.05 level.
**Sig. at 0.01 level.

3.4. The effect of force level

The push force-recall error mean for the highest force level was significantly higher than both of the other two force level means; the low and medium force level means for push force-recall error were not statistically different from each other. No significant differences were found among the grip force-recall error means for the three force levels.

4. Discussion

Test subjects tended to slightly overestimate grip and push forces at all levels of target force and vibration exposure. This result is consistent with early psychophysical studies of force estimation (Stevens and Mack, 1959; Stevens, 1960). While humans have demonstrated a tendency for overestimating static forces in non-vibration conditions, the force overestimations realized in this experiment and the previous experiment (McDowell et al., 2006) may have been further influenced by vibration disruptions in the muscle afferent flow. Research has indicated that vibration can excite muscle spindle primary endings, spindle secondary endings, Golgi tendon organs, and Pacinian corpuscles (e.g. Burke et al., 1976; Cafarelli and Kostka, 1981). The grip and push force overestimations observed in the present study support the hypothesis that vibration-induced afferent stimulation will lead to the perception of increased intensity of intramuscular tension as described by Cafarelli and Kostka (1981).

Nowak et al. (2004) suggested that the memory processes involved in grip force scaling are susceptible to vibration-induced disruptions. They further indicated that vibration affects the efferent components involved in the grip force memory process. Their findings may at least partially explain the grip and push force-recall errors observed in the present study.

The vibration effect demonstrated in this study is consistent with the results of our previous study (McDowell et al., 2006). To provide a more complete picture of the effect of vibration frequency, the results of the two experiments are combined and shown graphically in Fig. 4. It can be seen that vibration frequency similarly affected grip and push force-recall performance. As further indicated, overestimations were notably higher during
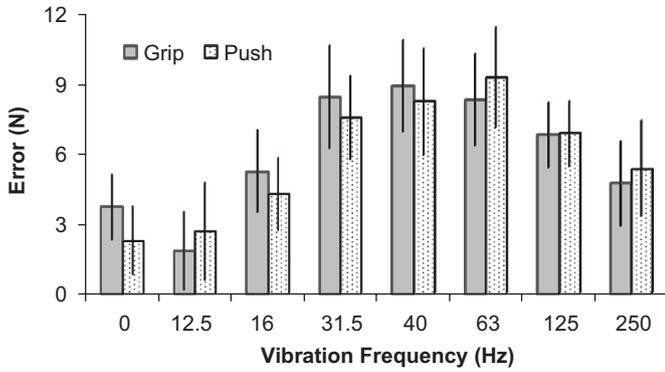
Fig. 4. Grip and push force-recall error means plotted against vibration frequencies evaluated in the present study and the previous study (McDowell et al., 2006).

vibration exposures in the range from 31.5 to 63 Hz for both grip and push force recall. Error means for 125 Hz exposures were found to be significant in the first experiment for both grip and push; this frequency was also found to be significant for push force recall in the present experiment. These frequencies fall within the resonance frequency ranges for the hand–arm system (25–63 Hz) and the fingers (80–250 Hz), respectively (Sörensson and Lundström, 1992; Kihlberg, 1995; ISO 10068, 1998; Dong et al., 2004a, b). At or near resonance, biomechanical systems and sub-systems are more responsive to vibration stimuli. It follows that vibration-induced disruptions in force memorization and recall processes are expected to be greater in these vibration frequency ranges. However, it should be noted that the present study revealed that low magnitude vibration exposures do not significantly affect force-recall accuracy (see Fig. 3). Thus, vibration exposures must be of sufficient magnitude to induce the vibration frequency effect.

The phenomenon known as the Tonic Vibration Reflex (TVR) may have influenced the grip and push force-recall results of this study. Radwin et al. (1987) reported that responses attributed to TVR were greatest at 40 Hz; the frequency which demonstrated the greatest mean error across the exposure conditions of the previous experiment (McDowell et al., 2006). In the present experiment, the greatest errors occurred at 31.5 and 63 Hz. Because the greatest force-recall errors occurred at and around 40 Hz in these two experiments, and as the experiments were not designed to rule out nor confirm the influence of TVR, the potential of TVR contribution to force-recall errors in this research cannot be ruled out.

The force level effect demonstrated in this study is somewhat contradictory to that found in our previous experiment (McDowell et al., 2006), even though the same force levels were used. However, when force recall performance is expressed in terms of percentage of the target force, a fairly consistent pattern emerges; force recall performance improves as relative force level increases for both gripping and pushing efforts. This trend is depicted in Fig. 5. In previous research, Lowe (1995) found that grip
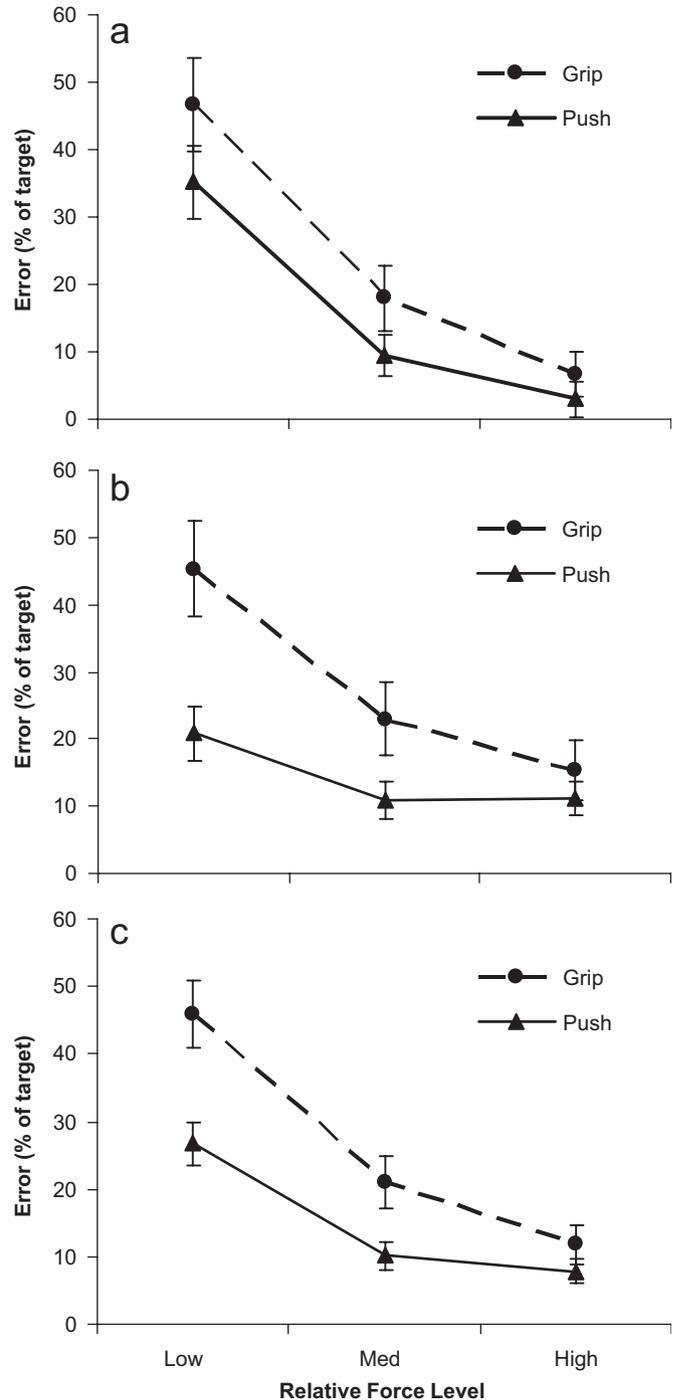

Fig. 5. Grip and push force-recall error means expressed as a percentage of the target force plotted against relative force level for (a) the previous study (McDowell et al., 2006), (b) the present study, and (c) the combined study data (Y error bars = 95% C.I.).

force-recall performance varies with the magnitude of the target force. Lowe's subjects were asked to match four levels of target grip force based on measurements of each subject's maximal voluntary contraction (MVC). Target levels were set at 20%, 35%, 50%, and 65% MVC. On average, Lowe's subjects' force-matching efforts were closer to the 50% and 65% MVC targets than with the

20% and 35% targets. While the present experiment did not include tests for subject strength, the trend depicted in Fig. 5 is consistent with Lowe's results.

5. Conclusions

The primary conclusion of this research is that this force-recall technique shows some promise as an alternative to expensive and fragile force-sensing instrumentation, and it should be further studied as a method for characterizing grip and push forces in field and laboratory settings. Subjects tended to overestimate grip and push forces over the entire range of operationally-relevant hand–handle coupling forces and vibration exposure conditions, especially at the lower force targets. Recalled grip and push force errors were relatively small at the highest force levels. This force-recall technique also produced strong test–retest correlations. As indicated in Table 4, the amount of time between test sessions seemed to have no effect on test–retest correlations.

This research has clearly identified three important factors that significantly affect grip and push force-recall performance:

(1) *Vibration exposure*: Recalled grip and push force errors were highest when vibration exposures were in the frequency range from 31.5 to 63 Hz. The resonance frequency of the human hand–arm system typically falls within this same frequency range. Errors were significantly greater at the higher magnitudes of vibration exposure in this study. Exposure to higher vibration magnitudes results in the activation of greater numbers of mechanoreceptors. This increase in afferent nervous activity likely contributes to greater overestimations of grip and push forces. Moreover, disruptions in efferent memory can be expected to increase with the increase of vibration magnitude. These two sources of disruption likely combine to cause a decrease in force-recall performance.
(2) *Relative force level*: Prior studies have shown that subjects are more accurate when matching forces closer to their maximal voluntary contraction forces. The results of this study support the previous research as force recall errors, expressed as percentages of the target forces, decreased as the target forces increased. A force-recall study with target forces based on percentages of each subject's maximal voluntary contraction (MVC) could further clarify the relationship between force level and force-recall performance.
(3) *Practice effect*: While force-recall error means were relatively small throughout both test sessions, the error means were significantly lower for the second test session than for the first test session. In this study, subjects were encouraged to do their best when memorizing and recalling grip and push forces. Beyond that encouragement, however, no attempts were made to improve force-recall performance. The instruction set was the same for each session and was designed to produce consistent results; the instructions were not intended to maximize accuracy. Furthermore, no feedback was given to the subjects regarding their performance during any individual trial or test session. Even so, force-recall errors were generally smaller during the second test session. The mechanisms by which the subjects improved their performances were not identified in this study.

This study identified some important factors that contribute to force-recall performance, but further experiments may be necessary before this technique can reach its full potential. For example, this study revealed that vibration must reach a certain magnitude before an effect on force-recall performance can be observed. However, details regarding this threshold remain unknown. It may also be beneficial to explore training methods to enhance force-recall performance before such techniques are field-implemented. It is likely that with training, an individual would be able to reliably reproduce the forces applied to a vibrating tool handle.

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