2011

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Recommended Citation

Dale, Ann Marie; Rohn, A E.; Burwell, A; Shannon, W; Standeven, J; Patton, A; and Evanoff, Bradley A., "Evaluation of anti-vibration interventions for the hand during sheet metal assembly work". *Work*, 39, 2, 169-176. 2011.

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Work 39 (2011) 169–176
DOI 10.3233/WOR-2011-1163
IOS Press

Evaluation of anti-vibration interventions for the hand during sheet metal assembly work

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Received 12 April 2010
Accepted 11 December 2010

Abstract. *Objective*: Occupational use of vibrating hand tools contributes to the development of upper extremity disorders. While several types of vibration damping materials are commercially available, reductions in vibration exposure are usually tested in the laboratory rather than in actual work environments. This study evaluated reductions in hand vibration with different vibration damping interventions under actual work conditions.
Methods: Three experienced sheet metal assemblers at a manufacturing facility installed sheet metal fasteners with a pneumatic tool using no vibration damping (bare hand) and each of six anti-vibration interventions (five different gloves and a viscoelastic tool wrap). Vibration was measured with tri-axial accelerometers on the tool and the back of the hand.
Results: Unweighted mean vibration measured at the hand showed reduced vibration ($p < 0.001$) for all six interventions (range = 3.07–5.56 m/s^2) compared to the bare hand condition (12.91 m/s^2).
Conclusions: All of the interventions were effective at reducing vibration at the hand during testing under usual work conditions. Field testing beyond laboratory-based testing accounts for the influences of worker, tools, and materials on vibration transmission to the body from specific work operations.

Keywords: Hand-arm vibration, ergonomic intervention, exposure reduction

1. Introduction

Occupational hand-transmitted vibration exposure has been linked to serious neurologic and vascular symptoms including hand-arm vibration syndrome and carpal tunnel syndrome [1–8]. Recent studies suggest that higher frequencies of vibration may result in damage to the smaller blood vessels of the hand [9–11]. Prevention of vibration exposures is most effectively managed through engineering controls [12], though tool modifications and development of hands-free work methods are costly and may not be feasible. A common short-term solution is the use of vibration damping materials applied to a tool handle or in a glove to form a protective barrier between the tool and hand [13]. These anti-vibration gloves and wraps are not frequently tested under actual working conditions.

Manufacturers typically measure the effectiveness of anti-vibration interventions using controlled laboratory test conditions. This method uses a constant grip and push force and measures vibration produced by different tools with each intervention [14]. These vibration levels do not account for variations of work technique including the hand postures and grip forces during normal tool use that have been shown to alter the vibration transmitted to the hand [15]. Griffin reported that actual working conditions may produce different amplitudes and frequencies of vibration exposures, possibly altering protection values measured in the laboratory [16]. Ideally, vibration exposures and physiological responses should be measured under real-work conditions [15, 17] so companies may select appropriate interventions to protect their workers.

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The effectiveness of anti-vibration gloves in reducing hand-arm vibration is controversial with mixed results from past studies [18,19]. The purpose of this study was to explore the effectiveness of various anti-vibration and impact gloves and one anti-vibration wrap for reducing vibration transmission to the hand under normal working conditions in a large manufacturing facility. The sheet metal assemblers in this facility are exposed to intermittent or prolonged vibration through the use of pneumatic tools to install metal fasteners. We hypothesized that vibration values measured from the back of the hand would be lower with use of any intervention compared to values measured with the bare hand condition.

2. Methods

The sponsoring manufacturing company gave approval for three operators to participate in this exploratory study. A convenience sample of three experienced full-time employed assemblers without symptoms of pain or numbness in the hands was selected. Each subject provided written informed consent from the academic and industry institutional review boards. Using a Hi-Lok® pneumatic tool (United Air Tool Model D2 250 SR, Carson City, NV), each subject performed five trials of metal fastening with each of the six tested interventions, as well as five trials with a bare hand. This pneumatic tool has a pistol-shaped handle, weighs 1.6 kilograms and is commonly used to install threaded HiLok fasteners ($^1/_4$" diameter HiLok pins (ST3M761V4) and HiLok threaded collars (ST3M526C4MA)). Installation time per fastener is brief (less than two seconds) although operators may install several hundred fasteners in a typical work day

Each subject provided personal information about age, hand dominance, and number of years of work experience at the company. Subject's performed maximal hand grip testing with their dominant hand using a hand-held dynamometer on the second setting (North Coast$^{\mathrm{TM}}$ Hydraulic Hand Dynamometer, Morgan Hill, CA). With the subject's elbow at 90 degrees and close to the body, and wrist in slight extension, the subject was instructed to squeeze the dynamometer until maximal force was achieved. Three trials were collected with at least 30 seconds between each trial and the peak force was recorded.

2.1. Interventions

Five of the interventions tested were gloves from two different manufacturers (Fig. 1). Two fingerless gloves contained a gel pad insert; one had a wrist support and one did not. One fingerless glove contained a small air bladder in the palm, while another fingerless glove contained individual air chambers. The full finger glove contained small closed-cell foam pads spaced over the palmar surface of the hand and fingers. The sixth intervention was a wrap material applied to the handle of the tool (Orthex Grip Wrap Kit #4716; Viscolas Inc.; Soddy Daisy, TN). This specially formulated $^1/_4$" thick viscoelastic polymer sheet was wrapped over all surfaces of the tool handle, except for the trigger mechanism with a thin protective grip covering over the viscoelastic sheet. Each intervention was used in accordance with manufacturers' guidelines. All interventions selected for the study were described as having anti-vibration characteristics according the manufacturer's informational materials although no vibration attenuation performance values were available from the manufacturers.

2.2. Vibration measurement system

The vibration measurement system included two tri-axial accelerometers (4.0 gram weight, 10.2 mm Cube, ± 500 g peak), Model 356A61 (PCB Piezotronics Inc., Depew, NY) whose output was attached to PCB 482A22 amplifiers and a National Instruments CB-68LP 16-channel analog to digital circuit board (National Instruments Corporation, Austin, TX) [20]. Each accelerometer produced three channels of data: one for each of the x, y, and z directions. The system incorporated anti-aliasing filters in the connectors of the amplifiers to form a low pass filter at the Nyquist frequency. The input from the amplifiers was passed to the computer's analog to digital circuit board. The accelerometer data were displayed on a standard desktop computer using LabView software (Base package #776671-03 for Windows; National Instruments Corporation; Austin, TX) [21]. The software recorded the data on the hard drive as a binary number proportional to voltage. This value was converted and displayed as decimal g's at a sampling rate of 10,000 samples per channel per second.

One accelerometer was firmly attached to the tool handle using thermoplastic hot melt glue. The accelerometer was placed on the side of tool handle below the thumb avoiding contact with the operator's hand

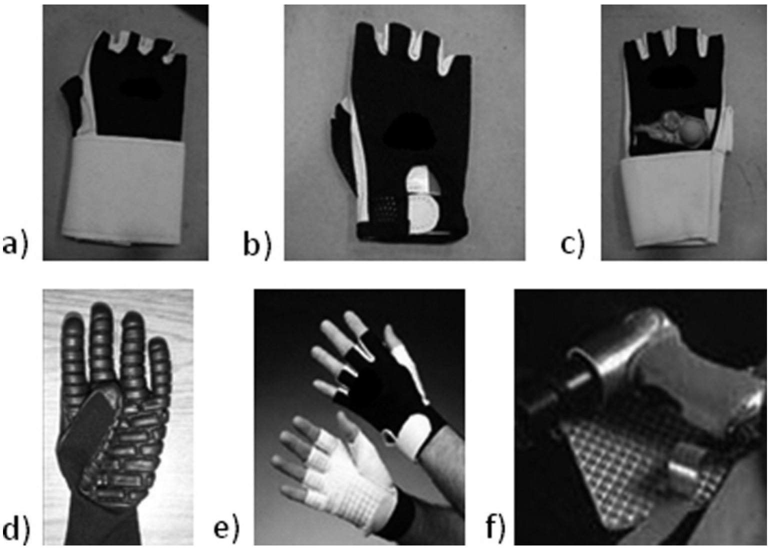

Fig. 1. Interventions used for the study in order from left to right: a) gel pad with wrist support, b) gel pad without wrist support, c) air bladder glove, d) foam pad glove, e) bubble glove and f) tool wrap. Note the air bladder glove shows the air bladder through a cut-away in the glove.

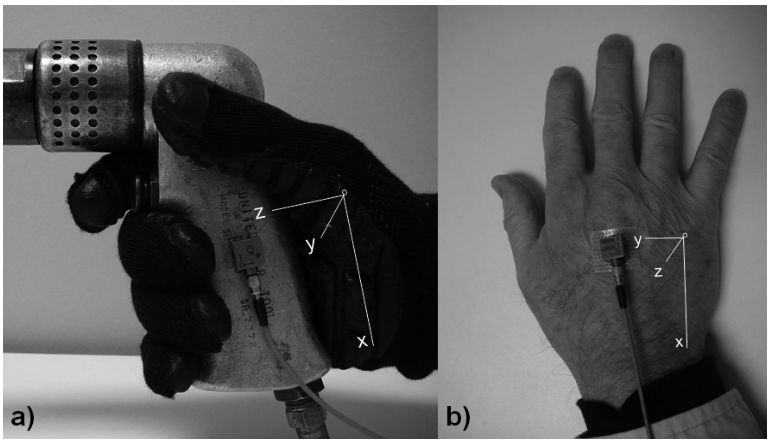

Fig. 2. Accelerometer location and orientation on a) tool and b) hand.

as shown in Fig. 2a. For trials with the viscoelastic wrap material, the accelerometer was attached to the tool handle at the same location and the material was cut-away from the accelerometer so the two did not touch.

The accelerometer orientation positioned the x-axis parallel to the equipment handle, the z-axis parallel to the axis of the fastener, and the y-axis perpendicular to both the equipment handle and the axis of the fastener [22]. The second accelerometer was attached directly to the skin on the back of the hand at the proximal end of the third knuckle using double-sided tape with tape wrapped over the accelerometer and around the palm of the hand as shown in Fig. 2b. The accelerometer on the hand was oriented with the x-axis parallel to the sides of the fingers, the y-axis parallel to the knuckles and the z-axis parallel to an imaginary line passing through the hand [15]. This orientation allowed the accelerometer wire to run parallel to the forearm, minimizing interference of the wire during tool use.

The tool, materials, and fasteners used for this study were the equipment and supplies commonly used by assemblers at this manufacturing facility. The subjects were told to grasp the tool handle using their typical work posture and grip force as they would during normal work to install the fastener. Vibration recordings began just prior to each trial and continued for approximately one second after seating of the fastener. The

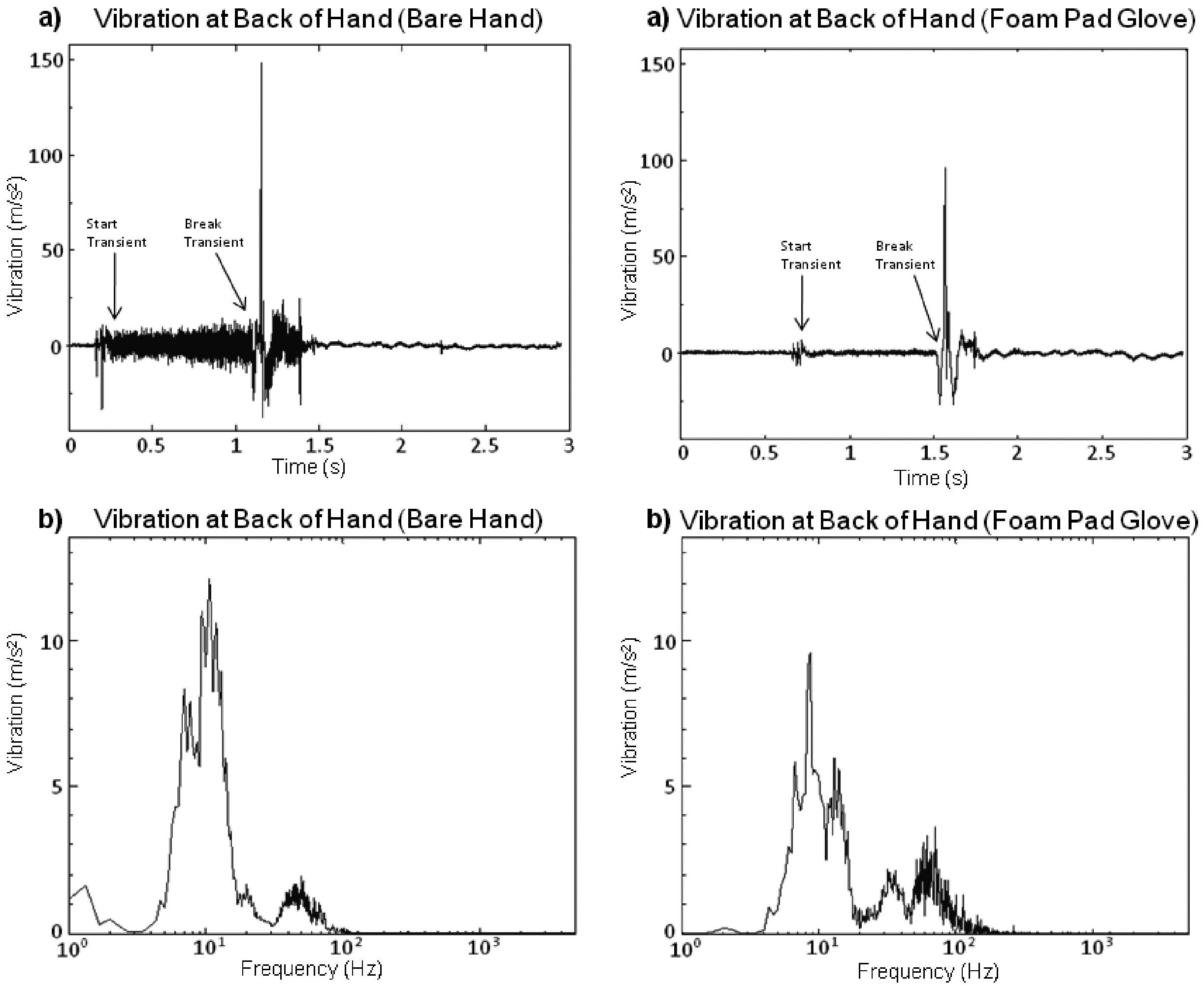

Fig. 3. Raw acceleration values in the time a) and frequency b) domains for single trials from the back of the hand and foam pad glove.

testing order for the interventions was the same for the three subjects. The brief time required for installation ($<$ 4 seconds) was much shorter than the time for set-up between trials (approximately 45 seconds).

2.3. Data processing and analysis

The vibration measured from the Hi-Lok® installations produced a characteristic waveform with a smooth running phase between two transients. Transients were noticeable graphical changes in the waveform caused by the start, end or significant change within a signal. The brief transients mark the start and break of the fastener installation (Fig. 3a). The smooth running phase of the vibration signal that captured the majority of the tool operation time (range = 0.5–1.0 seconds) was used in the data analysis. This selected portion of the waveform was evaluated in two ways: unweighted (raw waveform) and weighted (passing the waveform through two second order band filters in the frequency domain prior to analysis) [22]. For each waveform, the mean vibration values for the three individual axes (x, y, and z) for each trial were used to calculate the vector sum root-mean-square (rms) acceleration value. This calculation was repeated for both the tool handle and back of hand accelerometers.

A second analysis used Fast Fourier Transform (FFT) to calculate the frequency distributions of the wave forms. The FFT showed the magnitude of vibration values at each frequency of the spectrum during the fastener installation (Fig. 3b). The peak frequency for each trial in each axis was recorded.

We analyzed the consistency in responses within the five repeated trials for each condition. We calculat-

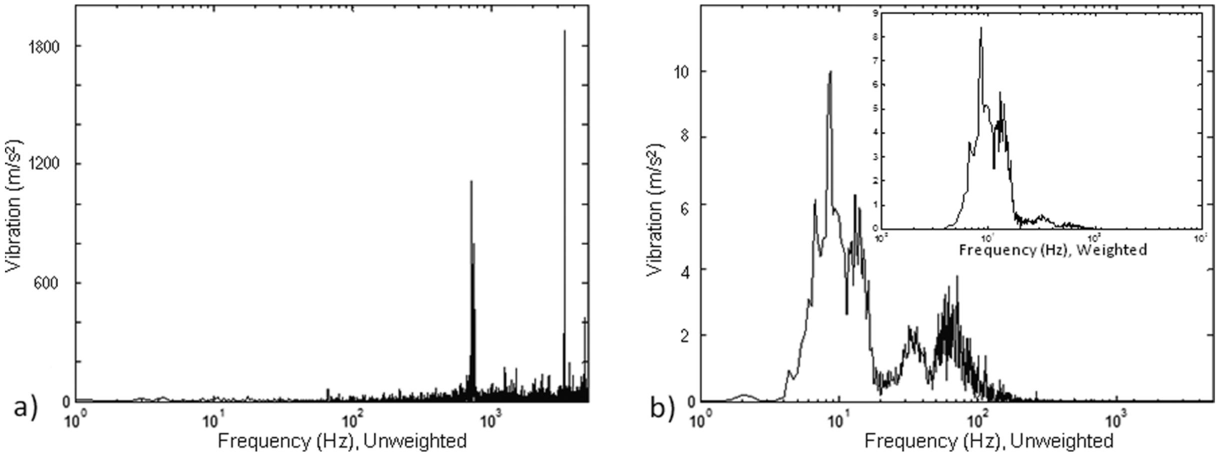

Fig. 4. Acceleration values in the frequency domain from the a) tool handle and b) back of hand for a single trial in the bare hand condition for the unweighted and weighted rms.

ed the coefficient of variation (COV) to determine the variability of the responses with respect to the mean (standard deviation/mean) of each series of five trials for each subject for the tool and hand accelerometers separately. To evaluate the differences in vibration transmission between the six interventions, the magnitudes of the vibration values measured on the back of the hand were compared between the interventions. Transmissibility of vibration was computed as the ratio of hand and tool values. To investigate the frequency profiles from the results on the hand for the different interventions, the peak frequency distributions (from the FFT computations) were examined graphically.

3. Results

The ages of the three male subjects were 37, 40, and 41 years with a mean (SD) of 11 years (4.7) of experience in assembly. Two of the subjects were right hand dominant and one was left-handed; subjects used their dominant hand for the fastener installation trials. The mean (SD) of the dominant hand grip force for the three subjects was 62.4 kg (1.8), 49.9 kg (2.1), and 43.2 kg (5.8) which are similar to the mean grip for individuals of the same age and gender [23].

The COV of the unweighted rms values for the repeated trials of each intervention was less than 15% for 80% of the computations (34 out of 42 calculations). There was no systematic variation of the COV by subject, intervention, or location of recording (tool versus hand).

As shown in Fig. 4a, high frequency vibration (in the 2000–4000 Hz range) was a large component to the total vibration measured at the tool handle, but these high frequency vibration components were not seen in the corresponding trial at the back of the hand (Fig. 4b). The inset in Fig. 4b shows that weighting of the frequency waveform primarily reduced the vibration signal around the 100 Hz frequency when recorded at the back of the hand. The time required to install each fastener shown in the time domain of Fig. 3a was similar for all trials (range 0.53–1.0 seconds). The amplitude of vibration was higher for the bare hand condition compared to the other interventions. Figure 3b shows the magnitude of the signal from the back of the hand across the frequency domain for the same two trials. The waveforms of these trials are generally representative of the overall patterns observed.

The results showed large differences in the mean vibration values (rms) measured from the tool compared to the back of the hand as shown in Table 1. The highest unweighted rms values for the tool and hand were measured in the bare hand condition. Reduced unweighted vibration levels were recorded at the back of the hand for all interventions but only the viscoelastic tool wrap appeared to reduce vibrations at the tool handle. A small proportion of the unweighted vibration rms was transmitted to the back of the hand from the tool (3.1%) with additional attenuation of 1-2% for each intervention compared to the bare hand condition. The filtered vibration levels that primarily eliminated the high frequency vibration components showed minimal change in transmissibility for the bare hand and inconsistent changes in transmissibility for the interventions.

Table 1
Mean (SD) vector sum root-mean-square (rms) values for each condition intervention

	Unweighted[A] tool rms (m/s^2)	Unweighted[A] hand rms (m/s^2)	Weighted[B] tool rms (m/s^2)	Weighted[B] hand rms (m/s^2)	% Trans of unweighted tool rms	% trans of weighted tool rms
Bare Hand	422.03 (77.43)	12.91 (4.18)	16.44 (4.48)	0.46 (0.11)	3.1%	2.8%
Gel pad glove with wrist support	334.26 (152.27)	3.07 (0.34)	11.91 (5.44)	0.21 (0.07)	0.9%	1.8%
Gel pad glove without wrist support	374.24 (171.65)	4.14 (0.96)	13.09 (5.74)	0.28 (0.16)	1.1%	2.1%
Air bladder glove	410.12 (103.29)	3.35 (0.45)	14.70 (6.36)	0.39 (0.37)	0.8%	2.7%
Foam pad glove	417.34 (98.03)	4.48 (3.18)	18.26 (10.66)	1.11 (1.66)	1.1%	6.1%
Bubble glove	410.59 (108.25)	4.21 (2.14)	14.88 (7.27)	0.69 (1.22)	1.0%	4.6%
Tool wrap	287.91 (67.74)	5.56 (2.00)	11.78 (4.96)	0.46 (0.69)	1.9%	3.9%

[A] Unweighted = raw, unadjusted values.
[B] Weighted = adjusted values according to ISO 5349.
Trans = Transmissibility.

4. Discussion

The results showed a reduction in the unweighted exposure values from the back of the hand for each vibration-damping intervention compared to the bare hand condition. Weighting the vibration signal, thus eliminating or attenuating the vibration components from the high frequency domain did not consistently reduce the vibration levels for the interventions compared to the bare hand, although the proportions of the weighted and unweighted tool vibration that reached the back of the hand were similar in the bare hand condition. Only a small portion of the tool vibration was transferred to the back of the hand as the vibration energy was dispersed throughout the system: some of this energy was absorbed by the hand, while other energy was dispersed to the tool, to the interface of the tool and fastener, to the pneumatic cable or power source, into the air as heat, and to the interface of the hand and tool handle.

The reduced unweighted vibration values for each intervention compared to the bare hand suggests that the vibration-damping properties of these interventions were effective in reducing vibration transmitted to the hand. All of the manufacturers of the gloves and tool wrap reported that the interventions had some vibration attenuating properties. Testing in the actual work setting with the materials and tools used by these workers could have altered the results found during product testing since factors such as hand grip and posture can affect the vibration signal [15]. The results of the unweighted values support the use of these interventions for the tested work conditions.

Weighting the vibration frequency spectrum to eliminate high frequency vibration signals has been recommended in order to select the low frequencies thought to be most harmful to the body [22]. For some interventions in this study, weighting of the high frequency vibration components produced higher transmissibility values suggesting that these interventions to some extent amplify the low frequency vibration levels. Using interventions that increase the low frequency portion of the signal may be problematic. However, recent studies have shown that frequency vibrations above 100 Hz produce physiological changes in the vascular system of rat tails [24] and these vascular changes may lead to dysfunction of the neurovascular system. Although resonant low frequencies are not desirable, the contribution of high frequencies should not be discounted [25]. Unweighted measurements account for both the high and low frequency vibration components. Given the uncertainty about which frequencies carry the greatest risk of injury, the National Institute of Occupational Safety and Health recommends that studies present weighted and unweighted results [12].

Even though the evaluation of glove interventions showed that they lowered the transmission of unweighted vibrations, the use of gloves is not the ideal solution. It is preferable to follow the hierarchy of controls and institute engineering solutions that would eliminate the vibration signal from its source through vibration-dampened tools or hands-free operations to avoid physical contact with a vibrating tool. Other considerations with the use of gloves include the increase in tool diameter created by the glove padding or possible finger contact with the tool handle with the use of fingerless gloves [25].

The results should be considered in light of several limitations. The small sample size limits our ability to make statistical inferences and generalizations about the results. We also measured vibration at the back of the hand as described by Dong et al. [15]. Even though the decrease in vibration measured for every intervention using this approach likely reflects true differences in vibration transmissibility to the hand, the lack of control of grip and feed forces during the fastener installation trials may have produced different vibration values from the true level; for example, in our study the tool was not stabilized and grasp of the tool handle and push force during fastener installation were not controlled. To approximate working conditions as closely as possible, we allowed workers to use their normal hand posture and grip for installing fasteners, assuming there would be low variability in hand push and grip force for these experienced workers. The coefficient of variation between repeated trials showed reasonable consistency in the current study but ideally, grip and push force and hand posture should be directly measured during evaluations of the interventions.

5. Conclusions

Commercial vibration-damping products may reduce some of the exposure to high-frequency vibration within given work conditions although the interventions from this small study appeared to reduce vibration of the low frequencies. Selection of a particular product should depend on the work conditions and human factors encountered at a specific work site. It is always preferable to avoid physical contact with vibrating devices and use of glove interventions should be used as a temporary solution. Further research is needed to determine how resonant frequencies of the hand-arm system are affected by vibration-damping materials, and how well laboratory measurements of vibration reflect actual working conditions.

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