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COMMENTARY

Anti-Vibration Gloves?

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ABSTRACT

For exposure to hand-transmitted vibration (HTV), personal protective equipment is sold in the form of anti-vibration (AV) gloves, but it remains unclear how much these gloves actually reduce vibration exposure or prevent the development of hand-arm vibration syndrome in the workplace. This commentary describes some of the issues that surround the classification of AV gloves, the assessment of their effectiveness and their applicability in the workplace. The available information shows that AV gloves are unreliable as devices for controlling HTV exposures. Other means of vibration control, such as using alternative production techniques, low-vibration machinery, routine preventative maintenance regimes, and controlling exposure durations are far more likely to deliver effective vibration reductions and should be implemented. Furthermore, AV gloves may introduce some adverse effects such as increasing grip force and reducing manual dexterity. Therefore, one should balance the benefits of AV gloves and their potential adverse effects if their use is considered.

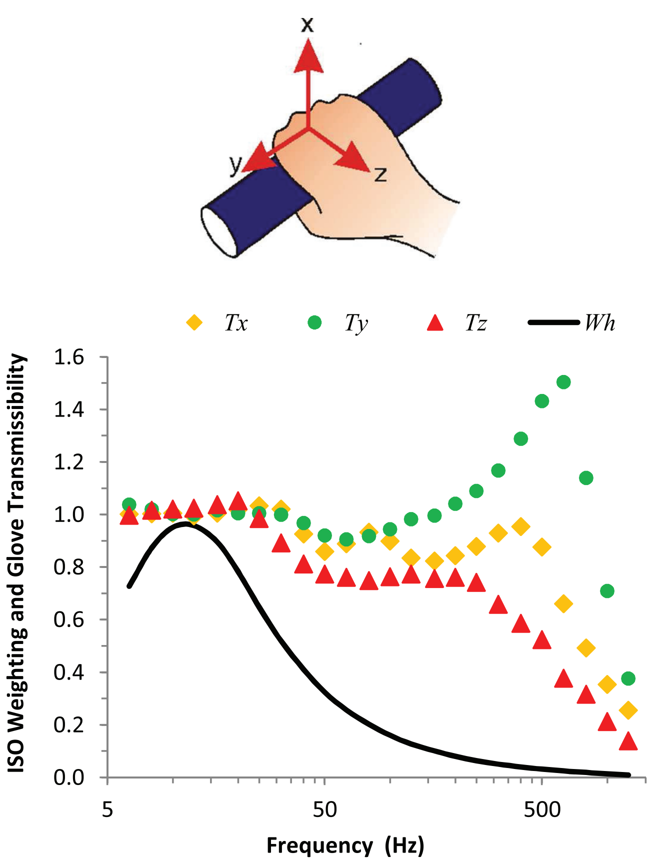
KEYWORDS: anti-vibration gloves, hand-arm vibration, hand-arm vibration syndrome, hand-transmitted vibration, personal protective equipment

Regular and prolonged use of powered hand tools, or hand contact with vibrating surfaces during a daily work routine can cause an individual to develop hand-arm vibration syndrome (HAVS). HAVS is a collective term for the effect that vibration can have on the blood vessels, nerves, muscles, bones and joints of the hand and arm and is a reportable condition under the UK Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR; Health and Safety Executive [HSE], 2013). Compensation for HAVS is awarded in the UK and also in some other countries. To reduce HAVS, some countries have introduced standards and/or regulations to help control exposure to hand-transmitted vibration (HTV) (EU Directive, 2002; ANSI S2.70, 2006).

A hierarchy of control for reducing exposure to HTV has also been proposed by the UK Health and Safety Executive (HSE, 2005). For most hazardous agents, the bottom of any list of available controls would be to use personal protective equipment (PPE) as is the case, e.g. with hearing protection devices for protection against noise. Anti-vibration (AV) gloves have been proposed as PPE for protection against HTV exposure (Goel and Rim, 1987; Rens *et al.*, 1987; Brown, 1990; Reynolds and Jetzer, 1998). However, AV gloves are not listed in HSE's methods for reducing exposure to HTV (HSE, 2005). HSE's guidance on AV gloves is based on assessments of the performance of gloves using current standardized methods and the fact that there is a lack of scientific evidence to show that AV gloves can significantly reduce vibration risk.

Estimation of vibration isolation effectiveness of AV gloves

The current internationally accepted method for assessing an individual's exposure to HTV is standardized in ISO 5349-1 (2001). The method combines information on the magnitude of the vibration, the duration of the exposure and the frequency weighting for HAVS, to produce a daily vibration dose. Specifically, the vibration magnitude, to which an individual is exposed, is measured at or near the gripping zone of a power tool, in terms of the root-mean-square acceleration in the three orthogonal directions, *x*, *y*, and *z*, as shown in Fig. 1. The measured acceleration is weighted using the frequency weighting defined in the standard (ISO 5349-1, 2001). The daily exposure duration can be measured by direct observation, video recording, or work piece counting. Then, the frequency-weighted acceleration and daily exposure duration are combined to calculate the daily vibration dose. The vibration isolation effectiveness of AV gloves is usually assessed by examining their effect on the frequency-weighted acceleration (ISO 10819,



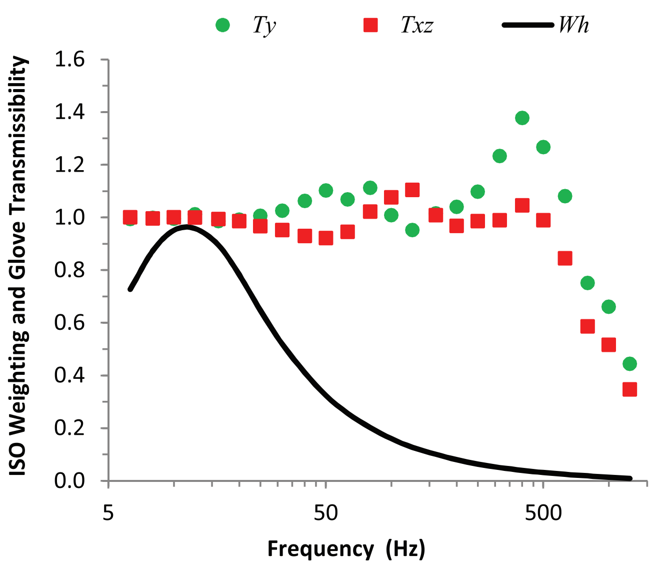
1 Diagram of the three orthogonal directions, *x*, *y* and *z* and graph to show frequency weighting factor (W_h) defined in ISO 5349-1 (2001) and the vibration transmissibility spectra (T_x, T_y and T_z) of an air bladder AV glove at the palm of the hand in the three orthogonal directions (Dong *et al.*, 2014), which are synthesized based primarily on the data reported by McDowell *et al.* (2013a) and Welcome *et al.* (2012).

1996, 2013). This is a primary issue which is discussed in this commentary.

The current HAVS frequency weighting curve in the one-third octave bands from 6.3 to 1250 Hz is plotted in Fig. 1 (ISO 5349-1, 2001). The figure also shows the vibration transmissibility spectra of a typical air bladder type AV glove at the palm of the hand in three orthogonal directions (Dong *et al.*, 2014), which were synthesised primarily based on the data reported by McDowell *et al.* (2013b) and Welcome *et al.* (2012). The transmissibility of the glove is a measure of how much vibration is being transmitted through the glove to the wearer. It is usually assessed by simultaneously measuring the vibration on the surface imparting the vibration and the vibration on the other side of the glove material, i.e. at the hand surface. A transmissibility value of more than 1.0 indicates amplification of the vibration, whereas a transmissibility of less than 1.0 indicates attenuation of the vibration.

According to the ISO frequency weighting curve shown in Fig. 1, the vibration around 6.3–25 Hz is given most weight in terms of its contribution to the frequency-weighted acceleration. Unfortunately, the typical AV glove actually slightly (usually <10%) amplifies the vibration transmitted to the hand through the glove at these frequencies (Dong *et al.*, 2004b; Hewitt, 2010; Welcome *et al.*, 2012; McDowell *et al.*, 2013b). Above 25 Hz, the frequency weighting decreases with the increase in frequency. At around this frequency, the glove starts to reduce the palm-transmitted vibration in some directions. While the relative importance of the vibration in the 500 Hz one-third octave band is only about 3% of that in the 12.5 Hz one-third octave band, the glove can provide a significant reduction at frequencies above 500 Hz in the x and z directions but not in the y direction. At frequencies above 1000 Hz, the glove becomes much more effective in all three directions, but such high-frequency vibration has a small, in most cases negligible, effect on the overall frequency-weighted level (the weighting factor at 500 Hz is <1.4% of that in the 12.5 Hz one-third octave band). From this it is clear that the current hand-arm frequency weighting has considerable impact on the assessment of AV glove effectiveness.

Figure 2 shows the transmissibility spectrum of the air bladder glove fingers in the y direction (T_y) and that for the combined x and z directions (T_{xz}; Welcome *et al.*, 2014a,b), together with the ISO frequency weighting curve. The use of the combined transmissibility for x and z is justified in part, because it is difficult to reliably separate the glove finger transmissibility in each of the x and z directions in the measurement of the transmissibility



2 Frequency weighting curve (W_h) defined in ISO 5349-1 (2001) and the vibration transmissibility spectra of an air bladder AV glove at the fingers in the y direction (T_y) and in the combined x and z directions (T_{xz}) (Welcome *et al.*, 2014b), which were synthesized based primarily on the data reported by Welcome *et al.* (2014a).

(Welcome *et al.*, 2014a,b). The combined transmissibility is also used because it is difficult to match the finger orientations applied during tool vibration measurements with those applied in glove transmissibility measurements in these two directions. This in turn makes it difficult to apply the transmissibility spectra to predict the gloved finger vibration exposure. The glove finger transmissibility shown in Fig. 2 is generally higher than the glove palm transmissibility shown in Fig. 1, except in the *y* direction at some frequencies. This is primarily because the finger effective mass is much less than that of the palm-wrist-arm substructures (Dong *et al.*, 2009). The basic differences between transmissibilities at the palm and fingers are also consistent with modelling predictions (Dong *et al.*, 2013). These differences indicate that AV gloves are generally less effective at the fingers than at the palm of the hand.

Besides the frequency dependency, the glove vibration transmissibility is also direction-specific. As also shown in Figs 1 and 2, the glove is generally most effective in isolating the vibration along the forearm direction, and it is least effective in the *y* direction or along the axis of a tool handle (McDowell *et al.*, 2013b). This is largely because the mass of the hand-arm system effectively involved in the response in the *y* direction is generally the lowest of the three directions (Dong *et al.*, 2013). Tool vibration is also generally frequency- and direction-specific, as illustrated in Fig. 3. The specific vibration isolation effectiveness of an AV glove depends on the combinations of the glove transmissibility spectra and tool vibration spectra in the three directions. As the first degree of approximation, the tool vibration spectra and the vibration transmissibility spectra of the glove were used to estimate the tool-specific performance of the glove (Rakheja *et al.*, 2002). Specifically, according to the total vibration (vector sum of the three-axial vibrations) defined in ISO 5349-1 (2001), the overall transmissibility value ($T_{\text{w-Palm}}$) for total vibration at the palm was calculated using the following formula (Dong *et al.*, 2002b):

$$T_{\text{w-Palm}} = \frac{\sqrt{\sum_i \{[T_x(\omega_i)\cdot a_x(\omega_i)]^2 + [T_y(\omega_i)\cdot a_y(\omega_i)]^2 + [T_z(\omega_i)\cdot a_z(\omega_i)]^2\}\cdot W_h^2(\omega_i)}}{\sqrt{\sum_i \{[a_x(\omega_i)]^2 + [a_y(\omega_i)]^2 + [a_z(\omega_i)]^2\}\cdot W_h^2(\omega_i)}}, \quad (1)$$

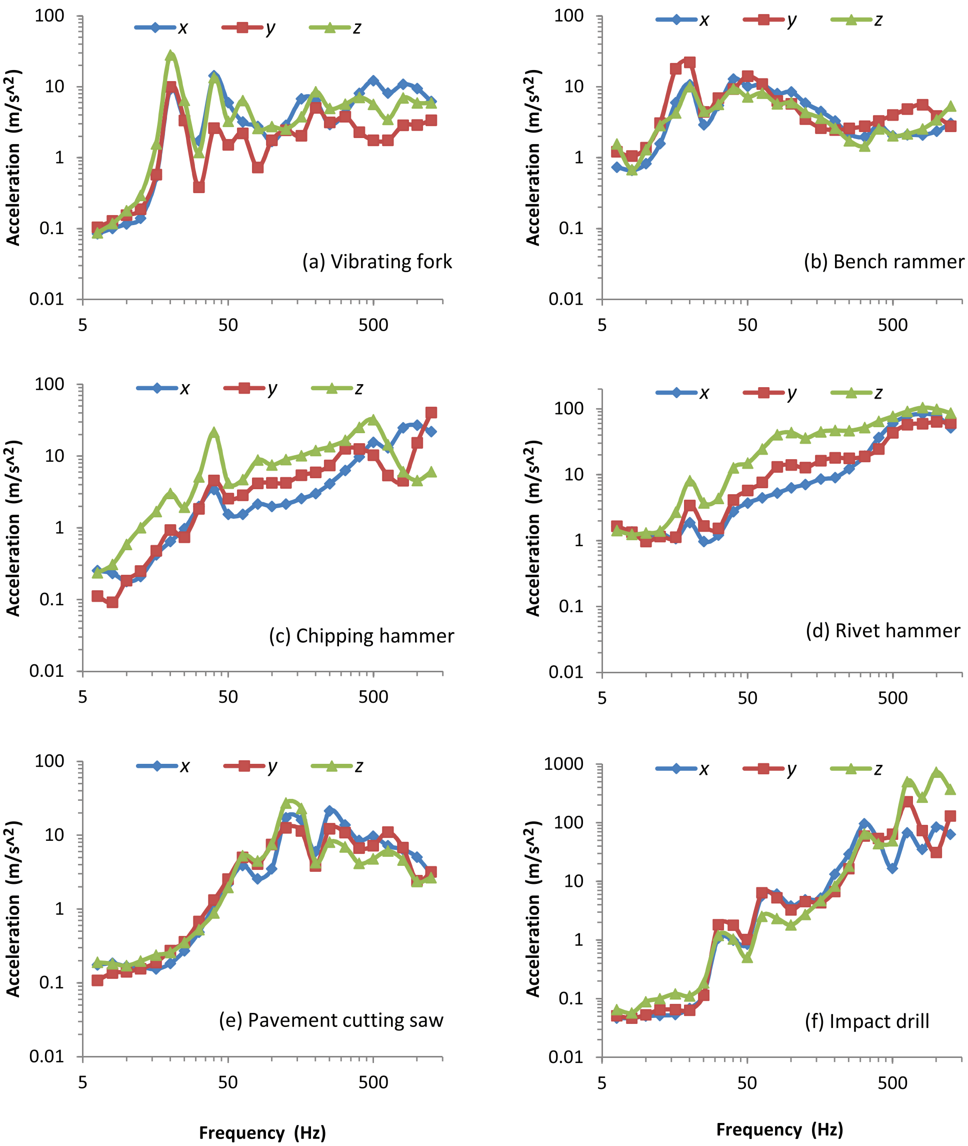
where T_x, T_y and T_z are the glove vibration transmissibility spectra in three orthogonal directions (*x*, *y*, and *z*), a_x, a_y and a_z are tool vibration spectra in three orthogonal directions, W_h is the frequency weighting factor for hand-arm vibration exposure defined in ISO 5349-1 (2001), and ω_i is the vibration frequency in Rad/s corresponding to 6.3–1250 Hz in the one-third octave bands. Similarly, the overall transmissibility value ($T_{\text{w-Fingers}}$) for total vibration at the fingers was calculated from:

$$T_{\text{w-Fingers}} = \frac{\sqrt{\sum_i \{T_{xz}^2(\omega_i)\cdot[a_x^2(\omega_i) + a_z^2(\omega_i)] + [T_y(\omega_i)\cdot a_y(\omega_i)]^2\}\cdot W_h^2(\omega_i)}}{\sqrt{\sum_i \{[a_x(\omega_i)]^2 + [a_y(\omega_i)]^2 + [a_z(\omega_i)]^2\}\cdot W_h^2(\omega_i)}}, \quad (2)$$

where T_y and T_{xz} are the glove vibration transmissibility spectra, respectively in the *y* direction and combined *x*–*z* direction. Then, the percent reduction (R_w) at each location was calculated from

$$R_w = (1 - T_w) \times 100\%. \quad (3)$$

Table 1 lists examples of the estimated tool-specific performance of the typical AV glove, which were calculated using the glove transmissibility spectra shown in Figs 1 and 2 and the tool vibration spectra measured by researchers in the UK Health and Safety Laboratory and the US National Institute for Occupational Safety and Health (NIOSH; Dong *et al.*, 2002a, 2004a; McDowell et al., 2009, 2012, 2013a; Pitts *et al.*, 2012). These examples indicate that the AV glove cannot significantly ($P > 0.05$) reduce the frequency-weighted vibration transmitted to the fingers in the operations of the vast majority of powered hand tools, but it can reduce a portion of the vibration transmitted to the palm in many cases. Glove effectiveness is tool-specific or tool vibration spectrum-specific. When the AV glove is used with a low-frequency tool such as the vibrating fork or rammer, it reduces little of the frequency-weighted vibration transmitted to both the palm and fingers of the hand. This is because the dominant frequency of vibration of such a tool is at or below 25 Hz, as shown in Fig. 3a,b. The vibration on the handles of impact tools such as chipping hammers or riveting hammers are in the medium- and high-frequency range (>25 Hz), as shown in Fig. 3c,d. The glove can reduce from



3 Samples of the tool vibration spectra in the three orthogonal directions.

5% to 20% of such vibration transmitted to the palm, depending on the specific tool. This also holds true for many other impact tools such as rock drills, stone hammers, and impact wrenches, as also indicated in Table 1. It is interesting to note that the glove may not be so effective at reducing the overall vibration from the chisel or bit of these tool types, where the operator typically grips the bit to better control the tool action. For example, while the glove may reduce the vibration on the main handle of the stone hammer by 17%, it may reduce only ~2% of the vibration from the chisel of the stone hammer. This is primarily because the major vibration of the chisel is in the pure shear, or *y* direction of the hand, but the major vibration on the handle is largely along the forearm or *z* direction of the hand-arm system.

The majority of grinders, sanders, and saws generate vibration primarily in the range of 80–200 Hz (Griffin, 1997). As an example, the vibration spectra of a saw are shown in Fig. 3e. Although the fundamental vibration frequencies of these tools are usually much higher than those of the impact tools, the AV glove may not

Table 1. Estimated percent reduction of the frequency-weighted vibration total value transmitted to the palm and fingers of the hand using a typical anti-vibrating glove (air bladder glove) in the operations of some tools (a negative value means amplification of the vibration by the glove).

Tool	Working conditions and data sources	a_{hv} (m·s²)	Percent reduction (%)	
			Palm	Fingers
Vibrating fork	Cleaning simulated beach sand contaminated by leaked oil (McDowell *et al.*, 2012)	12.7	−0.9	1.8
Paving tamper	Tamping asphalt pavement (Dong *et al.*, 2002a)	18.2	0.5	−0.2
Floor rammer	Ramming sand/cement mix into mould (HSL database)	23.7	0.1	−0.9
Bench rammer	Ramming sand/cement mix into mould (HSL database)	30.5	0.2	1.0
Electric heavy rotary hammer	11 kg, drilling concrete with 32 mm × 250 mm masonry bit (HSL database)	18.9	3.1	−0.6
Chisel of stone hammer	Chiseling granite with 1-inch masonry chisel (HSL database)	19.8	2.2	−8.2
Handle of stone hammer	Chiseling granite with 1-inch masonry chisel (HSL database)	21.4	17.0	0.8
Rivet hammer 1	Riveting airplane frames (McDowell *et al.*, 2013a)	20.8	7.2	0.4
Rivet hammer 2		15.9	4.7	−2.1
Rivet hammer 3		28.5	16.9	−0.4
Rivet hammer 4		29.7	8.5	1.3
Rivet hammer 5		13.6	8.3	−0.1
Rivet hammer 6		18.0	6.2	1.7
Rivet hammer 7		21.2	18.0	0.5
Rivet hammer 8		21.2	16.5	0.3
Chipping hammer A	6.6 kg chipping hammer; standard chipping hammer test (Dong *et al.*, 2004a)	11.0	15.6	3.6
Chipping hammer B	6.9 kg chipping hammer; standard chipping hammer test (Dong *et al.*, 2004a)	12.3	11.6	3.3
Electric impact drill A (3 kg)	Drilling concrete block (measured in the current study)	14.4	6.5	−1.4
Electric impact drill B (6 kg)		10.7	10.9	1.1
Electric impact drill C	8 mm masonry bit, drilling concrete block (HSL database)	20.2	33.6	17.3
Pneumatic rock drill	15.6 kg, drilling concrete (HSL database)	11.7	16.1	5.6
Chain saw	4.9 kg, idling (HSL database)	9.9	14.2	4.3

Table 1. *Continued*

Tool	Working conditions and data sources	a_{hv} (m·s^2)	Percent reduction (%)	
			Palm	Fingers
Pavement cutting saw	Cutting asphalt pavement (Dong *et al.*, 2002a)	12.1	15.4	−5.2
Impact wrench 1	Tightening 10 large nuts on a simulated workstation (McDowell *et al.*, 2009)	7.3	12.3	3.2
Impact wrench 2		2.7	2.7	1.0
Impact wrench 3		9.4	7.0	0.8
Impact wrench 4		8.3	5.7	−1.8
Impact wrench 5		5.5	11.4	−0.5
Electric angular grinder	Cutting paving slab with 230 diamond wheel (HSL database)	10.1	14.8	−4.5
Hedge trimmer	45 cm blade, trimming hedge (HSL database)	13.7	13.4	2.8
Strimmer	Strimming grass (HSL database)	7.4	8.9	−0.8
Electric multi-use tool	Cutting 20 mm chipboard with a 35 mm oscillating blade (HSL database)	13.9	17.4	4.6
Needle scaler	Scaling rusty metal with 19 mm × 3 mm chisel needle (HSL database)	11.9	7.3	−9.8
Random orbital sander	Preparing train carriage for repainting with 320 grit aluminum oxide (HSL database)	4.8	16.8	−6.1
Triple headed scabbler	Scabbling concrete (HSL database)	12.8	7.4	6.2

be more effective with these tools, as shown in Table 1. This is because the vibrations of such tools are distributed fairly evenly in two or three axes, as also shown in Fig. 3e; the minimal contribution of the glove in the *y* direction reduces the overall apparent effectiveness of the glove. Some other vibration-reducing gloves such as gel-filled types may reduce more vibration in the *x* and *y* directions than the air bladder-filled glove, but they are less effective at reducing the vibration in the *z* direction (McDowell *et al.*, 2013b).

In many cases, the vibration produced by electric impact drills is similar to that of many rock drills and stone hammers. In some special cases, such tools may generate vibration which is primarily in the very high-frequency range, as shown in Fig. 3f. (Note that there is a change in scale on the *y*-axis for this figure). In such cases, the glove could reduce the vibration transmitted to the palm by more than 30%, as indicated in Table 1 (Electric impact drill C). Such vibration characteristics are not observed with the vast majority of powered hand tools or machines (Griffin, 1997; Pitts *et al.*, 2012).

The current frequency weighting is not derived directly based on the frequency dependency of any vibration-induced injury or disorder, but it is derived primarily based on the equal vibration sensation contours of the entire hand-arm system (Miwa, 1967; Brammer, 1986). Since HAVS is a collection of multiple components, it is possible that the current frequency weighting may be more applicable to some HAVS components than it is to others. For example, the reported biodynamic frequency weighting of the palm-wrist-arm suggests that the current frequency weighting is reasonable for assessing the risk of vibration-induced injuries in these substructures (Dong *et al.*, 2006). The results of a reported epidemiological study also suggest that the current weighting is acceptable for assessing the risk of hand-wrist musculoskeletal and sensorineural disorders (Malchaire *et al.*, 2001). According to the proposed biodynamic response theory (Dong *et al.*, 2012), it may also be reasonable to use the palm-transmitted vibration exposure to assess the risk of potential injuries and disorders in the palm-wrist-arm substructures. These observations suggest that it may be acceptable to use the palm transmissibility value of the AV glove to estimate its vibration isolation benefit for these substructures.

According to the proposed biodynamic response theory (Dong *et al.*, 2012), vibration-induced finger injuries and disorders such as vibration-induced white finger are likely to be more closely associated with finger-transmitted vibration exposures than palm-transmitted vibration exposures. Consequently, the benefit of an AV glove for finger protection might be evaluated primarily based on its reduction of finger-transmitted vibration. According to the data listed in Table 1, AV gloves would have little value for reducing finger-transmitted weighted vibration, except in some special cases. This contradicts the finding of both a physiological study (Mahbub *et al.*, 2007) and a health effect study conducted at a workplace (Jetzer *et al.*, 2003), which reported that the use of AV gloves reduced some HAVS finger symptoms by about 30%. In the Jetzer study, where the use of AV gloves was combined with the use of reduced-vibration machines, the reported reduction in finger symptoms was doubled. It is difficult to explain such great benefits, even taking into account the contribution of the marginal reduction of the frequency-weighted palm-transmitted vibration for finger protection. These contradictions lead to the following two hypotheses:

(1.) the health benefits of AV gloves may be overestimated in some of the reported health effects studies, or some of the findings may not be generally applicable to many other cases;
(2.) the current frequency weighting does not sufficiently represent the frequency-dependency of vibration-induced finger or hand disorders, or it largely underestimates the high-frequency effects.

The second hypothesis is consistent with the findings of some other health effects studies (Dandanell and Engström, 1986; Nilsson *et al.*, 1989; Barregard *et al.*, 2003; Cherniack *et al.*, 2006). Another study also reported that the use of unweighted acceleration provided better predictions of vibration-induced white finger than the use of weighted acceleration (Griffin *et al.*, 2003). While the frequency-dependency of finger disorders is unlikely to be unity or independent of frequency in the entire frequency range of concern, the frequency-dependency of vibration-induced white finger proposed in another study suggests that the peak weighting value occurs at a frequency of 63 Hz, and the weighting value gradually reduces with the increase in frequency above 63 Hz (Tominaga, 2005). The finger biodynamic frequency weighting also suggests that the peak finger weighting is likely to be in the medium-frequency range (25–300 Hz) where the major finger resonances occur (Dong *et al.*, 2012). If these finger weighting proposals are substantiated, the real benefit of AV gloves is likely to be somewhere between the predictions using the weighted and unweighted accelerations in many cases. However, the exact mechanisms of damage for finger disorders have not been identified, and reliable relationships among HTV exposures and the various health effects have not been established (Bovenzi, 1998; ISO 5349-1, 2001). Without such knowledge, it is very difficult to define a suitable frequency weighting for finger disorders. Furthermore, the proposed alternative finger frequency weightings have not been sufficiently tested or supported (Bovenzi, 2012). Therefore, the determination of a reliable frequency weighting scheme remains a formidable research task. It is unlikely that the current frequency weighting and the standardized method for assessing the risk of HTV exposure will be changed in the near future (Pitts *et al.*, 2012).

Major limitations for further increasing the vibration isolation effectiveness of AV gloves

In principle, an AV glove basically provides a cushion between the tool or machine contact surface and the hand, similar to an automobile suspension system (Dong *et al.*, 2009). The cushion reduces the hand-handle interface stiffness, but the vibration isolation effectiveness of the AV glove also depends on the dynamic properties of the hand-arm system. The effective mass of the palm-wrist-arm sub-system, especially along the forearm or z direction, is much greater than that of the fingers, which explains why the AV glove can be shown to generally reduce more vibration transmitted to the palm than to the fingers. Because the effective mass of the hand-arm system is fixed, within limits, any increase in glove effectiveness has to result from the improvement of glove design. Theoretically, decreasing the glove cushion stiffness and optimizing its damping can increase the glove isolation effectiveness (Dong *et al.*, 2009). This can be achieved by using softer materials, or increasing the thickness of the glove material at the palmar side of the AV glove. However, these two tactics are limited because:

(1.) it is difficult to effectively control a vibrating tool if the glove contact stiffness is too low;
(2.) the reduced grip contact stiffness also requires an increase in grip effort for tool control (Wimer *et al.*, 2010), which may cause hand fatigue and other hand injuries;
(3.) when the glove thickness is beyond a certain point, the glove will not be wearable for practical applications because it is too bulky to grip; required grip force also generally increases with the thickness of the glove (Wimer *et al.*, 2010).

Therefore, it may be difficult to substantially increase the vibration isolation effectiveness of AV gloves from their current performance level.

The standard method for testing and evaluating AV gloves

ISO 10819 (1996) defines a method for testing and evaluating AV gloves. The major purpose of the test is not to determine the actual vibration isolation performance of the glove, but to provide an affordable and efficient method for screening gloves. The original standard was published in 1996, but it has been recently revised (ISO 10819, 2013). The basic testing and evaluating method remains unchanged in the revised version. Specifically, the standard method requires measuring the frequency-weighted vibration transmissibility (referred to as TR) of the glove at the palm of the hand (not the fingers) only along the forearm direction. Two transmissibility values, one for the medium-frequency range (TR_M) from 31.5 Hz (25 Hz in the revision) to 200 Hz; and one for the high-frequency range (TR_H) from 200 to 1250 Hz are evaluated. To decide whether a glove is suitable to be marketed as an AV glove, the criteria set in the 1996 version of the standard were: $TR_M < 1.0$ and $TR_H < 0.6$.

These criteria were actually not consistent because if a glove can reduce the vibration in the *z* direction in the high-frequency range by 40% or more, it can usually reduce the vibration by more than 10% in the medium-frequency range (Dong *et al.*, 2004b; Welcome *et al.*, 2012). Furthermore, the first criterion was not reasonable because the dominant frequencies of the vast majority of powered hand tools are within the medium-frequency range, but AV gloves were not required to provide any significant vibration reduction in this frequency range, which appears contrary to the purpose of using an AV glove. For this reason, this criterion has been revised from $TR_M < 1.0$ to $TR_M \leq 0.90$ in the revised version of the standard while TR_H (≤0.60) basically remains the same (ISO 10819, 2013).

The 2013 version of ISO 10819 also includes several other major technical improvements and simplifications. First, a single vibration spectrum is used in the new version to replace the two spectra in the original standard. This reduces the test time by half, without reducing the quality of the test results. To increase the reliability of the test, the number of test subjects is increased from three to five and the number of trials for each subject from two to three. Also, the original bare-hand adapter test is replaced with a bare adapter test to perform the in-situ calibration of the adapter and handle accelerometer, which avoids the unnecessary interference of the hand biodynamic response on the internal calibration. It was noticed that direct palm contact with the accelerometer installed on the adapter could affect measurement at low frequencies in some cases, which was one of the reasons requiring the bare hand test in the original standard (ISO 10819, 1996). While it is not reliable to compensate for such an effect using the spectrum measured in the bare hand test, this problem should be avoided. Although it is not required in the new version of the standard, the authors recommend conducting an additional bare hand test with 30 N grip and 50 N push, to check the in-situ behaviour of the accelerometer. To avoid the rocking and sliding of the adapter on the handle in such a test, two pieces of thin elastic strips (e.g., rubber bands) can be fixed on to the adapter contact surface with the handle, using double-side adhesive tape or electric tape, to form a stable contact in the test (Xu *et al.,* 2014). After normalisation with the spectrum measured in the bare adapter test, the transmissibility measured in the bare hand test should be close to unity (errors < 5%) at least at frequencies below 50 Hz. If not, the instrumented adapter is not acceptable for the glove test. One of the methods to avoid palm contact with the accelerometer and its wires is to design a pocket on the adapter at its handle contact side and to install the accelerometer in the pocket, as done in some of the reported studies (Dong *et al.,* 2002b; Welcome *et al.,* 2012). An alternative accelerometer may also be used to resolve the problem.

When the palm adapter is fitted inside a glove it is possible that a large misalignment of the palm adapter to the vibration direction may occur and result in underestimates of transmissibility up to, or even in excess of 20% (Dong *et al.,* 2002b), it is recommended to control the misalignment by making a slit along the seam and/or material between the base of the thumb and fore finger of each glove to facilitate viewing and adjusting the palm adapter position inside the glove (Hewitt, 1998). While the slit can reduce the error due to the adapter position misalignment, it may not reduce the misalignment due to the uneven deformation of the glove materials underneath the adapter, when subjected to uneven contact pressure (Dong *et al.,* 2002b; Welcome *et al.,* 2012). Hence, besides the slit method, a total vibration method (vector sum of the three-axis vibrations) is also recommended in the new version of the standard (ISO 10819, 2013), which requires replacing the single-axis accelerometers in both the handle and adapter with tri-axial accelerometers (Dong *et al.,* 2002b). While the implementation of the total vibration method is optional in the standard, it is unlikely to be selected to certify an AV glove. This is largely because the transmissibility value evaluated with the total vibration method is usually higher than that evaluated with the single-axis method, and it is more difficult to pass the test with the total vibration method (Dong *et al.,* 2002b; Welcome *et al.,* 2012). For real applications, however, it is more appropriate to assess the performance of a glove based on the transmissibility values evaluated using the total vibration method (Dong *et al.,* 2002b; Welcome *et al.,* 2012).

In addition to the TR_M and TR_H criteria, the 1996 version of ISO 10819 included a third criterion that "a glove shall only be considered as 'antivibration glove' … if the fingers of the glove have the same properties (materials and thickness) as the part of the glove covering the palm of the hand". Because it is both difficult and expensive to measure the glove finger transmissibility, there was no prescribed quantitative method of determining the properties of the glove fingers. It was assumed that the performance at the fingers would be equally as good, if not better than at the palm, if the material and thickness were the same. As observed in recent studies (Welcome *et al.,* 2014a,b), the finger transmissibility spectra of some AV gloves were similar to that of some non-AV gloves below 400 Hz; at higher frequencies, the non-AV gloves became more effective than the AV glove. These observations demonstrate that it is not necessary to require the glove fingers to have the same materials as those of the glove palm. It is also very difficult to implement the same thickness on the fingers and palm of the AV glove. An AV glove meeting the transmissibility criteria at the palm and the thickness criteria both at the palm and at the fingers, is unlikely to be usable for safe tool operation because it would be too bulky, and require too much grip force. In fact, none of the AV gloves currently available on the market meet the finger thickness requirement. For this reason, the requirement of the finger thickness is relaxed in the revision of the standard (ISO 10819, 2013), which requires "The thickness of vibration reducing material placed in the fingers and thumb sections of the glove shall be equal to or greater than 0.55 times the thickness of the vibration-reducing material placed in the palm section of the glove."

The revision of the standard also recommends that "the thickness of vibration-reducing material placed in the palm section of the glove should not be greater than 8 mm." It may be considered excessive to impose such specific thickness restrictions on the AV glove design, [and the bulkiness of the glove ought perhaps to be evaluated based on a functional test such as a grip strength test (Wimer *et al.,* 2010)]. The palm and finger thicknesses in the standard are determined, not based on any threshold of the glove material transmissibility, but based on the thicknesses of a selection of available vibration-reducing gloves. These revisions are aimed at balancing the usability of AV gloves with the vibration reduction performance. While it would be better to be able to specify glove materials at the fingers purely in terms of vibration reduction, this is not possible within a relatively simple test. However, the minimum thickness criterion appears to be based on the designs of glove on the market at the time of developing the standard. It is a concern that this thickness criterion may come to restrict the AV glove market in the future. The specifications of the thicknesses also require their measurements, which are also specified in the new version. In this respect the standard test has been made more complex and expensive.

Issues not addressed by the revision of ISO 10819 (2013)

The new version of the standard does not resolve many of the problems identified from the original standard (Griffin, 1998). For example, glove vibration transmissibility depends largely on the test subjects (Paddan and Griffin, 1997; Laszlo and Griffin, 2011; Welcome *et al.*, 2012). Considering the intersubject variation can be more than 20% (Dong *et al.*, 2002b, 2004b; Welcome *et al.*, 2012), the increase from three to five subjects in the new version may not be sufficient. A glove can pass the screening test by specifically selecting the five subjects. As a result, a glove certified as an AV glove by one laboratory may not pass the same standard test in other laboratories. While increasing the number of subjects to a sufficient level will substantially increase test expense, such limitations will likely continue.

The standard test only measures the transmissibility in a single direction, which is inconsistent with the HTV risk assessment method defined in ISO 5349-1 (2001). As shown in Fig. 1, the AV glove is generally most effective along the forearm or z direction adopted in the standard test (McDowell *et al.*, 2013b). The glove is also most effective at the measurement location used in the standard test because the maximum effective mass of the hand-arm system is also at this location (Dong *et al.*, 2013). Hence, it is not sufficient to evaluate the overall glove effectiveness by measuring the transmissibility at this one location in the z direction. Use of the total vibration method for evaluating the transmissibility cannot change this situation because the input vibration signal is only along the forearm direction in the standard test. The standard actually assumes that if one glove is more effective than another at the palm along the forearm direction, it is both more effective in the other directions and provides better protection of the fingers. Recent studies suggest that this assumption is not valid (McDowell *et al.*, 2013b; Welcome *et al.*, 2014a) and have shown that the performance of gloves varies considerably depending on direction of the vibration as well as whether they are assessed at the palm or at the fingers.

The use of the palm adapter in the test may also be a source of measurement errors because of its mass effect and its contact pressure concentration effect (Hewitt, 2010; Dong *et al.*, 2005). The position of the adapter within the palm of the hand has also been shown to affect results (Dong *et al.*, 2002b). It would be very difficult, if not impossible, to establish to what extent the differences in measured transmissibility using an adapter in the palm of the hand represent the real differences in vibration being transmitted to different operators, rather than differences which are an artifact of this measurement technique. The glove effectiveness is also affected by the applied hand forces and the postures of the hand and arm (Dong *et al.*, 2004b; Laszlo and Griffin, 2011), but only a single force combination (30 N grip and 50 N push) and a single hand and arm posture are used in the test. For these reasons, the laboratory test results may be significantly different from those at workplaces (Pinto *et al.*, 2001).

It is clear that resolution of the persisting issues with the standard would make the standard test too expensive, time-consuming, and/or technically difficult. They are unlikely to be considered as part of any future revisions of the standard. It is for these reasons, that the new version of the standard (ISO 10819, 2013) advised that the results of the standard test should be applied with caution.

Requirements of the PPE at Work Regulations 1992

The PPE at Work Regulations (HSE, 1992) require an employer to assess and select PPE according to its suitability. The employer must do this by comparing the characteristics of the risk with the characteristics of the PPE and to take into account any risks the PPE itself may cause. The standard test in ISO 10819 (1996, 2013) does not provide any direct information that can be used to estimate the protection that a glove may provide to the wearer. In addition, there are many uncertainties in the test results. Currently, there are no other standards for estimating the protection afforded by AV gloves when using vibrating machinery. This makes compliance with the PPE Regulations very difficult to achieve with respect to AV gloves, and also makes it very difficult to produce evidence, one way or another, about the effects that a glove has on the vibration exposure of an individual.

The standard ISO 5349-1 (2001) for evaluation of exposure to hand arm vibration requires measurement of three axes of data to provide a vibration total value. It therefore follows that any estimate of the performance of a glove intended to reduce the vibration exposure of an operator must also be made in terms of three axes. Since the standard test is performed in the most advantageous location and direction for gloves, the TR_M and TR_H values measured using the standard test may largely overestimate glove effectiveness for vibration reduction. The vibration exposure risk is likely to be underestimated if AV glove vibration transmissibility values are used to discount HTV exposure in risk assessment.

Other considerations

ISO 10819 assesses the performance of AV gloves. There is also a standard for measuring the performance of resilient materials used for AV gloves: ISO 13753 (2008), which superseded ISO 13753 (1999). Studies have been reported which investigate the properties of different materials using this test and have shown that in this test, resilient materials tend to produce amplification between 10 and 31.5 Hz (Koton *et al.*, 1998; Scarpa *et al.*, 2005). The revised standard test for AV gloves does not consider the performance of a glove below 25 Hz. It seems a serious omission to ignore the performance of a glove at the frequencies which are given the most weight by the current hand-arm frequency weighting, particularly when there is evidence from the materials test that there may be amplification at these frequencies. Furthermore, a related standard ISO 10068 (1998), which defines standard driving point impedances of the hand-arm system, has undergone a major revision, because the mechanical impedance data and computer models adopted in this standard have been demonstrated to be problematic.

A further consideration with regard to techniques for estimating the effectiveness of AV gloves is the use of averaging transmissibilities to represent the performance of a glove for the entire population. In the particular case of AV gloves, the inter-subject variability can be very large. As an example, data from recent research on one glove type (Hewitt, 2010) showed that for a tool with a dominant frequency at around 160 Hz, the difference in *y*-axis performance could range from 36% reduction to 79% amplification in vibration magnitude. This could mean that a glove and tool combination that appears to have the potential to provide protection for one tool operator could actually cause considerable amplification for another. Use of averaging techniques is intended to provide an adequate safety margin to take individual variability into account. However, without assessment on an individual basis, it would not be possible to identify which operator, glove, and tool combinations might actually result in potentially harmful exposures. Also the frequency spectrum for a given power tool is not always constant. Variability in the spectral shape with different applications, caused, e.g. by unmonitored changes in operating air pressure of pneumatic tools can occur. Any such changes in frequency content of the vibration from the tool could also influence the effectiveness of a glove in some circumstances.

Wearing gloves is generally recommended for operation of powered hand tools for many good reasons:

(1.) to keep the hands warm, clean, and dry, which is useful for reducing the potential for developing HAVS (Griffin, 1990);
(2.) to protect the hand from mechanical cuts, abrasions, etc.;
(3.) to protect the hand from burns, chemicals, and biological exposures.

AV gloves are usually thicker than regular working gloves. However, increased glove thickness results in some adverse ergonomic effects; the wearer of a thicker glove may need to exert greater grip force than would be the case without the glove, or with a thinner glove (Wimer *et al.*, 2010). This has the potential to cause muscle fatigue. Thicker gloves can also affect manual dexterity. Such effects would be very undesirable when using large power tools, possibly compromising safe use of the machinery. Also importantly, increasing the grip force may increase the incidence of carpal tunnel syndrome (Silverstein *et al.*, 1987). Wear and tear may also be important for AV gloves; resilient materials that are constantly compressed when in use may eventually remain partially compressed, losing much of their vibration attenuation performance; this also requires further studies.

CONCLUSIONS

Users of AV gloves are not provided with any information that allows them to evaluate the protection provided by the gloves when in use. The standard glove test code in ISO 10819 (2013) only demonstrates that the gloves can attenuate some vibration at the palm of the hand along the forearm direction and that they are unlikely to increase vibration exposures. Where evaluations have been done, they have shown that the vibration isolation effectiveness of a typical AV glove depends not only on the glove itself, but also on many factors such as tool operating conditions, working materials, vibration directions, assessment locations on the hand-arm system, individual differences between operators, varying grip and feed forces and postures. While it is very difficult to take all these factors into account in the assessment of the glove effectiveness, the reported studies have generally shown that AV gloves cannot reduce vibration exposure from low-frequency tools such as rammers, vibrating forks, or pavement tampers. In the operation of the vast majority of powered hand tools or machines such as chipping hammers, rock drills, riveting hammers, grinders, and sanders, AV gloves can marginally reduce the frequency-weighted vibration transmitted to the palm of the hand, but reduce little of the vibration transmitted to the fingers. If a tool primarily generates very high frequency vibrations (>250 Hz), an AV glove may substantially reduce the frequency-weighted vibration transmitted to the hand. However, such cases are very rare. So, based on the standard method for assessing the risk of HTV exposures, AV gloves do not have much apparent value, especially for reducing finger-transmitted vibration exposure.

It is hypothesized that the current hand-arm frequency weighting either does not sufficiently represent the frequency-dependency of vibration-induced finger or hand disorders, or largely underestimates the high-frequency effects. This means that the weighting currently used to assess the risk of HAVS may underestimate the harmful effects of vibration exposure as well as the actual vibration protection afforded by AV gloves. The level of any underestimation remains unknown. This situation is compounded by the lack of understanding of the mechanisms by which vibration causes damage to the hand-arm system, and the lack of sufficient evidence for demonstrating the real benefits of AV gloves at workplaces. Furthermore, AV gloves may introduce adverse effects, such as increasing grip force and reducing manual dexterity.

The available information shows that AV gloves are unreliable as devices for controlling HTV exposures. Other means of vibration control, such as using alternative production techniques, low-vibration machinery, routine preventative maintenance regimes and controlling exposure durations are far more likely to deliver effective vibration reductions and should be implemented. As the balance of the benefits of AV gloves and their potential adverse effects is individual-specific and has not been sufficiently investigated, it is advisable to use some caution when considering the role of AV gloves.

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DISCLAIMER

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