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Effectiveness of Antivibration Gloves When Used with a Light Electric Hammer. Differences Among Different Methods of Measurements

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ABSTRACT

The capability of antivibration (AV) gloves to reduce the vibration's transmissibility is not always proven, especially with percussive tools. Additionally, laboratory test results are sometimes dissimilar from the real field's one. The present paper investigates the properties of three different types of gloves air bubbles, gel, neoprene - specifically designed for vibration reduction, and of an ordinary working leather glove, during their use with a light (3 kg) electric hammer, in a real field, while chiseling a limestone block.
Outcomes reveal that AV gloves could provide benefits in reducing vibration when used with that type of tool, even though the protection is different to the one determined in laboratory test according to the ISO 10819 Standard.
The statistical analysis does not reveal differences for the triaxial transmissibility in the AV gloves in the range (6.3-1250 Hz), showing an average overall reduction of 26%, calculated with the corrected method specified by the ISO 10819:2013 Standard. The leather glove provides a reduction of around 8%. Similarly, statistical differences are not found with reference to transmissibility through the three main axes for the same type of glove, both in air and neoprene gloves. On the contrary, gel and leather gloves differ in transmissibility along the axes, showing a better reduction on the x- and z-axes, respectively. The transmissibility estimated with the direct method shows an average decrement of around 10% when compared to that resulting from the corrected one. The air glove provides the best triaxial transmissibility reduction at middle frequencies (25-200 Hz), while at high frequencies (200-1250 Hz), the best reduction is provided by the neoprene glove. At the peak percussion frequency of 63 Hz, measured on this tool, all the AV gloves provide some vibration attenuation - an average of 27% - with no statistical differences, while leather gloves show a little transmissibility increment (1.02).
Although the accelerometers used for the study are positioned as closely as possible, there are still differences between the acceleration measured on the bare-hand adaptor and the one directly on the handle, highlighting the importance of the corrected method application for better evaluating the gloves' transmissibility.

1. INTRODUCTION

Many tools usually used in workplaces are likely to generate high levels of vibration [1-3], which can be the origin of several diseases, generally called hand-arm vibration syndromes (HAVS). These pathologies are often related to the use of machines that require high efforts, repetitive movements, or not ergonomic postures [4, 5], such as the use of percussive tools [6].

Wearing personal protection equipment, such as vibration-reducing (VR) gloves, could be an option to reduce the vibration transmitted to the hand-arm system. The production and the distribution of this equipment have increased over the years due to their relatively low cost and their promising performance labeling.

The ISO 10819: 2013 Standard [7] specifies the must-have properties of gloves in terms of transmissibility, considered as the ratio between the vibration evaluated at the palm level inside the glove and the one on the handle, corrected with the transmissibility measured at the same condition in a bare-adaptor test. To be labeled as an antivibration (AV) glove, the transmissibility must be less than or equal to 0.9 in the middle-frequency range (25-200 Hz) and less than or equal to 0.6 in the high-frequency range (200-1250 Hz).

Anyhow, the effectiveness of AV gloves is controversial as it depends on many factors, which are often difficult to consider at the same time, when both the tests follow the ISO 10819:2013 Standard and the measurements are taken using real tools [8, 9]. In both cases, the risk of gloves performance overestimation can be high. Users may think that certified AV gloves have positive effects in vibration reduction, but as reported in some cases [10-12], gloves protection is lower than declared, sometimes it is similar to normal gloves. In fact, the standardized laboratory tests require the measurement of the transmissibility only in the forearm direction, applying a specified grip and push force on the handle of a monoaxial shaker, with subjects standing in a fixed position. These circumstances are not always representative of all types of tools, in particular when a different force is applied, affecting the transmissibility of the gloves [13]. Furthermore, real tools produce triaxial vibration, requiring AV/VR gloves to reduce the transmissibility not only in compression but also in shear. A few studies have demonstrated that gloves capability to reduce the vibration is higher in the compression compared to the other two directions. Therefore, the protection can be overestimated [11, 12, 14]. In other cases, gloves protection is higher in the real field rather than in the laboratory tests [15-17], due to the different experiment conditions, sometimes even when the transfer function is used [15, 18].

Additionally, increasing the thickness and the stiffness of VR gloves, compared to ordinary working gloves, the force applied by the workers may intensify, causing musculoskeletal problems, loss of dexterity, and affecting the ability to control safely the tool [18-20]. This represents another important issue, in particular when the reduction of the transmissibility provided by AV/VR gloves is little, as in the use of impact tools, which generally requires an intensive use of force.

In the light of the previous considerations, this paper investigates the AV properties, at palm level, of the three AV/VR gloves and an ordinary working leather glove. The transmissibility is examined during the use of a light electric hammer, in a real field, while chiseling a limestone block, through two different methods: direct and corrected calculation.

2. MATERIALS AND METHODS

The tool selected for the measurement operations is a Bosch PBH 2800 RE electric hammer drill (weight: 3 kg), with an impact frequency of 4000 r/min (66.67 Hz), equipped with a non-rotating flat chisel (20 × 250 mm). All the tests are performed on the same limestone block (100 × 50 × 35 cm), with the chisel perpendicular to the flat top surface of the block. The subjects are three healthy male workers, with the hand size between 7 and 10, and with expertise in drilling. For each measurement, the subjects maintain approximately the same body and hand-arm posture, holding the tool with both hands positioned on the rear and lateral handles. Measurements are taken only on the right hand, specifically on the rear handle of the tool. Since the aim of the study is to verify the attenuation in the transmissibility of AV/ VR gloves used in a real field, there is no control of the force applied by the workers. Thus, they are asked to operate as close as possible to the way they really do, allowing them to vary the grip and push forces as needed.

In order to maintain the accelerometer inside the glove in the same position during the different trials, a 3D-printed, modified hand-held adaptor is used to contain the accelerometer.

The adaptor was previously specifically designed and tested for measurements of the transmissibility of AV gloves [21]. The dimensions and the weight of the adaptor followed the ISO 10819:2013 [7], with a little variation (1.45 mm higher), in order to contain a 10-mm cube accelerometer (Larson & Davis three-axial SEN 040F, weight: 5 g).

The adaptor was created by a fused deposition modeling printer, by a 1.75-mm filament of polylactide and 0.4-mm nozzle at 70% of infill. A 3D-printed indicator (landmark) was drawn along the longitudinal axis of the adaptor (Figure 1) to help workers to maintain the accelerometer in the same position for all the measurements, reducing misalignments in the gloves. A reference point was also marked on the drill, allowing the subjects to hold the tool in the same way. A little slit in the seam of the glove, between the thumb and index finger, was made to allow the landmark to come out. Another accelerometer (Larson & Davis three-axial SEN 020, 14 × 20.3 × 14 mm, weight: 10.5 g) was positioned on the rear handle of the hammer, close to the trigger. It was oriented as the accelerometer inside the adaptor at 4 cm of distance, on the opposite side of the handle (Figure 2a). This accelerometer was firmly fixed-thanks to a hose metal clamp. Both accelerometers were oriented as reported in Figure 2b, with the z-axis rotated of approximately 10° from the percussion direction.

A multi-channel data acquisition system (Sinus Apollo Light Box_LT_8Ch) is used for the measurement campaign. The data are analyzed by the software Samurai, Excel, and SPSS.

Before and after each set of the measurements, the accelerometers are calibrated using the calibrator PCB 394C06.

Figure 1. 3-D printed adaptor with longitudinal landmark

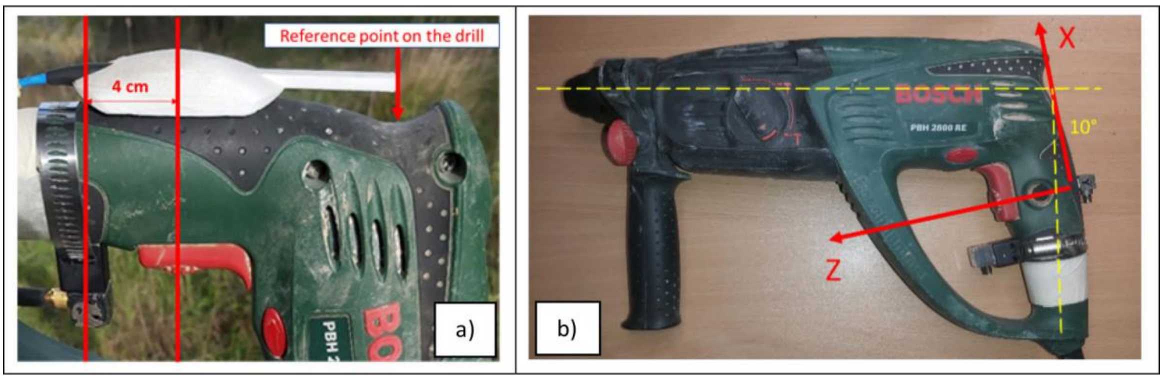

Figure 2. Position of the accelerometers

Figure 3. Tested gloves

The type of gloves analyzed are four, as reported in Figure 3. The first glove (a) is a multi-cell air bladder AV glove (external layer in leather - 1 mm thickness - with rubber dots on it; internal layer in air bubbles - 7 mm thickness). This glove is classified as AV according to the ISO 10819 Standard, performing transmissibility of T_c(M) = 0.75 and T_c(H) = 0.45, where T_c(M) is the average transmissibility in the middle-frequency range (25-200 Hz) and T_c(H) is that in the high-frequency range (200-1250 Hz). The second glove (b) is a vibration-reducing (VR) glove in gel (external layer in leather: 1 mm thickness; internal layer in gel: 5 mm thickness). The third glove (c) is an AV glove in neoprene (chloroprene rubber) (external layer in rubber: 7 mm thickness; internal layer in cotton: 1 mm thickness) with declared protection of T_c(M) = 0.86 and T_c(H) = 0.59. The fourth glove (d) is a standard working leather glove (external layer in leather: 1 mm thickness; internal layer in fleece: 1 mm thickness).

Each worker performs four trials, using the hammer for 20 seconds, without moving the chisel after the beginning of the penetration. A different penetration point is chosen for each trial. Measurement recordings start approximately 5 seconds after the tool is in function; and they end before the tool stops functioning.

As in the following formula, both the direct (T_d) and corrected (T_c) hand-arm weighted (W_h) vibration transmissibility are calculated. The direct transmissibility follows the method provided by the ISO 10819:2013 Standard; the corrected transmissibility partially takes into account the contribution of the hand-adaptor interaction, applying the method indicated by the ISO 1998 Standard, using the bare-hand adaptor acceleration, instead of the bare-adaptor acceleration.

$$T_{b(T)(M)(H)} = \frac{\sqrt{\sum_{i=i_L}^{i_U}\left(a_{bxi}\cdot W_{hi}\right)^2 + \sum_{i=i_L}^{i_U}\left(a_{byi}\cdot W_{hi}\right)^2 + \sum_{i=i_L}^{i_U}\left(a_{bzi}\cdot W_{hi}\right)^2}}{\sqrt{\sum_{i=i_L}^{i_U}\left(a_{Rxi}\cdot W_{hi}\right)^2 + \sum_{i=i_L}^{i_U}\left(a_{Ryi}\cdot W_{hi}\right)^2 + \sum_{i=i_L}^{i_U}\left(a_{Rzi}\cdot W_{hi}\right)^2}} \quad (1)$$

where,

$T_{b(T)}$ - $T_{b(M)}$ - $T_{b(H)}$ are the Total - Medium - High 'bare-hand' transmissibility measured when i_L = 6.3 Hz and i_U = 1250 Hz; i_L = 25 Hz and i_U = 200 Hz; i_L = 200 Hz and i_U = 1250 Hz, respectively;

a_{bxi} - a_{byi} - a_{bzi} are the accelerations measured at i-th frequency on the bare hand for x-y-z-axis, respectively;

W_{hi} is the hand-arm weighted value for i-th frequency;

a_{Rxi} - a_{Ryi} - a_{Rzi} are the accelerations measured at i-th frequency on the handle of the tool for x-y-z-axis, respectively.

$$T_{d(T)(M)(H)} = \frac{\sqrt{\sum_{i=i_L}^{i_U}\left(a_{gxi}\cdot W_{hi}\right)^2 + \sum_{i=i_L}^{i_U}\left(a_{gyi}\cdot W_{hi}\right)^2 + \sum_{i=i_L}^{i_U}\left(a_{gzi}\cdot W_{hi}\right)^2}}{\sqrt{\sum_{i=i_L}^{i_U}\left(a_{Rxi}\cdot W_{hi}\right)^2 + \sum_{i=i_L}^{i_U}\left(a_{Ryi}\cdot W_{hi}\right)^2 + \sum_{i=i_L}^{i_U}\left(a_{Rzi}\cdot W_{hi}\right)^2}} \quad (2)$$

where,

$T_{d(T)}$ - $T_{d(M)}$ - $T_{d(H)}$ are the Total - Medium - High 'direct' transmissibility measured when i_L = 6.3 Hz and i_U = 1250 Hz; i_L = 25 Hz and i_U = 200 Hz; and i_L = 200 Hz and i_U = 1250 Hz, respectively;

a_{gxi} - a_{gyi} - a_{gzi} are the accelerations measured at i-th frequency on the gloved hand for x-y-z axis, respectively.

$$T_{c(T)(M)(H)} = \frac{T_{d(T)(M)(H)}}{T_{b(T)(M)(H)}} \quad (3)$$

where,

$T_{c(T)}$ - $T_{c(M)}$ - $T_{c(H)}$ are the Total - Medium - High 'corrected' transmissibility measured when i_L = 6.3 Hz and i_U = 1250 Hz; i_L = 25 Hz and i_U = 200 Hz; i_L = 200 Hz and i_U = 1250 Hz, respectively.

3. RESULTS

Figure 4 shows both the unweighted and weighted three-axes acceleration spectra, measured by the accelerometer directly fixed onto the hammer. These spectra are characterized by having a percussion frequency of around 63 Hz and by producing high levels of vibration over 200 Hz. When the acceleration is W_h weighted, it is characterized by the production of a peak value of 5.9 m/s^2 at 63 Hz, and values in the range of 3.6-5.1 m/s^2, between 200 and 500 Hz. At all other higher frequencies, the W_h acceleration is less than 1.3 m/s^2, while at frequencies below 50 Hz, it is less than 0.3 m/s^2. The average W_h vibration (vector), measured for all the trials (48 measurements), is 12.28 m/s^2 (min: 9.62, max: 14.36 m/s^2), in line with that declared by the manufacturer for chiseling rock (12 ± 1.5 m/s^2). The statistical analysis (ANOVA) confirms the null hypothesis (P-value: 0.13), among the five different sets of trials (barehanded and gloves: a, b, c, d), in which the accelerometer is fixed to the handle.

Although the hammer is used only with its percussive function, with no bit rotation, the major vibration components are not presented along the z-axis, but on the x-axis (for the whole range of frequencies: $a_{wh,x}$ = 7.74 m/s^2 and $a_{wh,z}$ = 6.72 m/s^2; at 63 Hz: $a_{wh,x}$ = 4.78 m/s^2 and $a_{wh,z}$ = 2.43 m/s^2). This is due both to the internal rotation of the electric hammer components and to the rotation of the accelerometer the handle (10°), referred to the vertical direction of the chisel (Figure 2b).

Table 1 presents, for each subject, the average (four trials) W_h weighted transmissibility for all the tested gloves, using the methods of calculation (direct) uncorrected T_d and corrected T_c at 6.3-1250 Hz (T); 25-200 Hz (M); and 200-1250 Hz (H) frequencies range. Table 2 shows the overall average transmissibility and the percentage of vibration reduction.

The results within the entire frequencies range (6.3-1250 Hz), applying the corrected transmissibility, indicate a range of protection from 24% ($T_{c(T)}$ = 0.76) for the gel glove to 29% ($T_{c(T)}$ = 0.71) for the air glove. Then, the range of protection is higher if based on the direct transmissibility: from 35% ($T_{d(T)}$ = 0.64) for the gel glove to 39% ($T_{d(T)}$ = 0.61) for the air glove. In any case, the statistical analysis (one-way ANOVA) does not confirm the differences among the three AV/VR gloves (P-value = 0.214). In this case, an average protection of 26% ($T_{c(T)}$ = 0.74) and 37% ($T_{d(T)}$ = 0.63) can be representative for all the gloves, when both the methods are applied. The transmissibility of the leather glove differs from the others (P-value - Tukey test < 0.001), performing a protection of 8% ($T_{c(T)}$ = 0.92) when determined with the corrected method and 22% ($T_{d(T)}$ = 0.78) with the direct one.

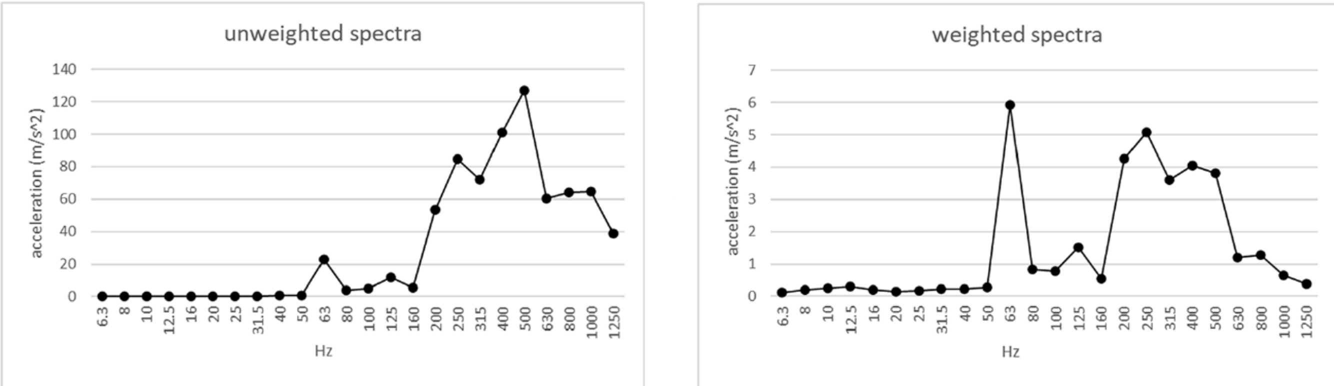

Figure 4. Unweighted and weighted spectra (three-axial acceleration x,y,z) of the hammer measured directly on the handle

Table 1. Average triaxial W_h transmissibility and the standard deviation for each subject at total (6.3- 1250 Hz), middle (25-200 Hz), and high (200-1250 Hz) frequencies range, for direct and corrected method

	$T_{d(T)air}$		$T_{d(M)air}$		$T_{d(H)air}$		$T_{c(T)air}$		$T_{c(M)air}$		$T_{c(H)air}$	
Subjects	Av	SD	Av	SD	Av	SD	Av	SD	Av	SD	Av	SD
1	0.58	0.03	0.70	0.03	0.49	0.02	0.67	0.03	0.63	0.03	0.81	0.03
2	0.57	0.03	0.71	0.04	0.50	0.03	0.66	0.03	0.63	0.04	0.81	0.04
3	0.65	0.08	0.82	0.06	0.49	0.02	0.76	0.09	0.73	0.05	0.80	0.04
Subjects	$T_{d(T)gel}$		$T_{d(M)gel}$		$T_{d(H)gel}$		$T_{c\ (T)gel}$		$T_{c\ (M)gel}$		$T_{c\ (H)gel}$	
	Av	SD	Av	SD	Av	SD	Av	SD	Av	SD	Av	SD
1	0.65	0.03	0.84	0.02	0.59	0.02	0.76	0.04	0.75	0.02	0.96	0.03
2	0.64	0.03	0.86	0.09	0.57	0.03	0.75	0.03	0.77	0.08	0.93	0.04
3	0.63	0.05	0.84	0.10	0.58	0.03	0.73	0.06	0.75	0.09	0.95	0.04
Subjects	$T_{d(T)neo}$		$T_{d(M)neo}$		$T_{d(H)neo}$		$T_{c\ (T)neo}$		$T_{c\ (M)neo}$		$T_{c\ (H)neo}$	
	Av	SD	Av	SD	Av	SD	Av	SD	Av	SD	Av	SD
1	0.58	0.04	0.77	0.06	0.50	0.02	0.67	0.05	0.69	0.06	0.82	0.04
2	0.65	0.12	0.89	0.10	0.41	0.05	0.76	0.13	0.79	0.09	0.67	0.09
3	0.66	0.05	0.89	0.09	0.46	0.06	0.77	0.06	0.80	0.08	0.76	0.10
Subjects	$T_{d(T)leat}$		$T_{d(M)leat}$		$T_{d(H)leat}$		$T_{c(T)leat}$		$T_{c(M)leat}$		$T_{c(H)leat}$	
	Av	SD	Av	SD	Av	SD	Av	SD	Av	SD	Av	SD
1	0.77	0.05	1.07	0.02	0.60	0.02	0.90	0.05	0.96	0.02	0.98	0.03
2	0.76	0.06	1.01	0.06	0.62	0.01	0.89	0.06	0.91	0.06	1.01	0.02
3	0.84	0.19	0.98	0.09	0.66	0.02	0.98	0.22	0.87	0.08	1.08	0.03

Table 2. Average triaxial W_h transmissibility at total (6.3-1250 Hz), middle (25-200 Hz), and high (200-1250 Hz) frequencies range, calculated by the direct and corrected methods

	Air	Gel	Neo	Leath
$T_{d(T)}$	0.61 (39%)	0.65 (35%)	0.64 (36%)	0.78 (22%)
$T_{d(M)}$	0.75 (25%)	0.86 (14%)	0.86 (14%)	1.01 (+1%)
$T_{d(H)}$	0.50 (50%)	0.58 (42%)	0.45 (55%)	0.63 (37%)
$T_{c(T)}$	0.71 (29%)	0.76 (24%)	0.74 (26%)	0.92 (8%)
$T_{c(M)}$	0.67 (33%)	0.77 (23%)	0.77 (23%)	0.90 (10%)
$T_{c(H)}$	0.81 (19%)	0.94 (6%)	0.74 (26%)	1.03 (+3%)

Looking at the middle frequencies range (25-200 Hz), the transmissibility measured with the direct method ($T_{d(M)}$) indicates a lower protection compared to that calculated with the corrected one ($T_{c(M)}$). The statistical analysis confirms the differences (P-value < 0.01), showing that the air glove is the most protective: 33% ($T_{c(M)}$ = 0.67) and 25% ($T_{d(M)}$ = 0.75) when calculated with the corrected and direct methods, respectively. Gel and neoprene gloves have the same protection within this range of frequencies, 23% ($T_{c(M)}$ = 0.77) and 14% ($T_{d(M)}$ = 0.86), respectively; the leather glove, instead, provides a protection of 10% ($T_{c(M)}$ = 0.9) when estimated with the corrected method, and no protection +1% ($T_{d(M)}$ = 1.01) with the direct one.

Looking at the high-frequency range (200-1250 Hz), the transmissibility measured with the direct method ($T_{d(H)}$) demonstrates a higher protection if compared to the corrected one ($T_{c(H)}$). The statistical analysis confirms all the differences (P-value < 0.03). The neoprene glove shows a better protection, with both methods, of the transmissibility 55% ($T_{d(H)}$ = 0.45) and 26% ($T_{c(H)}$ = 0.74); this is followed by the glove with air bubbles, 50% ($T_{d(H)}$ = 0.5) and 19% ($T_{c(H)}$ = 0.81), and the gel glove 42% ($T_{d(H)}$ = 0.58) and 6% ($T_{c(H)}$ = 0.94). As expected, the leather glove has a lower protection 37% ($T_{d(H)}$ = 0.63) and +3% ($T_{c(H)}$ = 1.03).

Figure 5 shows the weighted three-axial acceleration taken directly on the hammer handle, but also when the adaptor is used without the glove (bare hand). These two vibrations differ at quite all the frequencies, mainly at percussion frequency at 63 Hz and in the range 200-500 Hz. The reason is due to the different positioning of the accelerometers on the handle, and to the biodynamic response of the hand and the variation of the force applied [11, 22].

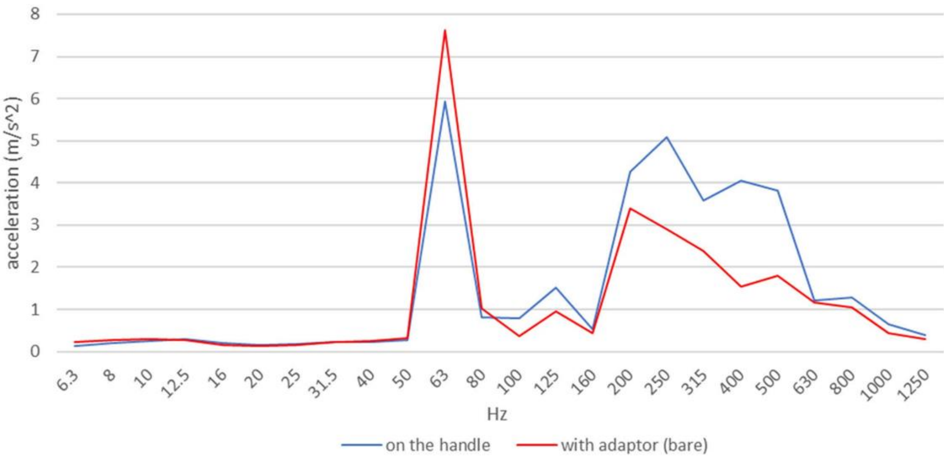

Figure 5. W_h triaxial acceleration measured directly on the handle of the hammer and with bare-hand adaptor

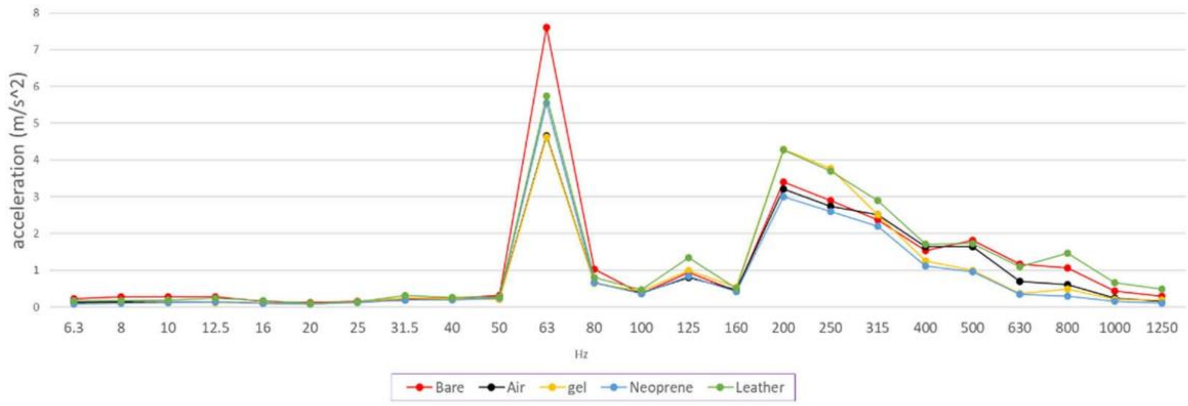

Figure 6. W_h three-axial accelerations measured on the bare-hand adaptor and wearing gloves

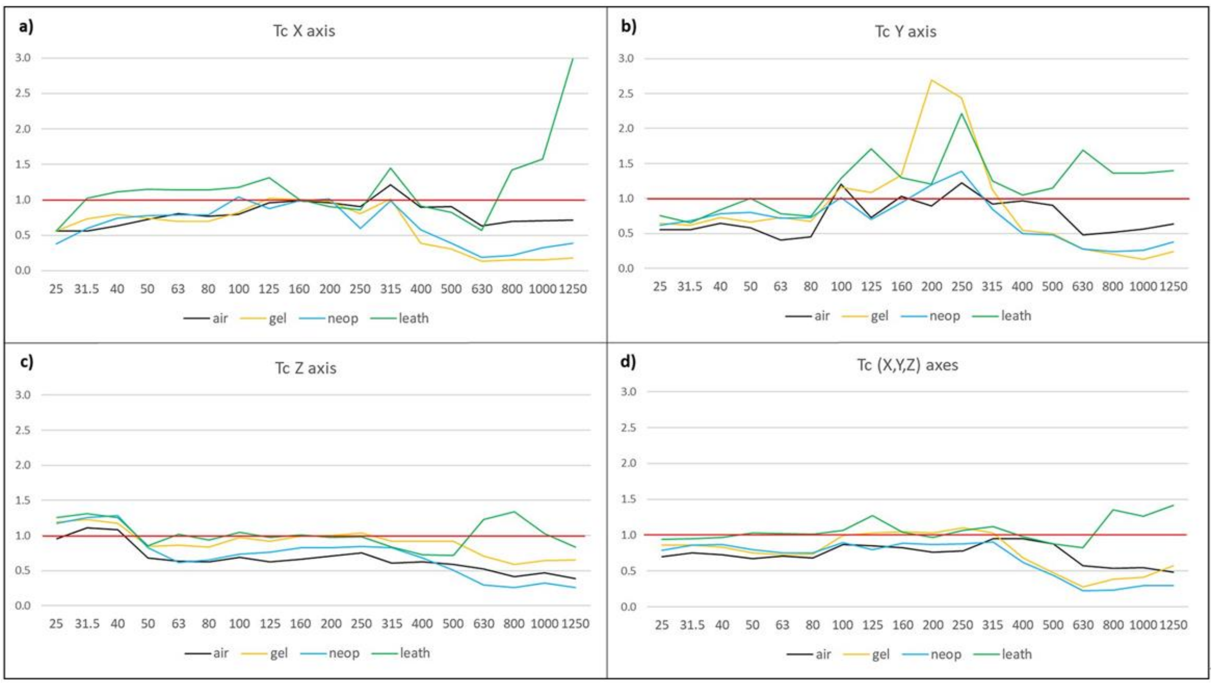

Figure 7. Total three-axes transmissibility and along each single axis

These differences explain why the transmissibility is higher if measured with the corrected method rather than the direct one, within high frequencies range, while the opposite occurs in the middle frequencies range. Within the range of 200-500 Hz, the vibration measured on the bare-hand adaptor is lower than the one directly on the handle. In the middle frequencies range, the opposite occurs at the percussion frequency of 63 Hz. Besides, since within the range of 100-160 Hz the handle vibration is higher than bare-hand one, the difference between $T_{c(M)}$ and $T_{d(M)}$ is less marked.

In Figure 6, the three-axes W_h weighted accelerations measured both on bare-hand adaptor and wearing gloves are shown. Within the range from 6.3 to 50 Hz, the vibration produced by the tool is too little for any consistent considerations about attenuation; nevertheless, at percussion frequency of 63 Hz, all the tested gloves, including the leather one, can reduce the acceleration, if compared with the bare-hand adaptor.

At 63 Hz, gel and air gloves perform the best reduction. The statistical analysis confirms the differences among all the couples of measurements (P-value < 0.05) except, as expected, those between neoprene and leather (P-value = 0.73), and air and gel (P-value = 0.98). In the high frequencies range (200-1250 Hz), the neoprene glove has a better acceleration reduction, compared to the bare hand. The air glove follows, while the gel glove provides an amplification within the range 200-315 Hz and a reduction in the range 400-1250 Hz. The leather glove increases the acceleration, within almost all the range between 100 and 1250 Hz.

The frequency analysis of the transmissibility calculated with the corrected method (T_c), for each axis and for the triaxial vector, is presented in Figure 7. Looking at the total transmissibility (Figure 7d), air and neoprene gloves reduce the vibration within all the frequencies range ($T_{c(T)min}$ = 0.50 at 1250 Hz - $T_{c(T)max}$ = 0.94 at 400 Hz for the air glove, and $T_{c(T)min}$ = 0.22 at 630 Hz - $T_{c(T)max}$ = 0.89 at 315 Hz for the neoprene glove); the gel glove increases the vibration within the range 125-315 Hz ($T_{c(T)min}$ = 0.27 at 630 Hz - $T_{c(T)max}$ = 1.12 at 250 Hz). The $T_{c(T)}$ for the leather glove is close to the unit at lower frequencies, but it increases over 630 Hz. The air glove is the best in reducing the vibration in the medium frequencies range 25-315 Hz, while, over 315 Hz, the neoprene glove performs the best reduction. At the percussion frequency of 63 Hz, all the gloves perform a similar triaxial reduction of the transmissibility, with no statistical differences (P-value > 0.3): $T_{c(63Hz)\text{-}air}$ = 0.71(29%), $T_{c(63Hz)\text{-}gel}$ = 0.73 (27%), and $T_{c(63Hz)\text{-}neop}$ = 0.76 (24%). Nevertheless, the leather glove shows a little increment of the transmissibility: $T_{c(63Hz)\text{-}leath}$ = 1.02. These results slightly vary from those that consider only the accelerations, measured using the adaptor (with and without the glove), as shown in Figure 6.

Along the z-axis, perpendicular to the palm of the hand (Figure 7c), the air glove also performs the best vibration reduction within the medium range (25-400 Hz); at high frequencies (over 500 Hz), instead, the neoprene glove is better. The gel glove shows the lowest vibration reduction within almost all the frequencies range. The leather glove performs a transmissibility close to the unit within the range of 50-250 Hz, a reduction (less than 12 %) within the range of 250-630 Hz, and an increment of the transmissibility within the range of 630-1000 Hz.

To compare the results to the ISO 10819 Standard (z-axis in M and H frequencies), the air glove performs the best reduction of the transmissibility both in the middle frequencies range (25-200 Hz), where $T_{c(M)Z}$ = 0.65 (35%), and in the high frequencies range (200-1250 Hz), where $T_{c(H)Z}$ = 0.71 (29%). The neoprene glove follows, where $T_{c(M)Z}$ = 0.75 (25%) and $T_{c(H)\,Z}$ = 0.80 (20%). The gel glove has the lowest protection, both at middle and high frequencies, which does not statistically differ from the leather glove: $T_{c(M)Z\ gel}$ = 0.86 (14%), $T_{c(M)Z\ leath}$ = 0.83 (17%) (P-value = 0.58) and $T_{c(H)Z\ gel}$ = 1.00 (0%), $T_{c(H)Z}$ = 0.97 (3%) (P-value = 0.192).

Along the x-axis (Figure 7a), the transmissibility of the AV/VR gloves is quite similar within the medium frequencies range (25-200 Hz), while at higher frequencies (over 315 Hz), the neoprene and gel gloves perform a better vibration reduction, compared to the air glove. The leather glove increases the vibration within all the frequencies range. Along the y-axis (Figure 7b), within the frequencies range of 100-315 Hz, the vibration reduction capability is much lower for all the gloves, in particular for the gel one. Over 315 Hz, the result is similar to that along the x-axis.

For the whole frequencies range, the statistical analysis reveals that air and neoprene gloves have similar protection in all the directions: $T_{cX\ air}$ = 0.72, $T_{cY\ air}$ = 0.66, $T_{cZ\ air}$ = 0.68 (ANOVA P-value = 0.076); $T_{cX\ neo}$ = 0.70, $T_{cY\ neo}$ = 0.70, $T_{cZ\ neo}$ = 0.78 (ANOVA P-value = 0.13). The gel glove has better protection along the x-axis: $T_{cX\ gel}$ = 0.60, $T_{cY\ gel}$ = 0.94, $T_{cZ\ gel}$ = 0.91 (ANOVA P-value = $6.42_E{}^{-14}$; Tukey test 0.001 for x-y and x-z and 0.44 for y-z).

4. CONCLUSIONS

The present investigation studies three different types of AV/VR gloves and a normal working leather glove, in terms of vibration reduction, during the use of a lightweight electric hammer (3 kg) for chiseling a limestone block.

Results show that AV/VR gloves could have some benefits in vibration reduction during the usage of that type of tool, even though the provided protection is dissimilar to that evaluated in laboratory tests, according to the ISO 10819 Standard.

Considering the total triaxial transmissibility within the entire frequencies range (6.3-1250 Hz), results show an average overall reduction of 26%, with no statistical differences among the AV/VR gloves; the working leather glove, instead, shows a reduction of 8%.

For neoprene and air gloves, the transmissibility along the three axes does not reveal statistical differences, evaluated for the same type of glove. The gel glove, on the contrary, shows a higher protection on the x-axis rather than on the other two. For the leather glove, the transmissibility is the lowest in the z-direction.

Outcomes are different when the transmissibility of gloves is evaluated separating the middle (25-200 Hz) and high (200-1250) frequencies range. Considering the triaxial accelerations, the air glove has the best vibration reduction (33%) at middle frequencies compared to the gel and neoprene gloves (23%); at high frequencies, the neoprene glove has the best reduction (19%), followed by the air glove (19%). The gel glove, in this case, provides a very little vibration reduction (6%).

In the compression (z-axis) at middle frequencies, all the AV/VR gloves provide higher protection if compared to that requested by the ISO Standard and to that declared by the manufacturer of certified gloves (Tc(M)z air = 0.65 - $T_{c(M)z\ neop}$ = 0.75 - $T_{c(M)z\ gel}$ = 0.86). At high frequencies, the protection is lower than that required by the ISO Standard ($T_{c(H)z\ air}$ = 0.71 -

$T_{c(H)z\ neop}$ = 0.80). In this specific case, the gel glove does not provide any protection.

Although the accelerometers used in the study are positioned as closely as possible, there are variations between the acceleration measured on the bare-hand adaptor and that on the handle. Other studies highlight these differences [11], as well, also with a jackleg drill [23]. The linear offsets of the reference accelerometer from the adaptor one, are here of 4 cm in the x-direction, and of 7.8 cm in the z-direction, resulting in moment arms that can affect the vibration revealed by the cubes. In other measurements not reported here, the reference accelerometer is put on the same side as the one inside the adaptor, but in this case, the differences between the two vibrations are greater. Moreover, the vibration measured by the reference accelerometer is in this case bigger than that declared by the manufacturer. These discordances are at the basis of the differences in the transmissibility evaluated with both the uncorrected and the corrected methods. In the present case, the uncorrected method overestimates the vibration reduction properties of the gloves of around 10%.

Results highlight also differences in the use of the reference accelerometer on the tool and on the bare-hand adaptor. The transmissibility calculated in the trials, which used only one accelerometer, (bare-hand adaptor), would have underestimated the protection of the gloves by around 6%.

Further considerations and limitations:

- the electric hammer used has a percussion frequency of 63 Hz and produces low vibration in a low frequencies range <50 Hz. This characteristic explains the reason why the tested gloves effectiveness is bit higher than the one evaluated in other experiments with percussive tools [8]. The vibration reduction capability of AV/VR gloves with percussive tools at frequencies below 40 Hz (typical of pneumatic hammers, breakers, or heavy electric hammers [24, 25]) is generally limited [26].
- Even though the study is conducted in a real field, while chiseling a limestone block, the measurements regard only the tool in its vertical position. This situation is not fully representative of its real usage.
- The workers involved in the tests are only three; this potentially results in imperfections regarding the estimation of the average transmissibility of the gloves, when used in a real field. To face this possible situation, we performed an increased number of trials (four) for each subject, apart from enlarging the time of chiseling (20 s for each trial).

5. DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available within the article. Its supplementary materials can be directly requested to the corresponding author: andrea.antonucci@unich.it.

6. COMPLIANCE STATEMENT

All the subjects involved in the study gave written informed consent.

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