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Vibration energy absorption (VEA) in human fingers-hand-arm system

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Abstract

A methodology for measuring the vibration energy absorbed into the fingers and the palm exposed to vibration is proposed to study the distribution of the vibration energy absorption (VEA) in the fingers-hand-arm system and to explore its potential association with vibration-induced white finger (VWF). The study involved 12 adult male subjects, constant-velocity sinusoidal excitations at 10 different discrete frequencies in the range of 16–1000 Hz, and four different hand-handle coupling conditions (finger pull-only, hand grip-only, palm push-only, and combined grip and push). The results of the study suggest that the VEA into the fingers is considerably less than that into the palm at low frequencies ($\leq$25 Hz). They are, however, comparable under the excitations in the 250–1000 Hz frequency range. The finger VEA at high frequencies ($\geq$100 Hz) is practically independent of the hand-handle coupling condition. The coupling conditions affect the VEA into the fingers and the palm very differently. The finger VEA results suggest that the ISO standardized frequency weighting (ISO 5349-1, 2001) may underestimate the effect of high frequency vibration on vibration-induced finger disorders. The proposed method may provide new opportunities to examine VEA and its association with VWF and other types of vibration-induced disorders in the hand-arm system.
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Keywords: Hand-arm vibration syndrome; Vibration-induced white fingers; Energy absorption; Human fingers and hand

1. Introduction

Prolonged exposure to hand-transmitted vibration is associated with a series of disorders in the vascular, sensorineural and musculoskeletal structures of human fingers-hand-arm system, which has been collectively called hand-arm vibration syndrome (HAVS) [1]. Vibration-induced white finger (VWF) is also frequently used to refer the vibration-induced disorders in the fingers and the hand in the literature, probably because blanching along with tingling and numbness in the fingers and the hand is a typical symptom of HAVS. VWF was first linked to use of pneumatic tools by Professor Loriga (cited in [2]) as early as the beginning of the 20th century. The first comprehensive investigation into VWF was performed in 1918 by Dr. Alice Hamilton (a copy of her study report is found in [3]). Since then, a considerable number of studies on VWF have been reported in the literature. However, the pathologic and physiologic mechanisms of VWF are not well understood. The vibration exposures required to cause VWF are not known precisely, neither with respect to vibration magnitude and frequency spectrum, nor with respect to daily and cumulative exposures, as noted in the updated international standard for measurement, evaluation and assessment of hand-transmitted vibration [4].

Consequently, it is unknown exactly which vibration characteristics may be responsible for VWF, and what the best measure of the vibration is for the exposure assessment [5]. For many practical reasons, such as technical availability and convenience and reliability of the measurement, the majority of the studies and all current national and international standards regarding

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hand-transmitted vibration (e.g. [4,6]) use tool handle acceleration spectrum as a measure to quantify the severity of vibration and to assess the risk of the exposure.

Several investigators [7–9] suggested that vibration energy absorption (VEA) may be a significant etiologic factor in regards to vibration injuries, and that VEA may provide a better indication of vibration-induced injuries than would a measure of the handle vibration spectrum. An epidemiological study on the relationship between the VEA and VWF was performed in the 1970s [8]. The results of this study indicted that there might be some correlation between the VEA and VWF, even though the reported data were far from sufficient to establish the relationship. Since this study, a great number of investigations [e.g. 10–15] on VEA have been reported. These studies have made substantial progress towards understanding the basic characteristics of the total VEA in the hand-arm system and the influencing factors. However, the development of a relationship between the VEA and VWF still remains a formidable task.

The measurement of the total VEA in the hand-arm system was exclusively used in the above-mentioned energy studies for VWF. However, there exists a critical problem with the total energy method. Some of the reported data indicate that the energy absorbed in the hand-arm system in the low-frequency range ($\leq$25 Hz) increases with the reduction of the vibration frequency [12], and low-frequency ($<$10 Hz) VEA along the forearm direction (the dominant vibration direction on many power tools) is higher than that in the middle-frequency range (25–250 Hz) [13]. This would suggest that low-frequency vibration would be more harmful than middle-frequency vibration. This directly contradicts the findings of many previously reported epidemiologic studies, which indicate that VWF is correlated to the use of vibrating tools with dominant frequencies in the middle-frequency range [5]. Few cases of VWF are associated with the tool operations that generate predominantly low-frequency vibration [16–17]. Therefore, the validity of the total energy approach for studying VWF is questionable.

The total energy method does not differentiate between the various parts of the hand-arm system where the VEA occurs, nor does it account for the distribution characteristics of the VEA at different frequencies. These seem to be fundamental deficiencies in the total energy method. As it has been well understood, VWF is a localized disease, even though the adverse effects of hand-transmitted vibration are not limited to the hand and fingers. It is because of this that almost all types of objective tests for VWF diagnosis focus the detection on the fingers or at the fingertips, as recently reviewed by many investigators [18]. It is also well understood that low-frequency vibration can be effectively transmitted to the arm and shoulders [19,20], and the transmitted vibration energy may cause discomfort, pain, and joint disorders at these locations [16,21,22]. Low-frequency vibration, however, may not be directly associated with the disorders in the fingers. Based on these arguments, we propose that there may be a stronger correlation between the finger VEA and VWF than between the total hand-arm system VEA and VWF. This hypothesis has not been seriously studied before.

To test this hypothesis, a method for measuring the energy flowing into and consumed by the fingers is proposed and evaluated in this study. It is used to examine the major differences between total hand-arm system VEA and finger VEA, and to explore the fundamental characteristics and distribution of the VEA in the fingers-hand-arm system, as well as the finger VEA association with VWF.

2. Methods

2.1. Theory for VEA measurement

Energy absorption per unit time or energy absorption rate may be directly associated with vibration-induced injuries. For this reason, VEA is usually quantified using the energy absorption rate or power. The power flowing into a system from another system at their interface can be calculated from

$$P(t) = \tilde{F}(t) \cdot \tilde{V}(t) \tag{1}$$

where $\tilde{F}$ and $\tilde{V}$ are the dynamic force and velocity at the interface, respectively.

The power can be expressed in the frequency domain, which can be obtained by calculating the cross-spectrum of the force and velocity [23]. Because of the phase difference, the cross-spectrum is normally complex, which can be generally expressed as follows:

$$P(\omega) = C(\omega) - jQ(\omega) \tag{2}$$

where the real component, C, is the coincident spectral density function (co-spectrum) and the imaginary component, Q, is the quadrature spectral density function (quad-spectrum) [23]. Applied to hand-transmitted vibration, the real component reflects the energy dissipated in the hand-arm system per unit time due to the friction at the interface between the hand and tool handle and the internal friction in the tissues of the hand-arm system. This component is usually termed as VEA or vibration energy dissipation. The imaginary component reflects the combination of the kinetic energy due to system inertia and the potential energy from the elasticity of the tissues. This portion of energy may feedback to the tool through the hand-tool interactions. There is a dynamic balance between the input and feedback energy at the interface in a steady-state vibration exposure. Therefore, the feedback energy may also be considered to be energy "stored" in the hand-arm system [24]. The imaginary component is generally much smaller than the real component [12]. While it remains unknown whether the stored energy can also be associated with the etiology of VWF, investigators have generally ignored this component.

The energy measurement concept has been widely used to quantify the total VEA in the studies of human whole body vibration [7,25], hand-transmitted vibration [8,13], and skin response to vibration [26]. For the purpose of the energy calculation, the acceleration measured on the tool handle is integrated to obtain velocity. Ideally, the dynamic force should be measured at the hand-tool interface to minimize the influence of the energy absorbed in an instrumented handle and the effect of the mass of the handle. Flexible force sensors have been proposed to perform such a measurement [27,28]. However, the reliability and repeatability of the measurement with such sensors have not been sufficiently evaluated. Piezoelectric force sensors have been widely applied for force measurement because of their rigidity and reliability.

As opposed to measuring VEA in the total hand-arm system, the power flowing into the fingers and the palm were measured separately in the present study. To accomplish this, the handle was evenly split into two parts at the centerline, as shown in Fig. 1. With such a split, the total vibrating force acting on the hand, $\tilde{F}$, can be considered as the sum of the two components acting on the surfaces of the two parts of the handle, such that:

$$\tilde{F} = \left(F + \tilde{F}_{\rm p}\right) - \left(F - \tilde{F}_{\rm f}\right) = \tilde{F}_{\rm p} + \tilde{F}_{\rm f} \tag{3}$$

where F is static grip force, $\tilde{F}_{\rm p}$ and $\tilde{F}_{\rm f}$ are the resultant dynamic forces acting on the palm and the fingers, respectively. If the connection between the two parts of the handle and the handle as a whole are sufficiently rigid in the frequency range of concern, the velocity ($\tilde{V}$), on each part will be the same. Therefore, the total power flowing into the hand-arm system (P) can be divided into the power flowing into the palm ($P_{\rm p}$) and the power flowing into the fingers ($P_{\rm f}$), which can be expressed as:

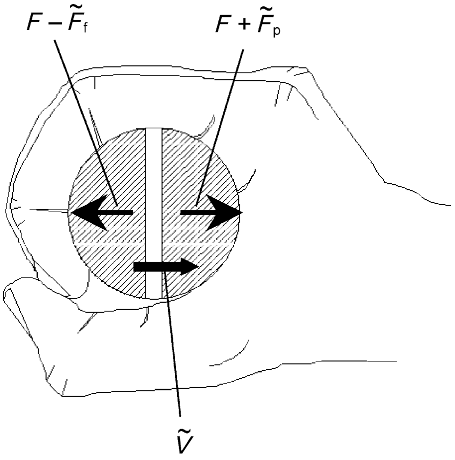

Fig. 1. Velocity and dynamic forces at the interfaces between the fingers and the handle, and between the palm and the handle (F: static grip force; $\tilde{F}_{\rm f}$: force acting on the fingers; $\tilde{F}_{\rm p}$: force on the palm; and $\tilde{V}$: Handle velocity).

$$P = P_{\rm p} + P_{\rm f} \tag{4}$$

The power flowing into both parts of the hand could be stored or absorbed anywhere in the hand-arm system, depending on the vibration characteristics (e.g. magnitude and frequency), the hand-handle coupling conditions, and so on. However, it is anticipated that the power flowing into the fingers would relate primarily to the biomechanical properties of the finger structures, and the power flowing into the palm would largely depend on the biomechanical properties of the palm-hand-arm system. The VEA in the fingers and the palm of the hand may thus be independently estimated, which is explored in this study.

As described in the next section, the measurement of the energy absorption was realized using an instrumented handle equipped with an accelerometer and two force sensors. Because the handle measuring cap and the sensors have some mass and damping characteristics, the directly measured VEA is the combined response of the handle and the fingers or palm-hand-arm system. The cancellations of the handle mass and damping effects can be achieved by using either a time-domain method or a frequency domain method. According to previous studies [29], the frequency domain method is superior. In this study, a cancellation formula was derived based on a measurement system model proposed by McConnel [29], which is expressed as follows:

$$P(\omega) = P_{\rm Rawdata}(\omega) - P_{\rm Handle}(\omega) \tag{5}$$

where $P_{\rm Rawdata}$ is the raw data measured in a subject test, and $P_{\rm Handle}$ is the energy absorption measured with an empty handle (without any hand coupling). This formula is valid only if the phase characteristics of the motion and force sensors are very comparable, and the electronic devices for the signal conditioning and data acquisition do not introduce any significant phase differences between their signals. In this study, these requirements were satisfied by choosing appropriate sensors and signal conditioners.

2.2. Instrumented handle

Based on the measurement principle described in the previous section, an instrumented handle for separately measuring the power flowing into the fingers and into the palm was designed and constructed. The design of the handle is shown in Fig. 2. It has a cylindrical shape with a diameter of 40 mm and an effective length of 110 mm. The handle structure consists of two parts: the handle base and the measuring cap. While the handle base is made of aluminum, the measuring cap is made of magnesium. Two piezoelectric single-axis force sensors (Kistler 9212) are sandwiched between the two parts along the centerline of the handle to measure the static and dynamic hand-handle coupling forces. An accelerometer (PCB 356A12) is positioned on the measuring cap at the center point of the handle.

The handle can be installed on a vibration exciter fixture at any desired orientation, which enables it to measure the power into both parts of the hand with the same test setup and with the same subject posture. The palm was placed on the measuring cap to assess the power flowing into the palm. To assess the power flowing into the fingers, the handle was rotated 180° about the longitudinal axis of the handle inside the fixture, while the fingers gripped the measuring cap.

The dynamic behaviors of the instrumented handle on the shaker are critical to the measurement of the biodynamic responses of the fingers-hand-arm system. To assure the accuracy and reliability of the measurement, the instrumented handle and the entire measurement system were comprehensively examined. The static calibration results from force range of -200 N (compression) to 30 N (tension) indicated that the handle exhibited excellent linear behavior. A scanning laser vibrometer (PSV-300) was used to examine the handle resonance and the vibration distribution pattern on the surface of the handle base and the measuring cap without human hand coupling [30]. The variation in the magnitude of vibration distributed along the handle centerline on the measuring cap at 1000 Hz was observed to be less than 5%. The fundamental resonant frequency of the handle-fixture system was determined to be approximately 1452 Hz. With a hand coupling, it was only marginally reduced to 1416 Hz. With the vibration test system used in this study, the effect of the resonance was effectively controlled and a consistent vibration input to the hand of each subject was guaranteed. The effective mass (= force/acceleration) of the measuring cap assembly was normally 105 g, with a maximum variation of less than 3 g in the frequency range of 10-1000 Hz under a constant vibration velocity (14 mm/s rms). The phase angle of the apparent mass was less than 3°, which suggested that the phase difference between the acceleration and force signals was negligible. This assured the validity of using Eq. (5) for the handle mass and damping cancellations. Overall, these performance features demonstrate that this instrumented handle can provide very reasonable measurements of the power absorption, at least in the frequency range of 10–1000 Hz.

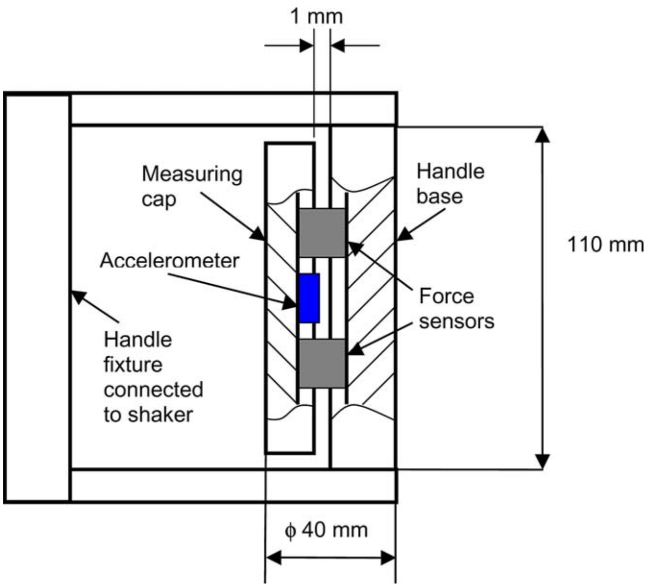

Fig. 2. A sketch of the instrumented handle used for the measurement of vibration energy absorbed in the fingers and the palm-hand-arm system.

2.3. Experimental set-up

The experimental set-up used in this study is illustrated in Fig. 3. The measured force signals were conditioned using a charge amplifier (Kistler Type 5010) and then fed into a data acquisition and analyzer system (B&K Type 3032A I/O Module). The acceleration signal was also fed into the system and integrated to obtain the velocity using the built-in integration function in the system. The energy absorption was determined by performing a cross-spectrum analysis using the standard cross-spectrum function built in the B&K PULSE program (Version 6.0).

As conventionally defined (ISO 10819, 2001) [31], the grip force shown in Fig. 1 is actually the quasi-static component of the force measured with the two force sensors depicted in Fig. 2. The measured force signal was thus branched to a low-pass filter with a 5 Hz cutoff frequency to derive the grip force. A custom program was developed using LabVIEW software (National Instruments, version 5.0) to display the grip force. The grip force was displayed on a computer monitor as a strip chart, which served as a feedback for the test subjects.

The pull or push force acting on the handle was measured using a force plate (Kistler 9286AA) and displayed as a strip chart on a separate computer monitor. The force plate measurements were verified using the instrumented handle when a pull-only or push-only action was required. A vibration test system equipped with a shaker (Unholtz-Dickie TA250-S032) and a

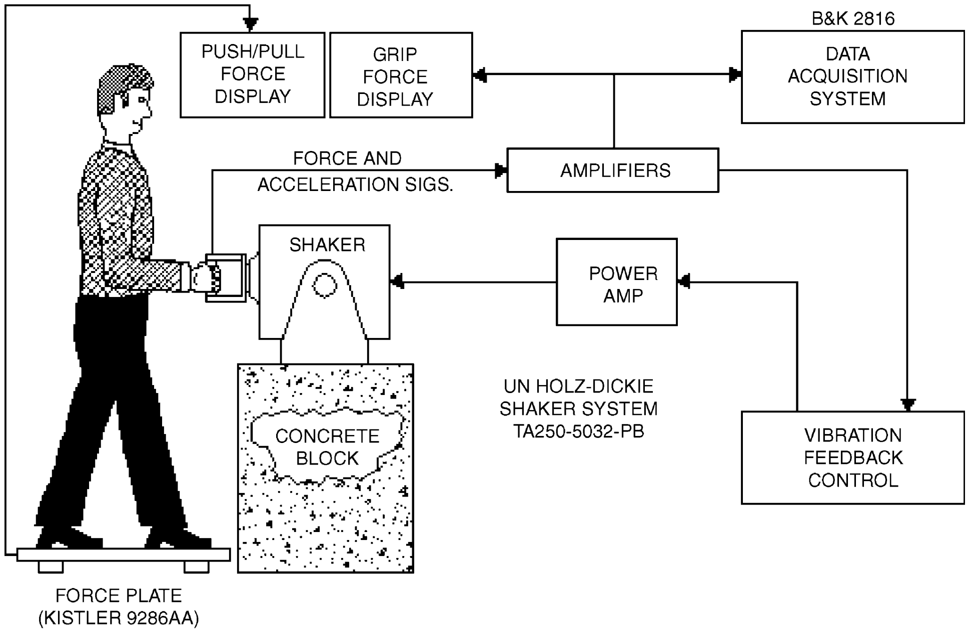

Fig. 3. Experiment set-up and subject posture.

control system (UD-VWIN V4.18) was employed to generate the desired vibration. The instrumented handle was fixed on the shaker of the test system using the specially designed handle-fixture with its long axis oriented vertically in the same manner as used in the ISO standardized glove test [31].

2.4. Subjects and studied variables

This study was carried out using 12 healthy male subjects, with no previous work-exposure to vibration. Some individual physical characteristics were measured for each subject and are presented in Table 1.

The test posture used in this study was the same as that required in the ISO standardized glove test [31] as depicted in Fig. 3. Briefly, each subject was required to stand upright on the force plate in front of the shaker, to keep the forearm at the same level as the handle, and to grip the vibrating handle with the elbow angled at 90°. With this hand-arm posture, the vibration was delivered to the hand in the Z_h-direction in the biodynamic coordinate system [4]. In order to identify the differences between the VEA values in the fingers and the palm-hand-arm system, the VEA was measured for both the fingers and the palm coupling conditions.

This study used four combinations of hand-handle coupling actions: (a) grip-only (50 N), (b) combined grip (50 N) and push (50 N), and either (c) pull-only (50 N) when measuring the VEA on the fingers or (d) palm-push-only (50 N) when measuring the VEA on the palm. Hence, there were three types of coupling actions for the evaluation of each part of the hand.

Discrete sinusoid vibrations with a constant velocity (14 mm/s rms) at 10 different frequencies (16, 25, 40, 63, 100, 160, 250, 400, 630 and 1000 Hz) were used in the experiment. These frequencies correspond to 10 different magnitudes of accelerations (1.4, 2.2, 3.5, 5.6, 8.8, 14.1, 21.9, 35.1, 55.0, 87.6 m/s^2 rms). Their corresponding frequency-weighted acceleration is approximately 1.4 m/s^2 rms, as calculated using the weighting specified in the current ISO standard [4].

2.5. Test procedures

The subjects wore normal office clothes without jackets. After going through the test explanation and consent-form-signing procedures, a short section of a first-aid bandage was placed on the back of the index finger of the right hand of a subject. A line was marked on the bandage in line with the crease at the base of the subject's third proximal phalange, which served as a reference for aligning the hand with the handle in the subsequent tests. The subject was asked to stand on the force plate adjusted to an appropriate height, and to grip the vibrating handle with the alignment mark in line with the handle-splitting line, which assured that the hand gripped the handle at the same location during each exposure. Once the grip posture and position were set, an investigator requested the subject to perform a specific hand-handle coupling. When the coupling force (grip, push, pull, or combined grip and push) was stable at the required 50 N level, the investigator recorded the test data for a period of 5 s. The subject was then advised to relax for 5 s, while keeping the same hand coupling posture and location before

Table 1
Some physical characteristics of the 12 male subjects

Subject	Height (m)	Weight (kg)	Hand breadth[a] (mm)	Hand circumference[a] (mm)	Hand length (mm)	Finger volume (ml)	Hand volume (ml)
1	1.8	141	101	261	192	105	560
2	1.75	77	84	210	191	50	375
3	1.73	75	86	213	190	56	355
4	1.85	97	101	231	200	77	445
5	1.75	73	83	205	192	60	390
6	1.78	86	97	240	203	72	440
7	1.8	93	90	230	194	65	445
8	1.75	77	85	205	190	63	375
9	1.8	86	90	231	190	65	460
10	1.75	74	87	215	184	45	330
11	1.83	80	90	220	196	65	380
12	1.83	89	90	223	196	75	475
Mean	1.79	87	90	224	193	67	419
STD	0.04	19	6	16	5	15	64

[a] Hand breadth and circumference were measured at the metacarpals.

performing the next requested coupling action, which minimized the variability of the hand-handle coupling position. Two test trials were performed for each of the three coupling actions at each part (fingers or palm) of the hand. Therefore, there were six trials at each of the 10 constant-velocity vibration exposures. These six trials were randomized among the subjects and vibration exposure frequencies. When all six trials were completed at a given frequency, the subject stepped off the test platform and took a one-minute rest before the next trial commenced under a different constant velocity vibration frequency. The sequence of the vibration exposure frequencies was independently randomized for each subject.

On a random basis, one-half of the subjects performed the finger VEA measurements first, and the others had their palm VEA measurements first. After the tests on the first part were completed, the instrumented handle was rotated 180° to measure the VEA on the other part of the hand. The subjects rested during the approximately 3 min it took to reorient the handle. Before resuming testing, the subject was re-instructed to keep the same hand grip alignment and hand-arm posture as in the first half of the experiment.

2.6. Statistical analyses

A two-factor repeated-measures analysis-of-variance (ANOVA) was performed; one factor reflected differences in the hand-handle coupling conditions, and the second factor reflected the 10 constant-velocity vibration exposure frequencies. The subject was used as a random factor in the analysis. The ANOVA was done using a conventional mixed model with the coupling action and exposure frequency as fixed effects and subject as a random effect. Pursuant to the results of the ANOVA, post-hoc analyses were undertaken. Pair-wise comparisons were performed using a Bonferroni correction [32] to assure proper levels of alpha protection.

3. Results

Fig. 4 depicts the mean values of the VEA measured on the fingers for the three finger-related hand-coupling combinations. The accelerations corresponding to the constant velocity excitation (14 mm/s rms) are also plotted in the figure.

The results of the two-factor repeated measures ANOVA yield significant effects for the coupling condition ($F_{2,22} = 57.92$, $p < 0.001$), exposure condition ($F_{9,99} = 56.36$, $p < 0.001$) and their interaction ($F_{18,198} = 44.41$, $p < 0.001$). The post-hoc analyses reveal that the VEA values at 25 and 40 Hz with the combined grip and push coupling test, which is the

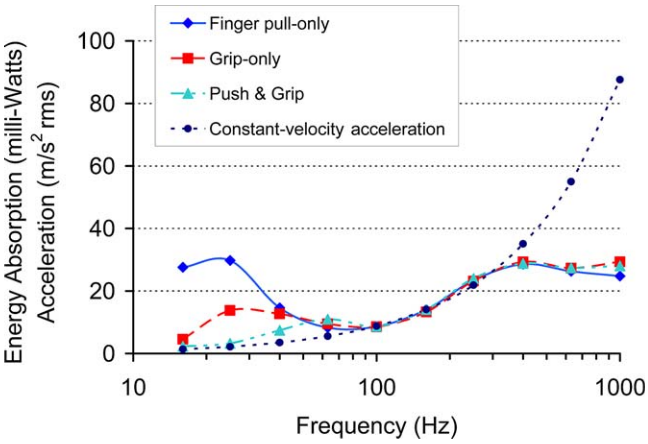

Fig. 4. VEA measured on the fingers under constant-velocity excitation and three different hand-handle coupling conditions.

highest effective hand-handle coupling among the three coupling conditions, are reliably lower ($p < 0.001$) than those measured with the other two coupling actions. In contrast, the VEA at 16 and 25 Hz with the pull-only coupling, which is the weakest effective hand-handle coupling, is the highest among the three couplings ($p < 0.001$). The average VEA value at 16 Hz with the combined coupling is also less than that of the grip-only coupling, but the difference is not statistically reliable ($p = 0.540$). At 40 Hz, the VEA values from the grip-only and pull-only couplings are also very close to each other ($p = 0.146$). At 63 Hz, the VEA from the pull-only coupling exchanges positions with the VEA values of the combined grip and push coupling, while those with the grip-only remaining in the middle ($p < 0.002$). At constant-velocity vibration exposures from 100 to 630 Hz, none of the differences were reliable ($0.078 < p < 0.965$). At 1000 Hz, the VEA value for the pull-only is marginally (15%) less than those for the combined grip and push coupling ($p < 0.001$).

The relationship between the VEA measured on the fingers and the constant-velocity acceleration can also be seen in Fig. 4. At frequencies below 100 Hz, the pattern of the relationship depends on the hand-handle coupling condition. At excitation in the 100–400 Hz frequency range, the VEA increases approximately proportionally to the magnitude of the constant-velocity acceleration, irrespective of the hand-handle coupling condition. Also irrespective of the coupling condition, the VEA remained more or less the same for excitation frequencies at or above 400 Hz.

Fig. 5 shows the VEA values measured on the palm under the three coupling conditions: push-only, grip-only and the combined grip and push. The data reveal that their basic trends are similar to each other but very different from those measured on the fingers. The ANOVA results also yield significant effects for coupling conditions ($F_{2,22} = 114.55$, $p < 0.001$), exposure conditions ($F_{9,99} = 28.35$, $p < 0.001$) and their interactions ($F_{18,198} = 14.16$, $p < 0.001$). The post-hoc analyses pertaining to the couplings reveal none of the differences at 25 Hz to be reliably different ($0.585 < p < 0.999$). At 16 Hz, the VEA for the combined coupling is not significantly different from that for the grip-only coupling ($p = 0.141$). The remaining 26 comparisons, however, indicate that the VEA values for different coupling conditions are reliably different ($p < 0.01$). The VEA for the grip-only coupling generally is the lowest while that for the combined coupling is the highest except at 16 and 25 Hz. The VEA measured at the palm has a resonant peak between 25 and 40 Hz, depending on the coupling condition. The lowest resonant frequency (25 Hz) was obtained under the grip-only action and the highest one (40 Hz) is associated with the combined grip and push coupling action.

Fig. 6 depicts the mean VEA values of the entire hand-arm system, derived from the superposition (Eq. (4)) of those measured on the fingers and the palm shown in Figs. 4 and 5, respectively. In reality, there is no combined action of the finger pull-only and the palm push-only couplings. For comparison, the data from these two couplings are also summed together and referred as a virtual combination in this study. As it can be seen, the basic trends in variation in overall VEA below 160 Hz are dominated by those measured on the palm. For frequencies at or above 160 Hz, the total VEA curves share the features of the VEA values measured independently at each part of the hand. The relative differences among the three coupling conditions become less significant under high frequency excitations (≥160 Hz) due to the consistency of the finger VEA (Fig. 4) and the reduced difference between the palm VEA values (Fig. 5).

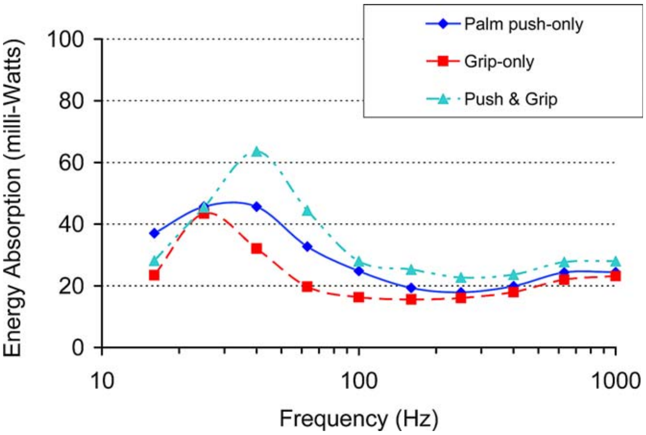

Fig. 5. VEA measured on the palm under constant-velocity excitation and three different hand-handle coupling conditions.

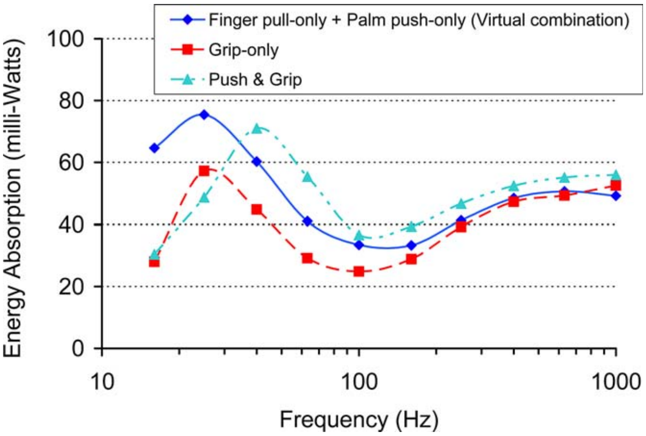

Fig. 6. Total VEA in the finger-hand-arm system calculated from the VEA values measured on the fingers and the palm in different hand-handle coupling conditions.

Under the grip-only action, there is also a resonant-like peak on the finger VEA curve (Fig. 4), which is at the same frequency (25 Hz) as that on the palm VEA curve (Fig. 5). This similar resonant feature indicates that the fingers' movement relative to the handle is similar to the palm's movement relative to the handle at the low frequencies. However, the similarity in the relative motions does not result in similar VEA values because the effective mass and damping characteristics of the fingers are very different from those in the palm-wrist-arm system at the low frequencies. The finger VEA only contributes 16% and 24% to the total hand VEA values at 16 and 25 Hz, respectively. In contrast, above 160 Hz, the finger VEA becomes greater than the palm VEA ($p < 0.001$). The majority of the total hand VEA below 160 Hz is associated with the palm ($p < 0.001$).

Under the combined grip and push coupling, the difference between the finger and palm VEA values below 160 Hz is even greater. At 16 and 25 Hz, less than 7% of the total hand VEA is attributed to the fingers' response. However, the finger and palm VEA values become fairly comparable at frequencies above 160 Hz (see Figs. 4 and 5).

The differences between the VEA values measured from the finger pull-only action and the palm push-only action are not as profound as those in the other two coupling actions. However, the difference pattern is similar to that in the other two coupling conditions (see Figs. 4 and 5).

4. Discussion

Similar to the energy dissipation density that has been successfully used to analyze the fatigue of materials [33], the VEA per unit volume of tissue, i.e., VEA density (VEAD), would perhaps be the best theoretical measurement of vibration exposure if the VEA is, indeed, associated with vibration injuries. This approach, however, requires determining the distribution of VEAD in the hand-arm system and identifying the critical locations of VEAD concentration. So far, it has been impractical to physically measure the distribution of the VEAD. The next best measurement may be the local VEA in the fingers or fingertips. The fingers are directly in contact with the vibration source and have much less tissue volume than the rest of the hand-arm system. This may result in high concentrations of VEA in the fingers and suggests that the critical VEAD may be located in the fingers. This assumption is further supported by the fact that blanching, tingling, and numbness associated with VWF usually starts in the fingers, and these symptoms are also usually the most severe in the fingers [2,5]. Therefore, there may be a correlation between the finger VEA and VWF. As a critical step to test the hypothesis, this study developed a method to separate the finger VEA from the total VEA in the continuous finger-hand-arm system, and studied the fundamental characteristics of the VEA values separately measured at the fingers and at the palm.

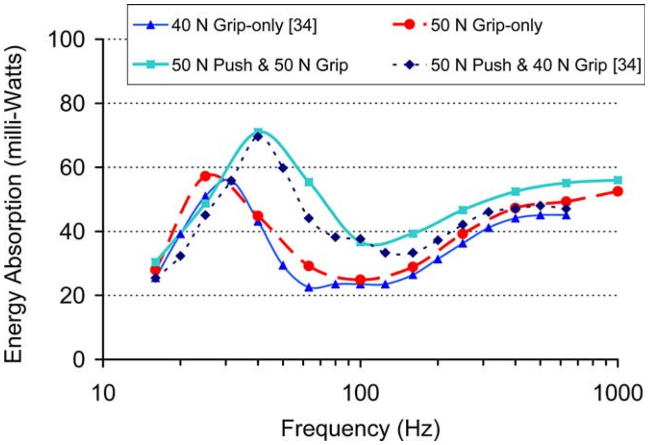

Fig. 7. Comparison of the total VEA values in the finger-hand-arm system obtained in the present study and those calculated using the mechanical impedance (MI) data reported from a previous study [34].

Fig. 7 shows a comparison of the total VEA of the hand-arm system obtained in the present study and that calculated from reported mechanical impedance (MI) data [34] using the following formula [12]:

$$P(\omega) = \text{Real}[\text{MI}(\omega)]\left|\tilde{V}\right|^2 \tag{6}$$

The velocity value of 14 mm/s rms was used in the calculation, which is the same as that used in the experiment. Different from the split handle method used in this study, the conventional method for directly measuring the biodynamic response of the entire hand-arm system was used for the MI measurement in the reported study [34]. As can be seen, the general patterns and values at different frequencies obtained from these two different approaches agree very well with each other. This agreement provides support for the measurement method proposed in the present study.

Vibration transmission to the finger-hand-arm system has been studied by many investigators [19,20,35–37], in which the acceleration or velocity due to vibration on the surface of the hand-arm system at several critical points was measured. These studies found that vibration at frequencies below 40 Hz could be effectively transmitted to the arms, shoulders and head; vibration at frequencies above 100 Hz was mainly limited to the hand; and less than 10% of vibration at frequencies above 250 Hz was transmitted to the wrist and beyond. Vibration energy can only be absorbed in the tissues to which vibration has been transmitted. Therefore, theoretically, the VEA measured at low frequencies should be distributed throughout the entire finger-hand-arm system; the VEA distribution along the finger-hand-arms-shoulder-head vibration transmission chain would decrease with an increase in vibration frequency; and the VEA at high frequencies should be limited to the local tissues close to the vibration source. These observations are consistent with those of the present study.

The results of the present study indicate that the VEA measured on the fingers at frequencies below 100 Hz is generally dependent on the palm-handle coupling condition. At higher frequencies, however, the measured VEA can be considered practically independent of the coupling condition. This suggests that only the local tissues of the fingers can effectively respond to high frequency excitation, and they likely absorb most of the transmitted energy at these frequencies.

The combined grip and push coupling represents the tightest effective hand-handle linking used in this study. Such a coupling is generally expected to be associated with relatively higher vibration transmission and energy absorption. This holds true for the palm VEA, as shown in Fig. 5. However, the tight coupling does not increase the finger VEA but reduces it dramatically at low frequencies ($\leq$25 Hz), as shown in Fig. 4. This phenomenon can be explained by the possible non-linear stiffness characteristics of the palm's soft tissues and the in-phase motion of the fingers and the palm at low frequencies. The combined coupling results in the highest palm contact force (100 N) that corresponds to the highest contact stiffness, as evidenced by the high VEA resonant frequency under this coupling. The increased stiffness at the palm increases the vibration transmission at the palm but decreases the relative motion between the fingers and the handle. Under the same finger force (50 N) at different palm coupling conditions, the finger contact stiffness may not change significantly. Hence, the decreased relative motion reduces the finger dynamic force and thus the energy transmission at the fingers.

In the pull-only coupling, there is effectively no palm coupling with the handle. This makes it relatively easy for the low-frequency vibration to be transmitted from the fingers into the other parts of the hand-arm system and absorbed in a large volume of tissues. This explains why the VEA under the pull-only coupling is obviously higher than the VEA values at the other coupling configurations at 16 and 25 Hz, as shown in Fig. 4. This also suggests that a large portion of the low-frequency VEA measured at the fingers in this coupling is not distributed in the fingers but rather in the other parts of the contiguous finger-hand-arm system. This is because the tissue in the fingers represents a small percentage of the tissue in the hand-arm system.

Obviously, at frequencies below 100 Hz, the VEA measured on the fingers generally consists of two components: the energy exclusively consumed in the finger tissues and that transmitted to and consumed in the other parts of the hand-arm structures. Because the effects of the palm coupling conditions generally decrease with an increase in vibration frequency, as shown in Fig. 4, the transmitted component likely increases with a decrease in frequency. This is also consistent with the general vibration transmission theory. Since only the absorbed component in the finger tissues may be closely associated with vibration-induced finger disorders, it may be useful to further differentiate these two components. This remains a formidable research task. As an alternative approach, a finite element model of a finger similar to that reported by Wu et al. [38] may be developed to help determine the local finger VEA and the VEAD distribution.

The comparisons of the VEA values measured on the fingers and on the palm plotted in Figs. 4 and 5 clearly indicate that the vibration energy consumed in the hand-arm system at 25 Hz and below was mainly transmitted through the palm. Moreover, it is likely that only a portion of the relatively high VEA measured on the fingers in the pull-only coupling at low frequencies is distributed within the finger tissues, as discussed above. These findings suggest that the majority of the total hand-arm system VEA in the low-frequency range ($\leq$25 Hz) is distributed through the palm-hand-arm system, which may not be closely associated with vibration-induced injuries in the fingers. Hence, it may be inappropriate to directly link low-frequency VEA with finger disorders. This may explain, at least partially, why the prediction from the total energy method contradicts the findings of the epidemiologic studies. Hence, while the VEA measured at the palm may have a better association with the disorders or injuries in the palm-wrist-arm-shoulder system, the finger VEA should be used to study VWF or other finger disorders.

The ISO standardized frequency weighting [4] is based on the basic assumption that at frequencies above 16 Hz, vibrations with the same velocity are equally harmful to the hand-arm system. The results of this study indicate that at constant velocities, the vibration energy actually absorbed in the fingers at low frequencies is significantly less than that at high frequencies. Therefore, from the point of view of energy absorption, the ISO weighting overestimates the effect of low-frequency vibration and/or underestimates the effect of the high-frequency vibration on vibration-induced finger disorders.

5. Conclusion

A methodology is developed to separately measure the VEA into the fingers and into the palm. This study finds that the finger VEA is considerably less than the palm VEA at low frequencies ($\leq$25 Hz). The VEA values are, however, comparable under excitations in the 250–1000 Hz frequency range. The finger VEA at high frequencies ($\geq$100 Hz) is practically independent of the hand-handle coupling condition. The coupling conditions affect the VEA into the fingers and the palm very differently. The finger VEA values suggest that the frequency weighting specified in the current ISO standard [4] may underestimate the effect of high frequency vibration on vibration-induced finger disorders.

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