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Influence of hand forces and handle size on power absorption of the human hand–arm exposed to z_h-axis vibration

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Abstract

The effect of handle size and hand forces, on the power absorbed by the hand–arm system, was investigated in a laboratory study using seven healthy male subjects exposed to two levels of broadband random vibration in the 8–1000 Hz frequency range along the z_h-axis. The measurements were performed with three instrumented cylindrical handles of different diameter (30, 40 and 50 mm). The influence of hand forces applied by the subjects holding the vibrating handles was investigated under nine different grip/push force combinations. The posture adopted by the subjects consisted of the bent forearm with elbow angle of 90° and neutral wrist position, as described in the ISO 10819 standard. The pressure distribution at the hand–handle interface was also measured to quantify the static contact force corresponding to each combination of grip force, push force and handle size. The hand–handle coupling force, as defined in ISO/WD 15230, was further evaluated by summing the grip and push forces. The measured total absorbed power revealed relatively low inter-subject variability (generally less than 12%). Total absorbed power was found to be better correlated with coupling force than the contact force, while most of the absorbed power occurred in the low-frequency range, below 200 Hz. The magnitude of power absorbed within the hand and arm was observed to be strongly dependent upon the handle size; larger handles cause higher absorption of energy. The results also suggested that the power absorption is influenced by the grip as well as push force.

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The results attained from ANOVA confirmed the significance of all studied factors, i.e. vibration magnitude, handle diameter, and the grip and push forces on the power absorbed into the human hand and arm exposed to vibration.

1. Introduction

Prolonged occupational exposure to hand–arm vibration arising from operation of hand-held power tools has been associated with many vascular, musculoskeletal and neurological disorders, collectively known as hand–arm vibration syndrome (HAVS). Measurement and risk assessment of hand-transmitted vibration is mostly based on the guidelines and dose–response relationship provided in the ISO 5349-1 standard [1]. These guidelines suggest that the magnitude, frequency, direction and duration of vibration exposure are the most important variables for the risk assessment of hand–arm vibration. However, the standard, which is based on the frequency-weighted rms acceleration at the tool handle, has been subjected to many criticisms regarding the frequency-weighting function, daily and lifetime exposures, as well as for the lack of consideration of other significant factors, such as coupling forces [2,3]. While some studies have suggested that the dose–effect relationship overestimates the potential health risks [4,5], others have shown that it underestimates the risk of the prevalence of HAVS [6,7].

An epidemiological study has shown that the prevalence of vibration-induced white finger could be related to the amount of energy absorbed by the operators [8]. Within related context, a reasonably good correlation between the power absorbed by the human body exposed to whole-body vibration and the subjective sensation of discomfort has also been reported [9]. In addition, it has been reported that the absorbed power by the human hand–arm system is perhaps a better estimate than the frequency-weighted acceleration, as recommended in the ISO 5349-1 for the risk assessment of hand-transmitted vibration [2,10]. From a physical point of view, the power generated in the hand–arm system can be of two forms: reactive and active. The reactive power, attributed to the potential and kinetic energies stored in the elastic tissues of the hand–arm system, does not contribute directly to the net flow of energy between the handle and the hand–arm system and thus there is no energy dissipation. On the other hand, the active component of the power is directly related to the net flow of energy from the handle to the hand. This form of energy is dissipated through the viscous elements of the hand–arm system, where it is converted into work and heat, and may thus be considered as a better measure of the risk imposed on the hand–arm tissues [11–13].

Although the notion of absorbed power for assessing the effects of hand-transmitted as well as whole-body vibration has been proposed for more than 30 years, the role of many contributory factors has not been systematically identified. Many studies have reported strong effects of different factors on the absorbed power, such as the intensity, frequency and direction of vibration, as well as the grip and push forces exerted on the handle. However, their findings are somewhat contradictory, even though the vast majority of the studies have been conducted by the same research group [2,10,14–20]. The differences in the reported absorbed power data could be observed not only in the vibration magnitude, but also in relation to other intrinsic and extrinsic factors. Burström and Lundström [10] investigated the power absorbed by the human hand–arm system exposed to sinusoidal vibration for three different postures along the x_h and z_h axes. While no significant difference in the absorbed power magnitude was observed between the x_h and z_h axes, an increase of power absorption with respect to frequency could be generally observed. Another study, conducted by the same authors, suggested that vibration along different axis (x_h, y_h or z_h) yields differences in power absorbed within the hand and arm, while an increase in the grip force leads to a linear increase in the absorbed power [16]. On the basis of measurements performed under exposure to vibration spectra of five different tools, it was further concluded that the vibration direction has a great influence on the absorbed power, which also increases rapidly with an increase in vibration magnitude [2]. The magnitudes of absorbed power varied from 0.4 to 1.5 W under selected vibration spectra with frequency-weighted rms acceleration ranging from 3.1 to 9.3 m/s^2. The power absorbed into the hand–arm system exposed to vibration can be indirectly estimated from the biodynamic response, mostly characterized in terms of the driving-point mechanical impedance (DPMI) [2,21–23]. Unlike the DPMI, which is almost independent of the vibration magnitude, significantly higher magnitudes of absorbed power are obtained under higher vibration magnitudes.

In another study, laboratory measurements performed under constant velocity spectra of different magnitudes of weighted acceleration in the 3–12 m/s^2 range resulted in peak absorbed power in all vibration directions in the order of 0.5 W [14]. Sörensson [19] measured the absorbed power under excitations representing four different tools (chipping hammer, impact drill, breaker and impact wrench), with weighted rms accelerations of 3 and 6 m/s^2, and reported that the magnitude of absorbed power lies in the 0.03–0.2 W range, while the effects of the grip and push forces were observed to be insignificant. Even lower levels of peak absorbed power by the hand and arm, in the order of 0.002 W, have been reported in a recent study [20]. This study involved measurements with 24 subjects exposed to constant-velocity random vibration spectra of two different magnitudes (3 and 6 m/s^2) along the x_h and z_h directions. These magnitudes of absorbed power were found to be considerably lower than those reported in earlier studies under comparable excitations [10,14]. The results of this study further showed negligible absorbed power under higher-frequency vibration, above 630 Hz.

A few studies have also concluded that the contact force between the hand and a tool handle affects the severity of exposure to the hand-transmitted vibration and causes hand–wrist cumulative trauma disorders [24–26]. Only a few attempts, however, have been made to quantify the contribution due to hand force on the DPMI and on the absorbed power. Studies involving both the driving-point mechanical impedance and the absorbed power have revealed contradictory effects of hand forces on these respective measures [2,18,23,27]. Riedel [28] concluded a strong effect of the hand–handle coupling force on the biodynamic response of the human hand and arm, where the coupling force was defined as the sum of grip and push forces, suggesting equal contribution due to both forces. However, a few other studies have suggested only little effect of the hand push force [22,29]. Considering that the hand–handle contact force depends upon the effective contact area of the hand–handle interface, the amount of absorbed power may be expected to be influenced by the handle size, which has not yet been investigated.

The primary objective of this study is to establish the dependence of the absorbed power on the excitation frequency, vibration intensity, handle size, hand forces (grip and push) applied on the handle, and coupling and contact forces developed at the hand–handle interface, under exposure to vibration along z_h direction. Owing to the considerable effects of hand forces on the hand–arm response to vibration, the influences of hand–handle interface forces on the power absorption are particularly explored.

2. Methods

Three instrumented cylindrical handles with different diameters (30, 40 and 50 mm) were designed to provide measures of the static and dynamic grip and push forces exerted by the hand. The handles were designed such that their respective first resonant frequencies were above 1.6 kHz. The handles were made of two aluminium semi-circular sections joined by two *Kistler* 9212 force sensors, which permitted the measurement of the grip force. A *PCB* SEN026 tri-axial accelerometer was mounted inside the handle to measure the handle acceleration, while two *Bruël & Kjær* 8200 force transducers located between the handle and handle support were used to measure the dynamic driving force, as well as the static push force. The base of the handle support was fixed to an Unholtz-Dickie electrodynamic shaker system with 890 N force capacity. The instrumented handle and the experimental setup are shown in Figs. 1 and 2.

The hand–handle interactions are characterized in terms of static grip and push forces, coupling force obtained as the sum of grip and push forces, and the contact force obtained through integration of the measured distributed pressure over the hand–handle contact surface area. The hand–handle interface contact pressure distributions were acquired using the EMED measurement system of *NOVEL Electronics* [30,31]. The measurement system consists of a 16 × 11 (16 rows and 11 columns) flexible capacitive pressure sensing grid, and a Pliance mobile data conditioning and acquisition system. The sensing grid inserted within an elastomeric mat was applied to the selected handle for measuring the hand–handle interface pressure distributions over the contact region. Each sensor covered an area of 0.766 cm^2, including the spacing between the adjacent sensors. A total of five and two rows of the sensing matrix were masked to eliminate the overlapping of the active sensors for 30 and 40 mm handles, respectively, while no masking was

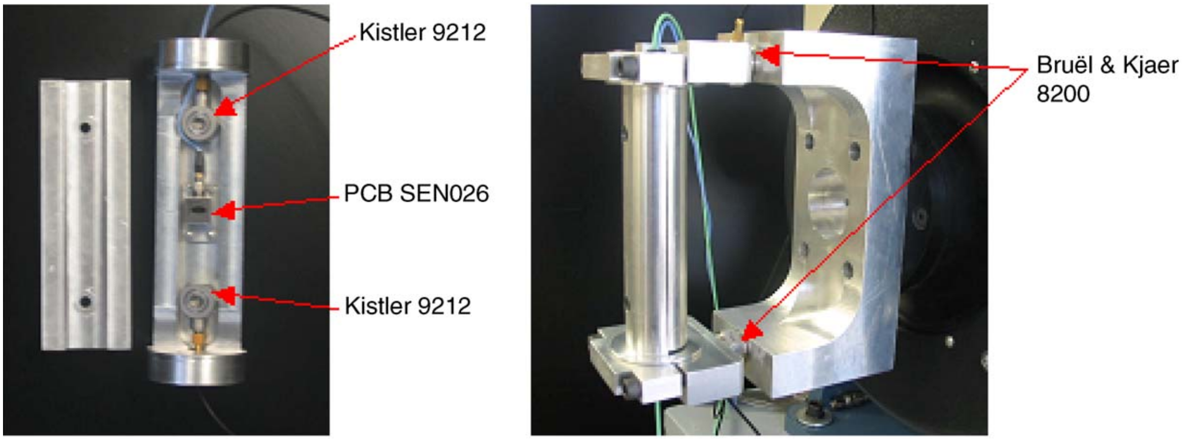

Fig. 1. Pictorial views of the instrumented handle (left) and the support (right).

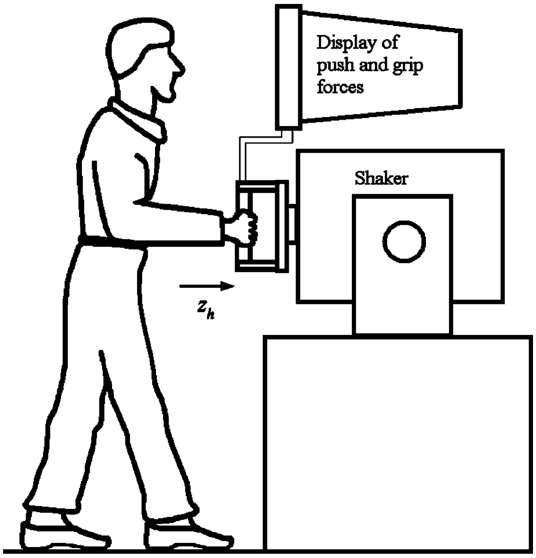

Fig. 2. Schematic of the experimental setup.

needed for the 50 mm handle. In a previous study, it had been shown that the hand/handle interface pressure distribution, the location and the magnitude of the interface peak pressures, and thus the total contact force vary with the hand forces and handle size [32].

The experiments were performed with seven adult male subjects under three different magnitudes of grip (10, 30 and 50 N) and push forces (25, 50 and 75 N) resulting in nine different grip and push force combinations. The measured grip and push forces, sampled at a rate of 4 samples/s, were displayed to the subject on a computer screen. The measurements were initiated by acquiring hand–handle static pressure distribution under the nine different combinations of static grip and push forces. Each subject was advised to grip the mounted handle using his right hand, while maintaining the forearm horizontally aligned with the handle, elbow bent at an angle of 90° and wrist in a neutral position, as described in ISO 10819 standard [33]. For each measurement, the subject was given adequate time to adjust the grip and push forces to the specified values by monitoring the displayed forces. The measured grip and push forces, as well as the pressure distribution, were averaged over a 10 s period.

Then, measurements were undertaken under two different levels of broadband random vibration with constant acceleration power spectral density in the 8–1000 Hz frequency range. The overall frequency-weighted rms acceleration ($a_{h,w}$) were computed following the ISO 5349-1 standard [1] as $a_{h,w} = 2.5\,\text{m/s}^2$ for the lower spectra and $a_{h,w} = 5.0\,\text{m/s}^2$ for the higher spectra. The synthesized vibration was applied to the hand–handle system along the z_h-axis and the resulting dynamic force and handle acceleration were acquired in a multi-channel data acquisition and analysis system (*Brüel & Kjær* Pulse system). The data corresponding to each measurement were acquired over a period of 7 s (25 averages using Hanning window and an overlap of 75%); while the subjects were asked to maintain the push and grip forces near the required values. Each experiment was performed twice, and the results were compared to ensure reasonable

Table 1
Range of experimental conditions considered in the study

Factor	Levels	Details
Frequency range	—	8–1000 Hz
Vibration level	2	2.5 and 5.0 m/s^2 rms weighted
Handle size	3	30, 40, 50 mm diameter
Hand–arm posture	1	90° flexion elbow
Grip force (F_g)	3	10, 30 and 50 N
Push force (F_p)	3	25, 50 and 75 N

repeatability. Additional trials were performed when the deviation between the two initial trials was judged to be high. Table 1 summarizes the test matrix considered in this study.

The absorbed power in the hand–arm system was derived from the measured dynamic force and from the driving-point velocity of the handle. The amount of average power transferred to the hand–arm system can be computed from

$$\bar{P} = \frac{1}{T}\int_0^T F(t)v(t)\,\mathrm{d}t, \tag{1}$$

where $\bar{P}$ is the average absorbed power, $F(t)$ and $v(t)$ are the dynamic force and velocity, respectively, measured at the driving point, and T is the time period considered. In the frequency domain, the amount of absorbed power can be derived from the cross-spectrum of the measured force and velocity. The real part of the cross-spectrum is directly related to the power absorption of the hand and arm, while the imaginary component relates to the stored energy [2]. The absorbed power is thus computed from the frequency spectrum of

$$P_{\mathrm{abs}}(\omega) = \mathrm{Re}[G_{Fv}(\mathrm{j}\omega)], \tag{2}$$

where G_{Fv} is the cross-spectrum of the measured force and velocity, ω is the angular frequency, "Re" refers to real part and $\mathrm{j} = \sqrt{-1}$. A subtraction of the residual absorbed power due to the handle inertial force was also performed, although its magnitude was negligible [2,10]. The measured data were analyzed to express the magnitudes of absorbed power corresponding to center frequency of each of the one-third octave bands in the 8–1000 Hz frequency range. The total absorbed power was then computed through summation of power values within each one-third octave band.

3. Results and discussions

The power absorbed into the hand–arm system was measured for all seven subjects while exposed to two different levels of broadband random vibration along the z_h-axis, three handle sizes and nine grip/push force combinations. The results are analyzed to identify important trends in view of the various factors considered, namely, the handle size, vibration intensity, hand grip and push forces.

Fig. 3 illustrates the spectra of absorbed power for all three handles and all seven participants subject to 2.5 m/s^2 vibration excitation, 30 N grip force and 50 N push force. The results,

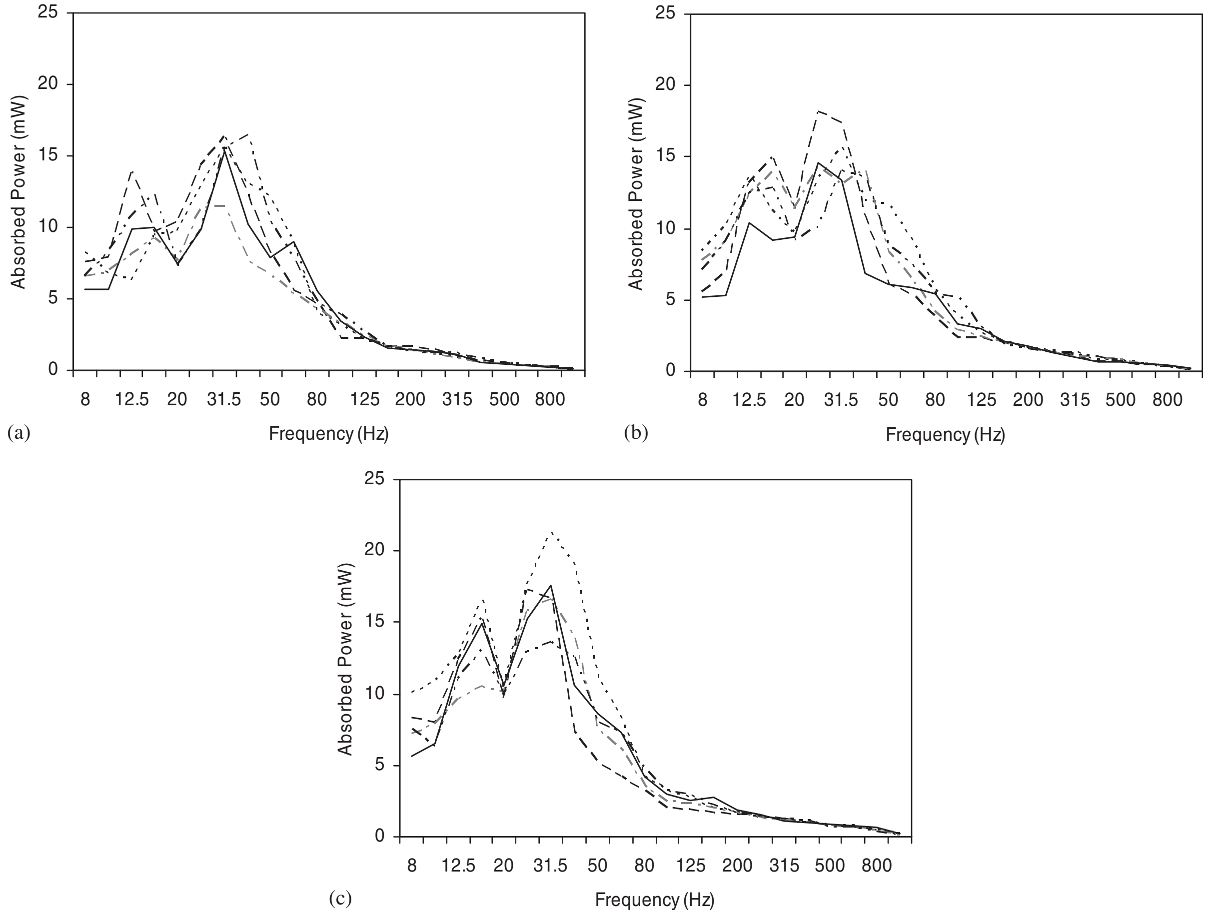

Fig. 3. Comparison of individual absorbed power measured for all three handles and for all seven subjects under 30 N grip and 50 N push forces ($a_{h,w} = 2.5\,\mathrm{m/s^2}$); (a) 30 mm handle, (b) 40 mm handle, (c) 50 mm handle.

corresponding to the center frequencies of the one-third octave bands in the 8–1000 Hz frequency range, show considerable dispersion among the data acquired for different subjects, although some definite trends are clearly evident. The results clearly show strong dependence of the absorbed power on the frequency of vibration. Beyond 50 Hz, the absorbed power tends to decline rapidly as the frequency increases, irrespective of the handle size. In addition, the data show the existence of two peaks occurring in the 10–16 and 31.5–50 Hz frequency bands for all three handles. These frequency bands of maximum absorbed power are comparable to those reported in a recent study by Bylun and Burström [20]. Furthermore, the frequency range of the second peak (31.5–50 Hz) corresponds very well with that of the peak DPMI magnitude response of the human hand–arm system exposed to z_h-axis vibration [29,30,34,35]. While the results have been presented for the 30 N grip and 50 N push force combination only, similar trends were observed for the other force combinations. The measured data further show that the majority of the absorbed power occurs at frequencies below 200 Hz.

Table 2
Statistical significance analysis corresponding to selected one-third octave bands and two levels of excitation

Factor(s)	Center Frequency (Hz)													
$a_{h,w} = 2.5$ m/s^2	**8**	**10**	**12.5**	**16**	**20**	**25**	**31.5**	**40**	**50**	**63**	**100**	**315**	**500**	**1000**
F_g	0.07	0.01	0.04	0.11	0.06	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F_p	0.02	0.24	0.10	0.09	0.04	0.03	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.45
D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.72	0.18	0.00	0.00	0.00	0.00
$F_g *F_p$	0.85	0.55	0.57	0.15	0.16	0.20	0.00	0.01	0.89	0.32	0.35	0.07	0.53	0.18
$F_g *D$	0.64	0.70	0.19	0.58	0.30	0.52	0.04	0.36	0.34	0.31	0.11	0.00	0.00	0.00
$F_p *D$	0.15	0.99	0.49	0.58	0.57	0.68	0.54	0.03	0.16	0.16	0.38	0.02	0.11	0.28
$a_{h,w} = 5.0$ m/s^2														
F_g	0.17	0.02	0.00	0.00	0.03	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F_p	0.04	0.83	0.00	0.01	0.10	0.05	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.85
D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00
$F_g* F_p$	0.08	0.44	0.08	0.02	0.66	0.03	0.01	0.03	0.23	0.02	0.02	0.91	0.89	0.89
F_g*D	0.58	0.59	0.15	0.01	0.08	0.48	0.31	0.04	0.07	0.11	0.07	0.05	0.00	0.04
F_p*D	0.30	0.34	0.03	0.10	0.07	0.66	0.27	0.01	0.01	0.00	0.02	0.01	0.27	0.28

Multifactor ANOVA was performed using the SPSS software to verify the statistical significance of the main factors upon the total absorbed power, such as handle size, push and grip forces, and excitation level. The results revealed high statistical significance of all main factors, i.e. handle size, excitation level, and grip and push forces. No interactions were detected between the grip force and the handle diameter, neither between the push force and the handle diameter. Strong interactions were observed between the excitation level and all the other main factors, as well as between the grip and push forces.

The statistical significance of three different parameters on the mean absorbed power responses corresponding to different one-third octave frequency bands was further evaluated through three-way ANOVA, main factors and two-way interactions. The analyses involve the handle diameter (D), as well as the grip (F_g) and push (F_p) forces. The analyses for the two levels of excitation were carried out independently. Table 2 summarizes the results of the statistical analysis on the mean absorbed power for the different factors in the selected one-third octave bands, where a factor associated with a p value of less than 0.05 is considered to be statistically significant. The table further summarizes the significance analysis of the interactions between the selected factors.

3.1. Inter-subject variability

Despite the consistent trends observed between all subjects, the results show considerable inter-subject variability on the absorbed power in the one-third octave bands. The results reported on the power absorbed in the human hand and arm also show significant variations partly attributed to individual anthropomorphic characteristics [10,14], however the inter-subject variability of the measured data was not reported in those studies. Fig. 4 illustrates the coefficients of variation (COV) of the mean measured absorbed power in one-third octave bands for different

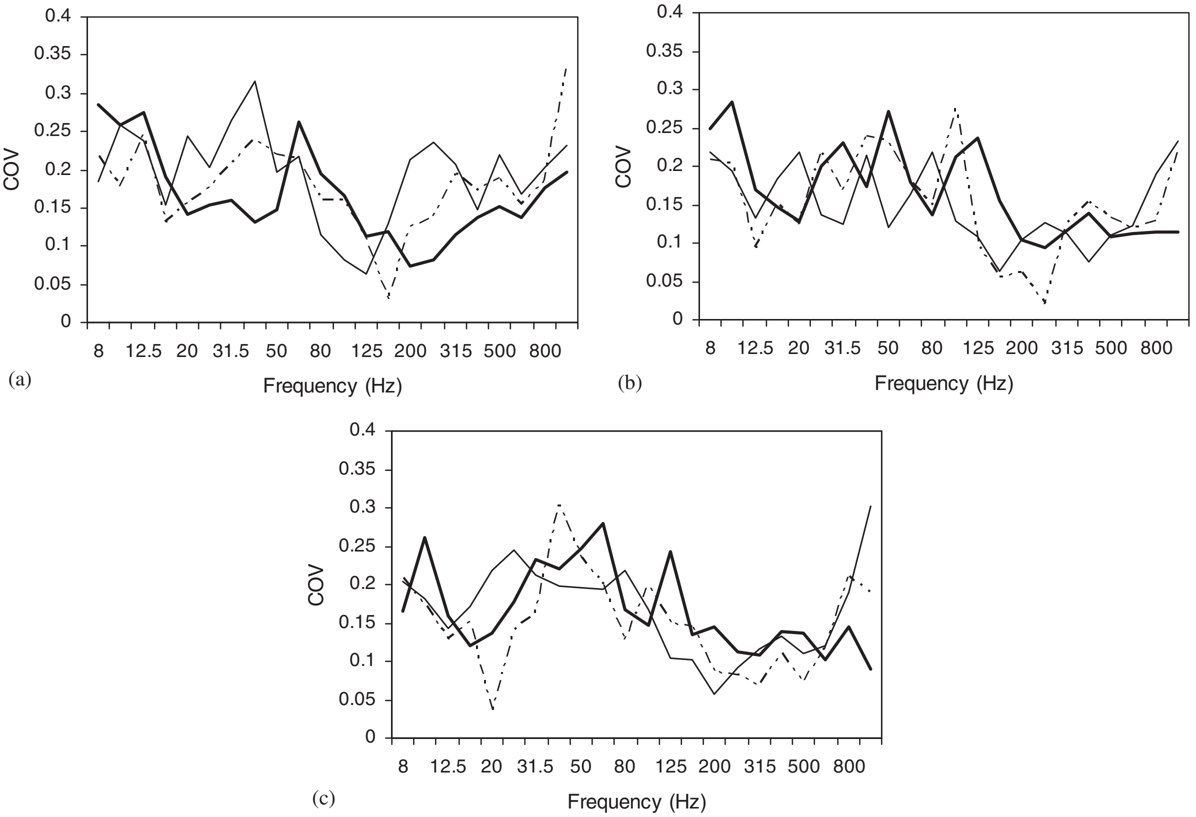

Fig. 4. Coefficients of variation (COV), for all three handles, of the mean absorbed power of all seven subjects under three different force combinations ($a_{h,w} = 2.5\,\mathrm{m/s^2}$); (a) 30 mm handle, (b) 40 mm handle, (c) 50 mm handle (——, 10 g–25 p; - · · - ·, 30 g–50 p; ——, 50 g–75 p).

combinations of grip and push forces, and all three handles. The grip and push force combinations are represented by “*mm*g-*nn*p”, where “*mm*” and “*nn*” represent the grip and push forces in N, respectively. The results obtained for the lower excitation magnitude ($a_{h,w} = 2.5\,\mathrm{m/s^2}$) reveal maximum values of COV in the order of 30%, occurring mostly at frequencies below 200 Hz. Such variations may be attributed to individual differences of the hand–arm structure and to some variations in the posture maintained by the subjects. Similar trends were also observed from the data acquired under different grip/push force combinations. While the reported studies on absorbed power did not specify the magnitudes of inter-subject variabilities, comparable variations have been reported for whole body vibration absorbed power [37]. The COV values, however, tend to be lower when the total hand–arm system absorbed power is considered. Fig. 5 illustrates the COV of the mean absorbed power for all three handles and all combinations of hand forces under the excitation level of $a_{h,w} = 2.5\,\mathrm{m/s^2}$. The COV of the mean total absorbed power are observed to be within 9% for the 40 mm handle, and within 14% for the 30 and 50 mm handles.

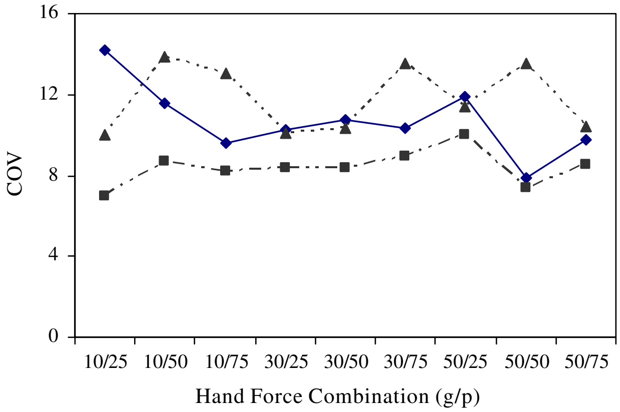

Fig. 5. Coefficients of variation (COV), for all three handles, of the mean absorbed power of all seven subjects for different force combinations ($a_{h,w} = 2.5\,\mathrm{m/s^2}$) (—◆—, 30 mm handle; - -■- -, 40 mm handle; ···▲···, 50 mm handle).

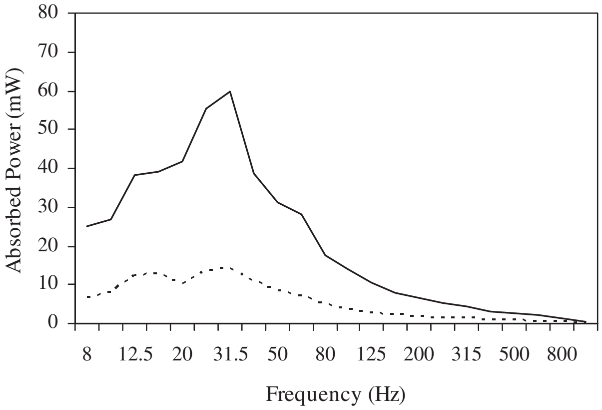

Fig. 6. Mean absorbed power for the two vibration levels (seven subjects, 40 mm handle, 30 N grip and 50 N push forces) (· · · · · · · , $a_{h,w} = 2.5\,\mathrm{m/s^2}$; ——, $a_{h,w} = 5\,\mathrm{m/s^2}$).

3.2. Influence of vibration magnitude on absorbed power

The power absorbed into the human hand and arm is strongly dependent upon the magnitude of vibration. The data obtained for the seven subjects are analyzed to derive the mean values of absorbed power corresponding to different handles, hand forces and excitation magnitudes. Fig. 6 shows the effect of vibration magnitude on the mean absorbed power within different one-third octave bands for the 40 mm handle, and the "30g50p" hand force combination. An increase in vibration magnitude from 2.5 to $5.0\,\mathrm{m/s^2}$ results in significant increase in the absorbed power, specifically at frequencies below 200 Hz.

The influence of vibration magnitude is further evaluated in terms of mean total absorbed power for all three handles and is presented in Fig. 7. The results presented for the "30g50p" force combination show that the total absorbed power under the higher excitation level ($a_{h,w} = 5.0\,\mathrm{m/s^2}$)

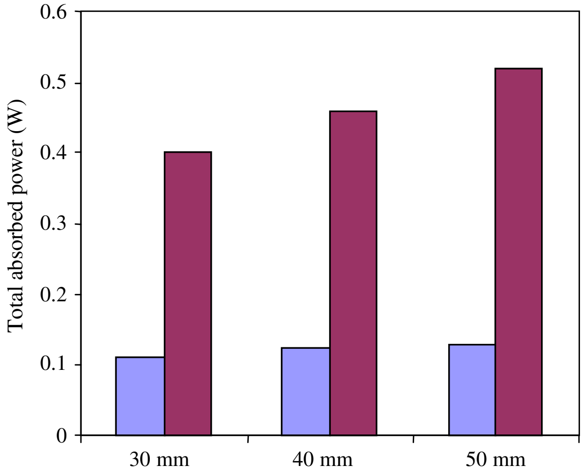

Fig. 7. Total mean absorbed power of all seven subjects for all three handles, under 30 N grip and 50 N push, exposed to two levels of vibration (🟦, $a_{h,w} = 2.5\ \mathrm{m/s^2}$; 🟥, $a_{h,w} = 5\ \mathrm{m/s^2}$).

Table 3
Mean and standard deviation of the ratio of the total absorbed power under high spectra ($5.0\,\mathrm{m/s^2}$) to that under the lower spectra ($2.5\,\mathrm{m/s^2}$)

Handle diameter (mm)	Ratio	
	Mean	Standard deviation
30	3.60	0.10
40	3.80	0.08
50	4.01	0.11

is approximately four times higher than that obtained under the lower excitation level ($a_{h,w} = 2.5\,\mathrm{m/s^2}$).

3.3. *Influence of handle size on absorbed power*

The handle size also affects the magnitude of total power absorbed into the hand and arm as it is obvious from the mean total power presented in Fig. 7. The significance of the handle size is also evident from Table 2, where $p < 0.05$ for all frequency bands and for both vibration magnitudes, except for the 40, 50 and 63 Hz bands for the low excitation magnitude.

The influence of handle size on the total mean absorbed power is further investigated by computing the ratio of the total absorbed power under high excitation level ($5.0\,\mathrm{m/s^2}$) to that attained under the lower excitation ($2.5\,\mathrm{m/s^2}$) for each handle. The ratios are averaged over all hand force combinations, and the mean and standard deviation of these ratios are presented in Table 3, for each handle size. Depending on the handle size, the ratios vary from 3.6 to 4.0. Smaller handles tend to diminish the effect of increased vibration magnitude over the absorbed power. The results suggest that a two-fold increase in the weighted magnitude of the excitation would yield nearly four-fold increase in the total absorbed power. This can also be deduced from the absorbed power estimated from the DPMI response and handle velocity $v(\mathrm{j}\omega)$, such that

$$P_{\mathrm{abs}}(\omega) = \mathrm{Re}[\mathrm{DPMI}(\mathrm{j}\omega)]\left|v(\mathrm{j}\omega)\right|^2. \tag{3}$$

It has been widely reported that the variations in excitation magnitude yield relatively small variations in the DPMI response of the human hand–arm system exposed to hand-transmitted vibration [30,35]. The above equation would thus justify the general observation made on the influence of excitation magnitude, while the variations with the handle size are most likely attributed to the dependence of the DPMI response on the handle size [30].

The ratio of the total power obtained under $5.0\,\mathrm{m/s^2}$ excitation to that corresponding to $2.5\,\mathrm{m/s^2}$ excitation (a measure of the amplification of absorbed power under higher vibration excitation) is not considerably influenced by the grip/push force combination for a given handle, as evident from the low standard deviation of the amplification factors presented in Table 3. The mean values, however, show strong effect of the handle diameter. A larger handle would cause a higher amplification of the total absorbed power, when compared to that of a smaller handle subject to an identical increase in the vibration magnitude.

The influence of handle size on the mean absorbed power in the different one-third octave bands is shown in Fig. 8 for the two excitation magnitudes, and 30 N grip and 50 N push force combination. The results clearly show that the magnitude of power absorbed into the hand–arm system increases with increase in the handle diameter. The increase is more obvious in the low-frequency range (below 50 Hz). Similar trends were also observed from the data acquired under different grip/push force combinations. Owing to the relatively modest effect of the hand–force combination observed from Table 3, the normalized values were averaged over the nine different combinations of grip and push forces, for each handle size and excitation level. Table 4 summarizes the results of the normalized total power attained for the 40 and 50 mm handles, with respect to the mean total power of the 30 mm handle, corresponding to each excitation spectra. High-excitation magnitude yields relatively higher increase in the normalized absorbed power

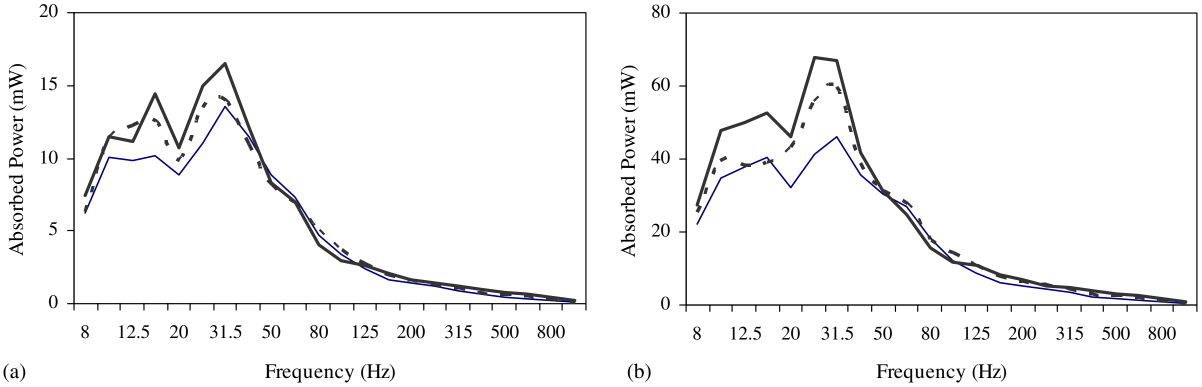

Fig. 8. Influence of handle size on the mean absorbed power of all seven subjects measured under 30 N grip and 50 N push force; (a) $a_{h,w} = 2.5\,\mathrm{m/s^2}$, (b) $a_{h,w} = 5.0\,\mathrm{m/s^2}$ (——, 30 mm handle; - - - - , 40 mm handle; ——, 50 mm handle).

Table 4
Mean and standard deviation of the total absorbed power measured with 40 and 50 mm handles normalized to that measured with the 30 mm handle

Handle diameter (mm)	Normalized total power (Mean; standard deviation)	
	$a_{h,w} = 5.0\,\mathrm{m/s^2}$	$a_{h,w} = 2.5\,\mathrm{m/s^2}$
40	1.146; 0.023	1.083; 0.024
50	1.297; 0.036	1.161; 0.037

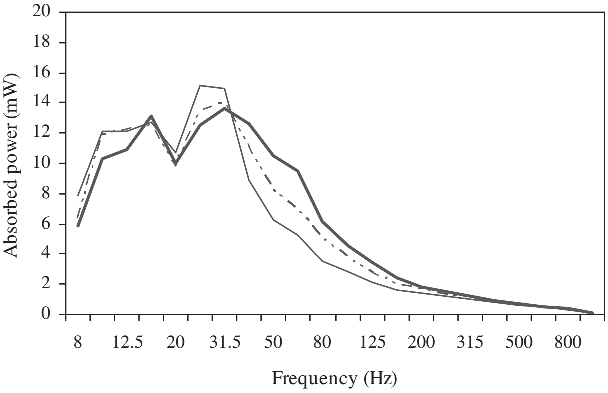

Fig. 9. Influence of push force on absorbed power under 30 N grip force for 40 mm handle ($a_{h,w} = 2.5\,\mathrm{m/s^2}$) (——, 25 N push; - · · - · ·, 50 N push; ——, 75 N push).

with increasing handle size. The results also show significantly lower standard deviation values, suggesting low variability of the normalized power with variations in the hand forces.

3.4. Influence of grip and push forces on the absorbed power

The statistical analysis results clearly show that the effects of grip and push force on the absorbed power are statistically significant in the majority of the frequency bands, except for some low-frequency bands, as evident in Table 2. The push force and its interactions with the other main factors appear to be insignificant in the 1000 Hz band, irrespective of the excitation level. In addition, the grip force appears to be insignificant in the 8, 16, 20 and 25 Hz bands, while the push force is insignificant in the 10, 12.5, 16, 20, 25 and 31.5 Hz bands, as well as for the 1000 Hz band for both vibration magnitudes.

Fig. 9 illustrates the variations in the mean absorbed power of the human hand and arm exposed to $2.5\,\mathrm{m/s^2}$ excitation with variations in the push force, for the 40 mm handle, while the grip force is held constant at 30 N. The results do not show a definite trend with regard to the influence of push force on the mean absorbed power at frequencies below 40 Hz. The effect of push force, however, is evident in the higher-frequency bands; an increase in the push force causes higher absorbed power in the 40–200 Hz frequency band. The effect at frequencies above 200 Hz appears to be only minor, although the magnitude of absorbed power in this frequency range is very small. Similar trends were also observed under other grip levels, i.e. 10 and 50 N, under the higher level of excitation (5.0 $\mathrm{m/s^2}$) and also with the 30 and 50 mm handles. The observed trends tend to contradict some of the reported findings. Burström and Lundström [38] reported that the energy absorption increases, in general, with increasing push force, while opposite trends were observed at frequencies below 16 Hz. The results obtained for the 40 mm handle show some agreement with the reported results for frequencies below 16 Hz. Another study by Burström [39] has reported that higher push forces result in higher power absorption at frequencies below 100 Hz. The lack of a definite trend in the dependence of low-frequency absorbed power on the push force (Fig. 9) together with the contradictory findings of the reported study may suggest relatively small influence of the push force, well within the range of inter-subject variability.

In a similar manner, Fig. 10 illustrates the influence of grip force on the mean absorbed power measured under an excitation level $a_{h,w} = 2.5\,\mathrm{m/s^2}$, for the 40 mm handle, while the push force is held constant at 50 N. The results show trends that are similar to those observed with variations in the push force (Fig. 9), i.e. no clear influence at frequencies below 40 Hz, increase in absorbed power in the 40–200 Hz range with increasing grip force, and negligible effect of the grip force at frequencies above 200 Hz. An increase in the grip force, in general, causes a shift of the second absorbed power peak (around 31.5 Hz) slightly to the right in the frequency domain. This is in agreement with results from Jandák [40], which showed that an increase in the grip force does not yield higher-energy dissipation but rather causes a shift in the frequency of the peak-absorbed energy. Burström and Lundström [10], on the other hand, concluded that a higher grip force causes higher amounts of dissipated energy over the entire frequency range, except at low frequencies where the effect is negligible. Similar effects of the grip force have also been observed on the driving-point mechanical impedance characteristics of the hand–arm system [30].

The influence of hand push and grip forces is further investigated by evaluating total absorbed power corresponding to different combinations of hand forces. Figs. 11 and 12 illustrate the influences of push and grip forces on the total mean absorbed power, for the three handles, and

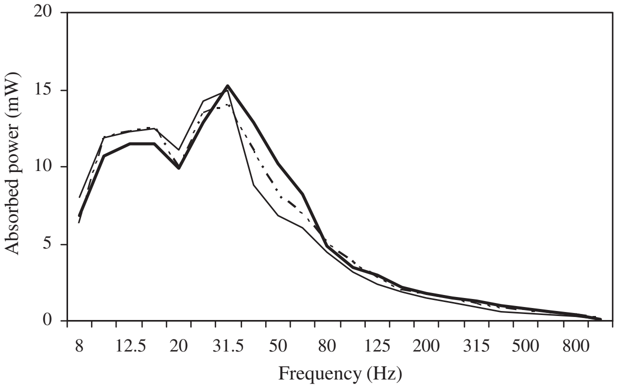

Fig. 10. Influence of grip force on absorbed power under 50 N push force for 40 mm handle ($a_{h,w} = 2.5\,\mathrm{m/s^2}$) (——, 10 N grip; - · · · -, 30 N grip; ——, 50 N grip).

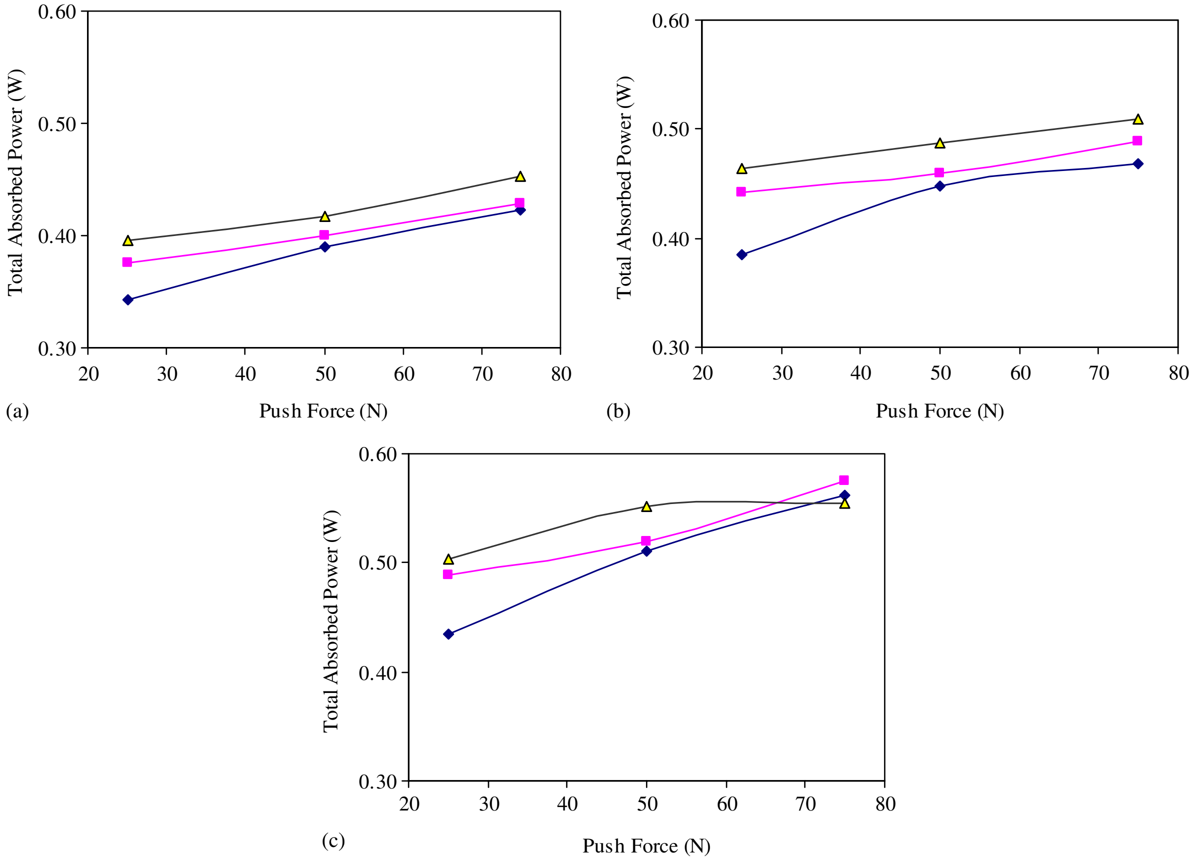

Fig. 11. The mean absorbed power, for all three handles and all three levels of grip force, as a function of push force ($a_{h,w} = 5.0\,\mathrm{m/s^2}$); (a) 30 mm handle, (b) 40 mm handle, (c) 50 mm handle (—◆—, 10 N grip; —■—, 30 N grip; —▲—, 50 N grip).

$a_{h,w} = 5.0\,\mathrm{m/s^2}$. The results, in general, show similar effects of grip and push forces on the total absorbed power, irrespective of the handle size. An increase in either force leads to an increase in the total absorbed power, with the exception of high grip and push forces imposed on the 50 mm diameter handle. In this case, an increase in the grip force above 30 N together with a push force in excess of 50 N yields a decrease of the total absorbed power. This may be attributed to saturation of the effective contact area under high magnitudes of grip and push forces applied on a large size handle, and/or difficulties encountered by some of the subjects in maintaining such high forces, such as 50 N grip and 75 N push forces. This is also evident from the high inter-subject variability under high magnitudes of hand forces, as shown in Fig. 5.

Assessing the effect of varying either the grip or push force on the total absorbed power is, however, difficult due to the lack of definite trends in the low-frequency range (Figs. 9 and 10). The effect of variations in these forces on the total absorbed power would thus rely on the relative contribution of the absorbed power in the low-frequency range. The measured data are thus further analyzed to derive the mean total power in two different frequency ranges: 8–31.5 and

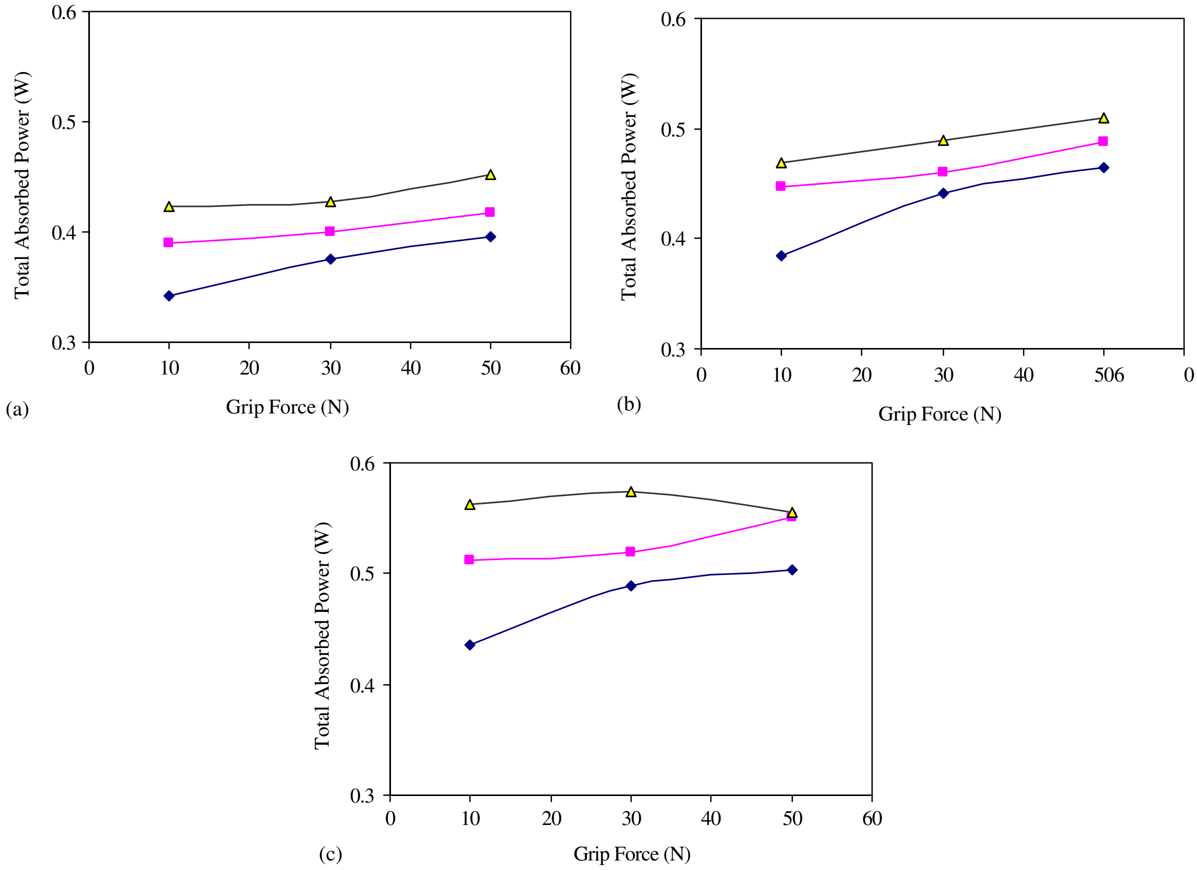

Fig. 12. The mean absorbed power, for all three handles and all three levels of push force, as a function of grip force ($a_{h,w} = 5.0\,\mathrm{m/s^2}$); (a) 30 mm handle, (b) 40 mm handle, (c) 50 mm handle (—◆—, 25 N push; —■—, 50 N push; —△—, 75 N push).

31.5–1000 Hz. Fig. 13 illustrates the total mean power measured in the two frequency ranges, as a function of the push and grip forces, for all three handles. The results clearly show an increase in the total absorbed power in the 31.5–1000 Hz range (lower curves) with an increase in either of the hand forces, irrespective of the handle size. Furthermore, in most cases, the increase in the absorbed power in this frequency range is nearly linear with the push force. No clear trends, however, could be observed on the effects of hand grip and push forces on the mean total absorbed power in the low-frequency range (8–31.5 Hz). The results, however, show that the total absorbed power in this low-frequency range is considerably larger than that in the high-frequency range, irrespective of the handle size. The results may suggest relatively small influence of the hand forces on the absorbed power in the low-frequency range, which is consistent with the observations made from the measured driving-point mechanical impedance data reported by Marcotte et al. [30]. This coupled with relatively higher inter-subject variability in the lower-frequency range (Fig. 4) could contribute to the contradictory conclusions reported in different studies concerning the role of hand forces on the absorbed power response of the human

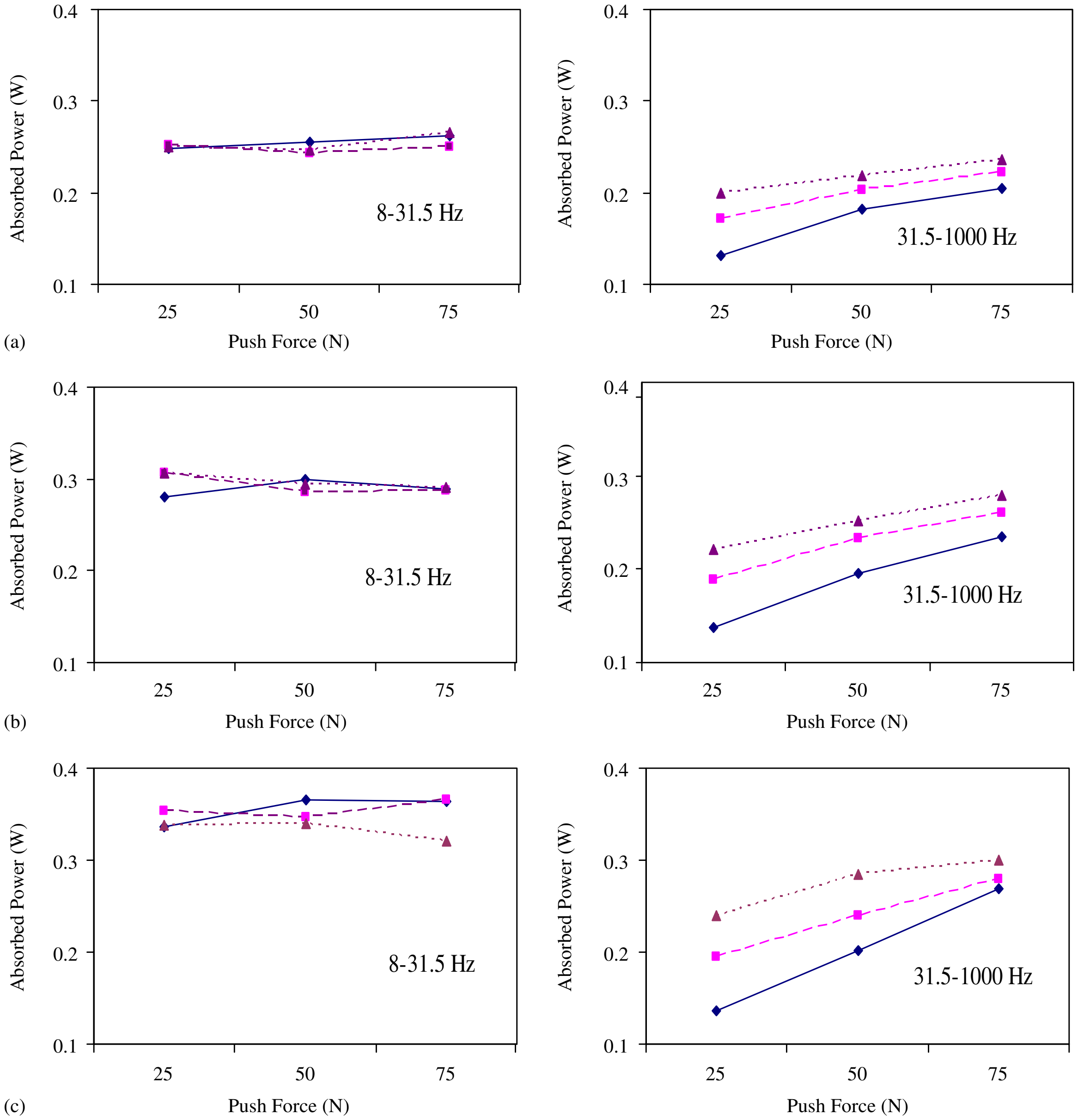

Fig. 13. Variation of total mean absorbed power, as a function of push force in the 8–31.5 Hz frequency range and in the 31.5–1000 Hz frequency range ($a_{h,w} = 5.0\,\mathrm{m/s^2}$); (a) 30 mm handle, (b) 40 mm handle, (c) 50 mm handle. (—◆—, 10 N grip; —■—, 30 N grip; —▲—, 50 N grip).

hand–arm system [2,10,16,18]. The results also show the effect of handle size on the total mean absorbed power; larger handles yield higher absorbed power in both the frequency ranges considered.

3.5. Relationship with coupling and contact forces

The ISO/WD 15230 working draft [41], defines the hand–handle interface force in terms of the coupling and contact forces. The coupling force is expressed as a direct summation of the push and grip force magnitudes exerted by the hand on the handle, while the contact force is evaluated upon summation of the distributed forces at the hand–handle interface. The hand–handle contact force was derived from the measured distributed pressure at the hand–handle interface for each of the nine grip and push force combinations. The contact force was derived upon integration of the measured pressure distribution over the contact area, such that

$$F_c = \sum_{i=1}^{n} p_i \Delta A, \tag{4}$$

where F_c is the hand–handle contact force, p_i is the pressure measured by sensor i in the sensing grid, ΔA is the constant sensor area and n is the total number of sensors used, which differs for different handle sizes. A linear multiple regression analysis revealed nearly linear dependence of the contact force on both the grip and push forces, such that [30]

$$F_c = \alpha + \beta F_g + \gamma F_p, \tag{5}$$

where F_g and F_p are the magnitudes of the static grip and push forces, respectively, and coefficients β and γ represent their relative contributions. The constant α represents the bias in the contact force, attributed to an offset in the sensing grid [30].

The mean and standard deviations of the grip and push force coefficients, derived for all subjects and different handle sizes, are shown in Table 5. For each subject, the linear regressions lead to correlation coefficients (r^2 values) in excess of 0.99, for all three handle sizes. These results show that the mean push force coefficient is close to unity for all handles, while the mean grip force coefficient varies from 2.69 to 3.40, decreasing with increase in the handle diameter. The grip force thus appears to contribute, on average, nearly three times as much as the push force to the total contact force, its contribution reducing as the handle diameter increases [30].

A few studies have concluded that the hand–handle coupling and contact forces strongly affect the biodynamic response, the severity of exposure to the hand-transmitted vibration and hand–wrist cumulative trauma disorders [24–26,28,30]. The measured data are thus analyzed to study the effects of both the coupling and the contact forces on the absorbed power. Fig. 14 shows the variation in the total mean absorbed power with the hand–handle coupling and contact forces. The results suggest nearly linear variations in the total mean absorbed power with the coupling force for all three handles, with correlation factors varying from 0.78 to 0.94 under high magnitude spectra ($a_{h,w} = 5.0\,\mathrm{m/s^2}$). While similar trends are also evident with variations in the

Table 5
Mean and standard deviations of the grip and push force coefficients

Handle diameter (mm)	Grip coefficient, β	Push coefficient, γ
30	3.40; 0.26	0.97; 0.12
40	2.82; 0.27	1.00; 0.13
50	2.69; 0.14	1.03; 0.10

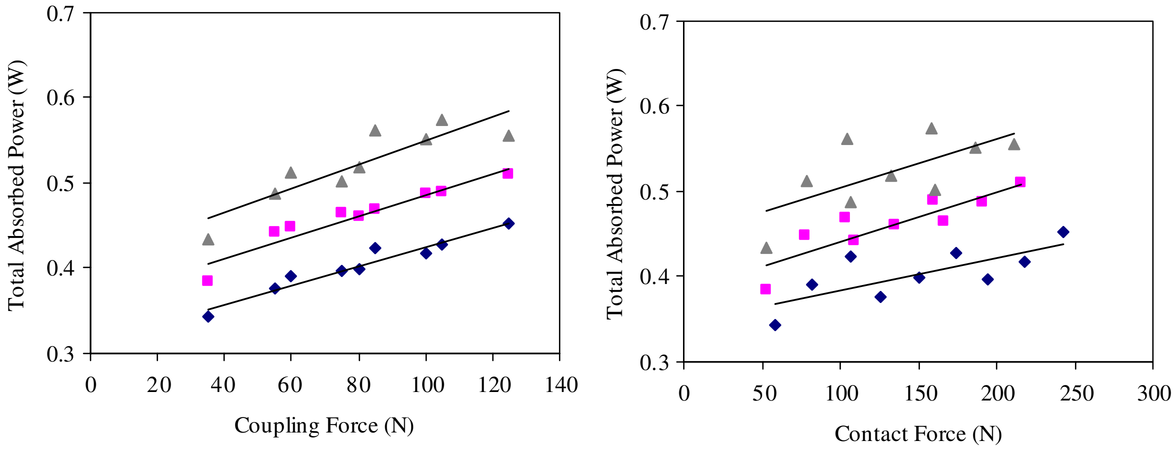

Fig. 14. Variation of mean total absorbed power in the 8–1000 frequency range, as a function of coupling and contact forces ($a_{h,w} = 5.0\,\mathrm{m/s^2}$) (◆, 30 mm handle; ■, 40 mm handle; ▲; 50 mm handle).

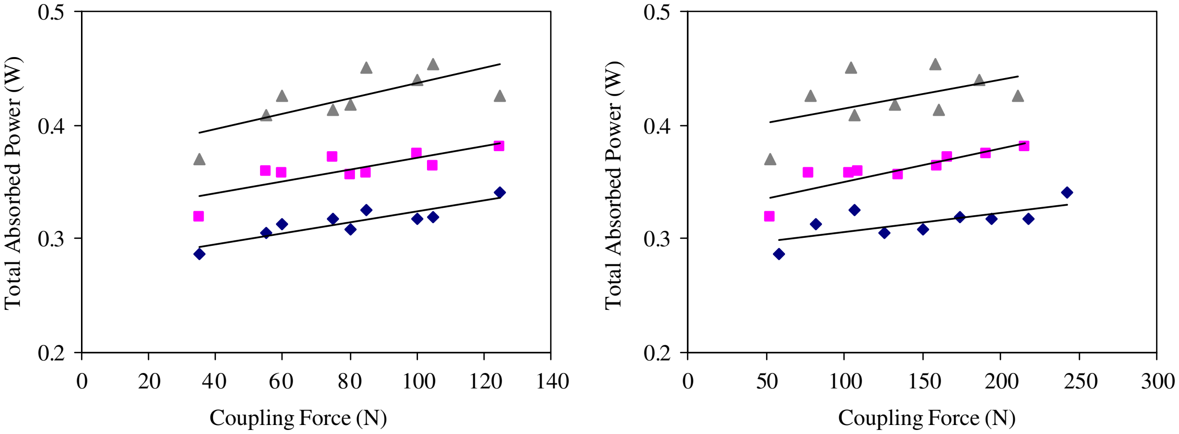

Fig. 15. Variation in mean total absorbed power in the 8–50 frequency range, as a function of coupling and contact forces ($a_{h,w} = 5.0\,\mathrm{m/s^2}$) (◆, 30 mm handle; ■, 40 mm handle; ▲; 50 mm handle).

contact force, relatively poor correlations are obtained, with correlation factors varying from 0.45 to 0.77 for the high excitation spectra. The results further show that the larger handle leads to more power absorption, while it develops less contact force. Similar trends were also observed for the low excitation spectra ($a_{h,w} = 2.5\,\mathrm{m/s^2}$).

Further analysis of the measured data in various frequency bands yields somewhat different relationships between the total mean absorbed power, and the coupling and contact forces. The mean absorbed power, in general, shows weak correlation with the coupling force in the 8–50 Hz frequency range, as seen in Fig. 15, for the high excitation spectra (r^2 values ranging 0.55 to 0.80 for the different handles) and even weaker correlation with the contact force (r^2 values ranging from 0.26 to 0.74). On the other hand, high correlation factors are observed with the coupling

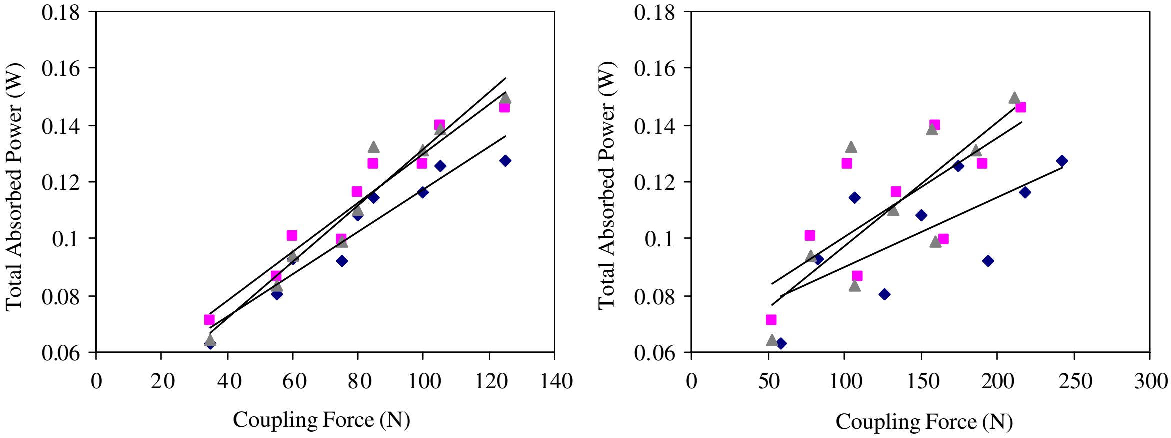

Fig. 16. Variation in total mean absorbed power in the 50–200 frequency range, as a function of coupling and contact forces ($a_{h,w}$ = 5.0 m/s^2) (◆, 30 mm handle; ■, 40 mm handle; ▲; 50 mm handle).

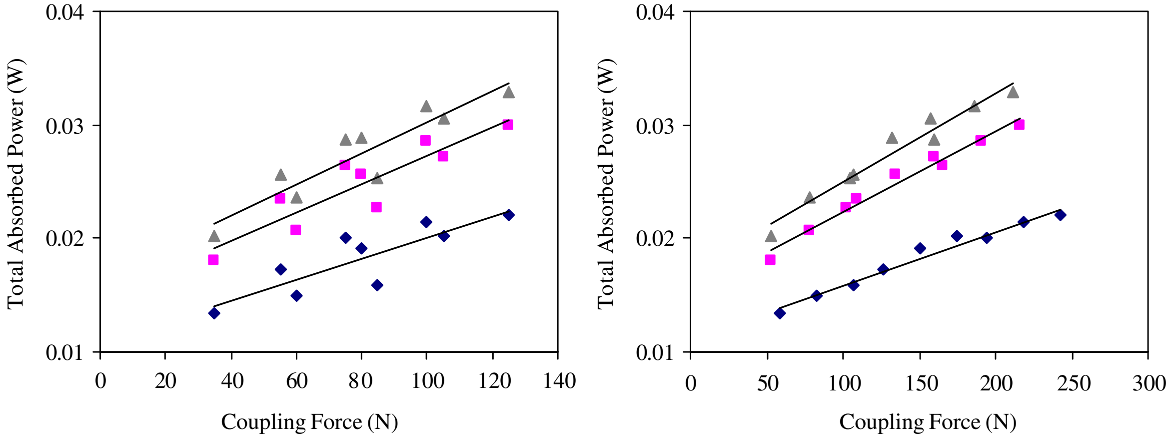

Fig. 17. Variation in total mean absorbed power in the 200–1000 frequency range, as a function of coupling and contact forces ($a_{h,w}$ = 5.0 m/s^2) (◆, 30 mm handle; ■, 40 mm handle; ▲; 50 mm handle).

force in the 50–200 Hz frequency range (r^2 = 0.92–0.94) while poor correlation between the mean absorbed power and the contact force (r^2 = 0.49–0.62) at the same frequency range is obvious as illustrated in Fig. 16. On the contrary, the absorbed power shows excellent correlation ($r^2 \geqslant 0.96$) with the contact force in the 200–1000 Hz frequency range, irrespective of the handle size, and lower correlation factors with coupling force (0.73–0.84) for different handles, as seen in Fig. 17. Similar correlations between the driving-point mechanical impedance and the hand–handle coupling and contact forces have also been reported in a recent study [30]. Considering that the majority of the power absorption by the hand–arm system occurs in the frequency range up to 200 Hz, the absorbed power is, in general, expected to be more related to the hand–handle coupling force than to the contact force.

3.6. Influence of excitation frequency

The role of vibration frequency is investigated by analyzing the proportion of power absorbed within a frequency band to the total absorbed power. For this purpose, the measured data are analyzed to derive the mean values of total absorbed power for each handle and hand force combination under both excitation levels. Considering that the total absorbed power in the frequency range above 200 Hz represents only 5% or less of the total absorbed power, the analyses are limited to frequencies up to 200 Hz. The total absorbed power is thus computed within three frequency bands (8–50, 8–100 and 8–200 Hz) and normalized with respect to the total absorbed power over the entire frequency range for each handle size, excitation spectrum and hand–force combination, in order to study the relative proportions of absorbed power in these low-frequency bands. The mean values of the proportions of the absorbed power within the selected frequency bands together with the standard deviations are summarized in Table 6, as a function of the hand force combination, for both magnitude spectra and all three handle sizes. The proportion of the total absorbed power in the selected frequency bands does not vary considerably with either the handle diameter or the vibration magnitude, as evident from the relatively low standard deviation values. The proportions, however, show significant variations with the grip and push force combinations, while no clear trend can be observed. Table 6 shows that 75% to 84% of the total power is dissipated in the 8–50 Hz frequency range, irrespective of the excitation magnitude, handle size and hand forces. This would represent the most significant frequency range in view of the injury potential, since a large number of hand power tools transmit predominant vibration in this frequency range [42]. The proportions of the absorbed power increase only slightly with increase in the frequency range. It is evident that the proportion of the absorbed power in the 8–100 and 8–200 Hz frequency ranges vary from 91–93% and 96–97%, respectively. For the 8–200 Hz range, the ratio of absorbed power to the total absorbed power is around 96% for all force combinations, suggesting insignificant effect of hand–handle applied forces.

The results attained on power absorbed into the hand–arm system somewhat agree with the frequency-weighting defined in the ISO-5349-1 [1], which yields zero attenuation at frequencies below and up to 16 Hz and thus emphasizes high importance of hand-transmitted vibration at low frequencies. The weighting function, however, tends to suppress the effect of transmitted vibration

Table 6
Mean and standard deviation of the proportion of absorbed power in three frequency ranges, as a function of the hand–force combination

Frequency range		Hand grip/push forces								
		10/25	10/50	10/75	30/25	30/50	30/75	50/25	50/50	50/75
8–50 Hz	Mean	0.84	0.81	0.78	0.82	0.79	0.76	0.80	0.77	0.75
	SD	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.01
8–100 Hz	Mean	0.93	0.92	0.92	0.92	0.91	0.91	0.91	0.91	0.90
	SD	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
8–200 Hz	Mean	0.97	0.97	0.97	0.96	0.96	0.96	0.96	0.96	0.96
	SD	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

at frequencies above 16 Hz, as its magnitude is reduced by 6 dB/octave. The results obtained from the present study suggest that the importance of low-frequency vibrations should be extended up to 50 Hz, where the majority of absorbed power occurs, and where a large number of hand power tools transmit predominant vibration.

A study on the transmission of vibration through the human hand–arm system has shown that the lower-frequency vibration (<50 Hz) is transmitted with little attenuation along the hand and forearm [3]. The study also reported gradual attenuation of transmitted vibration at frequencies above 50 Hz, and negligible transmission at frequencies above 200 Hz. The handle vibration above 150–200 Hz becomes localized within the hand, leading to majority of the energy dissipation in the tissues of the hand and the fingers [3].

4. Conclusion

The influences of vibration magnitude, handle size, grip and push forces on the mechanical power absorbed into the hand–arm system exposed to z_h-axis vibration in the 8–1000 Hz frequency range, have been investigated on a population of seven healthy male subjects using three different instrumented handles of 30, 40 and 50 mm diameter. The absorbed power was found to vary in a nearly quadratic manner with respect to the vibration magnitudes considered in the study, while 96% of the absorbed power occurred within the 8–200 Hz frequency range. The handle diameter was found to have an obvious effect on the absorbed power; the amount of power absorbed into the hand increased with the handle diameter. The absorbed power at frequencies above 40 Hz generally increased with increase in the grip and push forces, while the increase was observed to be nonlinear. The influence of hand forces on the absorbed power at frequencies below 40 Hz, however, was found to be unclear. Owing to relatively small variations in the absorbed power due to variations in the hand forces and high inter-subject variability in the low-frequency range, the effect of hand forces was judged to be minimal in this frequency range. The results obtained from ANOVA also confirmed this finding.

The total absorbed power was found to be more correlated with the coupling force rather than with the contact force. This result is consistent with other observations, i.e. namely a larger handle leads to lower contact force and higher absorbed energy, when compared to that of the smaller handles. Considering that the coupling force represents equal contribution of the grip and push forces, and that the contact force emphasizes a considerable larger weighting on the grip force, the results suggest that the total amount of absorbed power of the hand–arm system would likely be most dependent on the push force. This could mean that the majority of the absorbed power enters the hand–arm system at the upper lateral side of the palm, which mostly contributes to the realization of the push force. The power absorbed in the frequency range above 200 Hz showed strong correlation with the contact force, which is consistent with the finding of another study based on the driving-point mechanical impedance of the hand–arm system.

The results suggest that 75–84% of the total power is dissipated in the 8–50 Hz frequency range, irrespective of the excitation magnitude, handle size and hand forces. Considering that a large number of percussion and rotary hand power tools transmit predominant vibration at frequencies below 50 Hz, relatively high injury risk may be associated with exposure to hand-transmitted vibration in this frequency range. Although the frequency-weighting defined in the current standard (ISO 5349-1) emphasizes the importance of transmitted vibration up to 16 Hz, it suppresses the vibration at frequencies above 16 Hz at a rate of dB/decade. The results obtained in this study suggest that the weighting function may provide an underestimate of the injury potential. The cut-off frequency of the recommended weighting function in the order of 50 Hz may better represent the power dissipation properties of the human hand and arm exposed to hand-transmitted vibration.

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