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Effect of handle size and hand–handle contact force on the biodynamic response of the hand–arm system under z_h-axis vibration

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Abstract

The influences of the handle size and of the hand forces exerted on a vibrating tool handle on the driving-point mechanical impedance (DPMI) response of the human hand–arm system have been investigated through laboratory measurements performed on seven adult male subjects. Measurements were performed with three instrumented cylindrical handles with different diameters (30, 40 and 50 mm) exposed to two different levels of broadband random vibration (2.5 and 5.0 m/s^2) along the z_h axis, while the variations in the hand forces were realized through nine different combinations of grip (10, 30 and 50 N) and push (25, 50 and 75 N) forces. The static hand–handle contact forces were also evaluated for each combination of grip and push forces, and each handle size through measurements of pressure distribution at the hand–handle interface. The results have shown that the average contact force is a linear combination of the push and grip forces, while the contribution due to grip force is considerably larger than the push force and dependent upon the handle size. The hand–handle coupling force, as defined in ISO/WD-15230, was further evaluated by summing the grip and push forces, which is independent of the handle size. The results have shown that the DPMI magnitude tends to increase with an increase in both the grip and push forces at frequencies above 25 Hz, while the increase in DPMI magnitude was better correlated with the coupling force below 200 Hz. A better correlation with the contact force, however, was attained at frequencies above 200 Hz, suggesting a stronger dependence on the grip force at higher frequencies. The DPMI magnitude response

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was also found to be influenced by the handle diameter. Increasing the handle size yielded higher peak DPMI magnitude response, specifically under medium to high hand–handle coupling forces (30 N grip and 50 N push; 50 N grip and 75 N push).

1. Introduction

The operators of hand-held power tools, commonly used in several industries, are exposed to comprehensive levels of hand–arm vibration (HAV) at the tool–hand interface. Continual use of vibrating tools has been associated with vascular, sensorineural and musculoskeletal disorders of the hand–arm system, collectively known as hand–arm vibration syndrome (HAVS). The risk of developing HAVS has been reported to depend on the magnitude of vibration transmitted to the tool handle, on the mechanical coupling between the hand and the handle, on the duration of vibration exposure and on the user sensitivity to hand–arm vibrations [1–3]. The biodynamic response of the human hand–arm system to hand transmitted vibration forms an essential basis to effectively evaluate vibration exposures, vibration response of the coupled hand–tool system and to investigate the potential injury mechanisms. The driving-point mechanical impedance (DPMI) at the hand–tool handle interface has been widely used to characterize the biodynamic response of the hand–arm system exposed to tool handle vibration [4–6]. Even though the DPMI does not directly relate to tissue loading and dynamics of the musculoskeletal structure of the hand–arm system, the DPMI modulus and phase fully describe the overall mass–spring–damper-like behavior of the hand–arm system. The DPMI can thus be effectively applied to estimate the amount of mechanical energy dissipated by the hand–arm structure under a specified hand tool vibration spectrum.

Despite the fact that the DPMI response of the hand–arm system has been measured in many studies under carefully controlled test conditions, considerable differences are known to exist among the data reported by different investigators. Although the dependence of the impedance response on various intrinsic and extrinsic variables, including the frequency and the direction of vibration, the grip and push forces, the vibration amplitude and individual characteristics has been widely acknowledged in the reported studies, only limited efforts have been made to systematically quantify the influences of many of these factors. On the basis of a synthesis of the widely varying reported data sets, the International Standard ISO 10068:1998 [7] defines the ranges of free driving-point mechanical impedance of the human hand–arm system under vibration in the 20–500 Hz along the three translational axes of the basicentric coordinate system, namely x_h, y_h and z_h. While the differences between the lower and upper bounds of the standardized modulus and phase responses are quite large, the data are reported to be applicable under specific experimental conditions (grip forces in the 25–50 N range, push force not greater than 50 N, and elbow angle close to 90°), except for the handle diameter which varies widely in the 19–45 mm range. The standard, however, does not address the role of various contributing factors, such as grip and push forces and the handle size.

A few studies have suggested a strong influence of grip force on the DMPI magnitude [5,6,8], while its quantitative effect has not yet been clearly established. An increase in the hand grip force yields higher impedance magnitude at frequencies above 50 Hz [7]. The effect of push force on the DPMI has been studied only in a few studies with somewhat contradictory findings. Bernard [9] showed that push force has little effect on the DPMI magnitude at frequencies above 100 Hz and less than 10% variation in the 20–70 Hz frequency range, while Jandák [10] found the effect as being negligible for push forces up to 100 N. In contrast, Burström [6] concluded that an increase in push force leads to higher DPMI magnitude at higher frequencies. A study conducted by Riedel [3] concluded to 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 of these forces on the DPMI. Hartung et al. [2] showed that the DPMI magnitude increases with increasing hand–handle coupling intensity. The use of a weighting factor to account for the coupling force in the exposure assessment of hand–arm vibrations has thus been suggested. A few other studies have also concluded that the contact force between the hand and a tool handle affects the severity of exposure to hand-transmitted vibrations and hand–wrist cumulative trauma disorders [1,11,12]. Unlike the coupling force, the contact force is defined as the sum of the normal components (perpendicular to the vibrating surface) of the distributed static forces acting between the hand and the vibrating surface [13,15].

Considering that the hand–handle contact force depends upon the effective contact area of the hand–handle interface, which further depends on the handle size, the biodynamic response of the hand–arm system would be expected to be influenced by the handle dimensions and geometry. Only a few studies, however, have considered the effect of the handle size on the DPMI [14]. This paper attempts to establish the dependence of the hand–arm DPMI response on the handle size, on the hand forces (grip and push) exerted on the handle, and on the coupling and contact forces developed at the hand–handle interface.

2. Methods

Three instrumented cylindrical handles with different diameters (30, 40 and 50 mm) were designed and instrumented to provide measurement of the static and dynamic hand–handle forces and of the hand–arm DPMI response. The handles were designed such that their respective first resonant frequencies were above 2 kHz. Each handle consisted of two aluminum semi-circular sections, which were joined together through two Kistler 9212 force sensors for measuring the grip force. A PCB SEN026 tri-axial accelerometer was also mounted within one of the semi-circular section of the handle to measure the handle acceleration. The handle was mounted on an Unholtz-Dickie electrodynamic shaker system with 890 N force capacity through a support fixture and two Bruël & Kjær 8200 force transducers to measure the static and dynamic push forces, as illustrated in Figs. 1 and 2. The handle and the support structure were oriented along the z_h-axis to study the biodynamic response of the human hand–arm exposed to vibration along this axis.

The total contact force between the hand and the handle was first evaluated for seven healthy adult male subjects using the Novel PLIANCE system, which consists of a flexible pressure sensing mat with a 16×11 matrix of capacitive pressure sensors. The sensing mat was wrapped around each handle and the contact force was evaluated through integration of the measured pressure distribution over the contact area, while the subjects gripped the handle under specified grip and push forces. The experiments were performed under three different magnitudes of grip

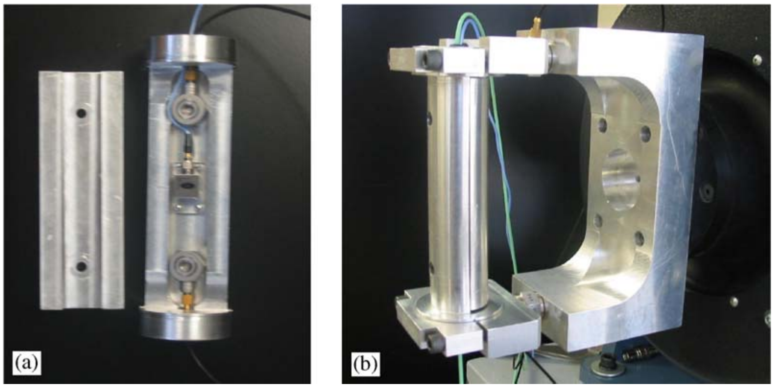

Fig. 1. Pictorial views of: (a) the instrumented handle and (b) the support.

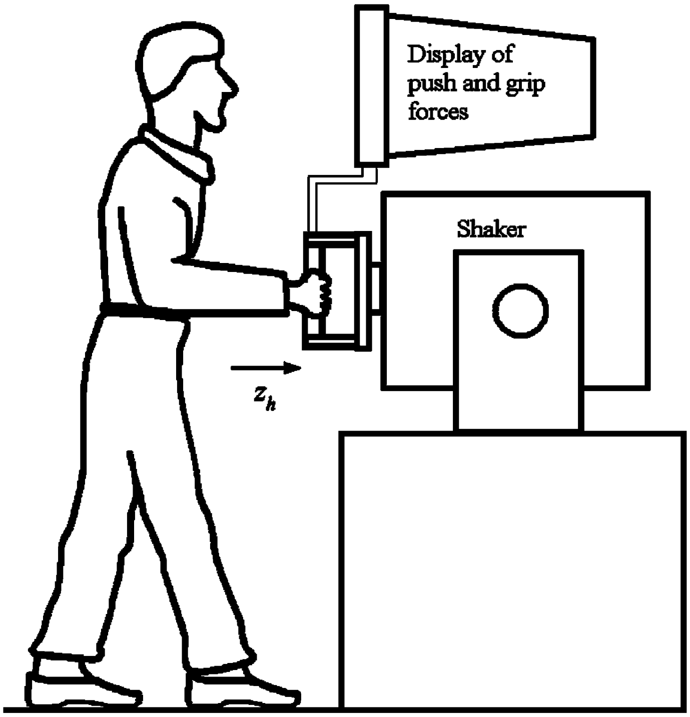

Fig. 2. Schematic of the experimental setup.

forces (10, 30 and 50 N) and three push forces (25, 50 and 75 N), resulting in nine different grip and push force combinations. For each measurement, the subject was given sufficient time to adjust the grip and push forces to the specified values. The measured grip and push forces, contact force and the interface pressure distribution were averaged over a 10-s period, while the subjects maintained constant the specified forces, using displays of the grip and push forces. For all subjects, the measurements were performed on the right hand, while maintaining the fore-arm horizontally aligned with the handle, elbow bent at an angle of 90° and the wrist in a neutral position, corresponding to the posture defined in ISO 10819 [16]. In order to avoid drift problems associated with capacitive force sensors, the sensors were zeroed between successive measurements. Each measurement was repeated until two similar patterns could be obtained to ensure data reproducibility.

Following the measurement of the static contact force, the driving-point mechanical impedance of the human hand–arm system exposed to vibration along the z_h direction was measured for all seven subjects, using the three handles and the same nine combinations of push and grip forces. The DPMI was measured under two levels of broadband random excitations in the 8–1000 Hz frequency range with frequency-weighted rms acceleration values of 2.5 and 5.0 m/s^2. The frequency weighting defined in ISO 5349-1 [17] was applied to compute the frequency weighted rms accelerations. Data corresponding to each measurement were acquired for a period of 7 s (25 averages with an overlap of 75%), while the subjects were asked to maintain the mean push and grip forces near the required values using the visual feedback from the force displays. The data acquisition and analysis were performed using a multichannel signal analyzer (Bruël & Kjær Pulse system). Again, each measurement was repeated until two similar measures could be obtained to ensure data reproducibility.

3. Experimental results

3.1. Static contact force measurements

The static contact force developed within the hand–handle interface under different combinations of handle sizes, and of grip and push forces was initially evaluated by integrating the measured pressure distribution over the total contact area of the hand with the sensing mat. While all 16 rows of the sensor mat were used for the 50 mm handle, two and five rows of the mat were masked for the 40 and 30 mm handles, respectively, to eliminate overlapping of the sensors. Fig. 3 illustrates the variations in mean values of contact force acquired for seven subjects for each handle as a function of the grip force (constant push force of 50 N), and as a function of push force (constant grip force of 50 N). The figure also shows the coupling force, defined as the sum of grip and push forces [3,13]. The results suggest that the hand–handle contact force varies with variations in the handle size and, grip and push forces, while the variations in coupling force are independent of the handle size. Furthermore, the contact force is observed to vary with grip and push forces in a linear fashion, irrespective of the handle size. This trend has also been reported in a recent study by Welcome et al. [15]. A multiple linear regression analysis was thus performed to account for contributions of grip and push forces to the contact force developed within the hand–handle interface.

Assuming a linear relationship with respect to the grip F_g and push F_p forces, the contact force F_c can be expressed as

$$F_c = \alpha + \beta F_g + \gamma F_p, \tag{1}$$

where F_g and F_p are the constant grip and push forces, respectively. The coefficient α is used to take into account the contact force offset caused by the presence of the sensing mat around the

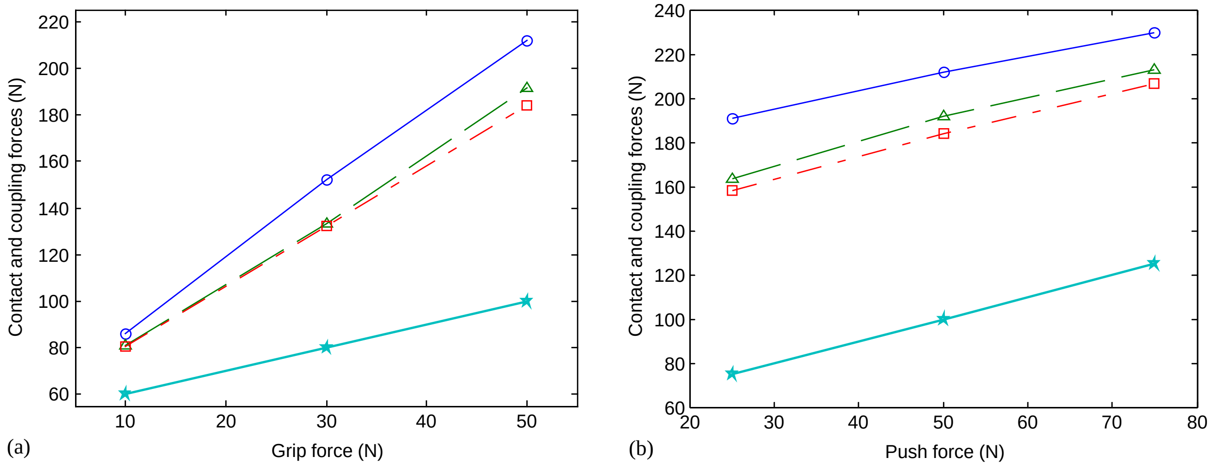

Fig. 3. Variations in hand–handle coupling and contact forces with push and grip forces: (a) variation of the grip force (push force = 50 N); (b) variation of the push force (grip force = 50 N) (—○—, contact force: 30 mm handle;—△—, contact force: 40 mm handle;—□—, contact force: 50 mm handle;—★—, coupling force: all handle).

Table 1
Coefficients representing contribution of the grip and push forces to the total contact force

Subject	Handle diameter					
	30 mm		40 mm		50 mm	
	β	γ	β	γ	β	γ
A	3.47	0.88	2.71	1.08	2.62	1.05
B	3.88	1.20	2.98	0.90	2.80	0.96
C	3.54	1.03	3.13	1.17	2.85	1.16
D	3.10	0.95	2.35	1.10	2.59	1.12
E	3.38	0.92	2.74	1.02	2.55	1.05
F	3.24	0.87	3.09	0.88	2.84	0.90
G	3.17	0.92	2.76	0.83	2.55	0.94
Mean; std. dev.	3.40, 0.26	0.97, 0.12	2.82, 0.27	1.00, 0.13	2.69, 0.14	1.03, 0.10

handle, while β and γ are the constant coefficients representing the contributions due to grip and push forces, respectively, which depend upon the handle diameter. Following the linear regression analysis, the contact force offset is removed by setting $\alpha = 0$. The grip and push force coefficients, derived for each subject, together with their mean values and standard deviations are summarized in Table 1 for the different handle sizes. For each subject and handle combination, the linear regressions lead to correlation coefficients (R^2 values) of over 0.99.

These results show that, despite some variations between individuals, 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 handle diameter. The grip force thus contributes on the average three times as much as the push force to the total contact force, while its contribution decreases as the handle diameter increases. The push force can be considered to contribute almost directly to the contact force, since it is applied over a small portion of the hand surface area (upper lateral side of the palm) normal to the applied push force axis. The grip force, on the other hand, causes application of pressure over a larger surface of the handle and thus yields considerably larger contribution to the total contact force, which is derived from the summation of grip pressure-induced force components acting normally to the entire contact area. The grip force, as defined in ISO/WD 15230 [13], involves measurement of the axial component alone acting along the z_h-axis, while neglecting the non-axial components acting on the handle surface. The consideration of these non-axial components yields considerably larger values of the grip force coefficients. Moreover, as the handle diameter increases, the subjects' hands apply grip pressure over partial handle surface as limited by the hand size, which results in relatively smaller contribution of the grip component to the contact force. In contrast, the subjects' hands cover larger proportion of the handle surface while gripping a smaller diameter handle, leading to a larger grip force coefficient. The results presented in Fig. 3 further show that the coupling force, as defined in Refs. [3,13], is significantly smaller than the contact force, as it involves only direct contribution of the grip force. The hand–handle contact force estimated from Eq. (1) correlated very well with the mean of the measured data attained for the seven subjects ($R^2 = 0.999$), for all three handles. Fig. 4 illustrates the results obtained for the 40 mm handle.

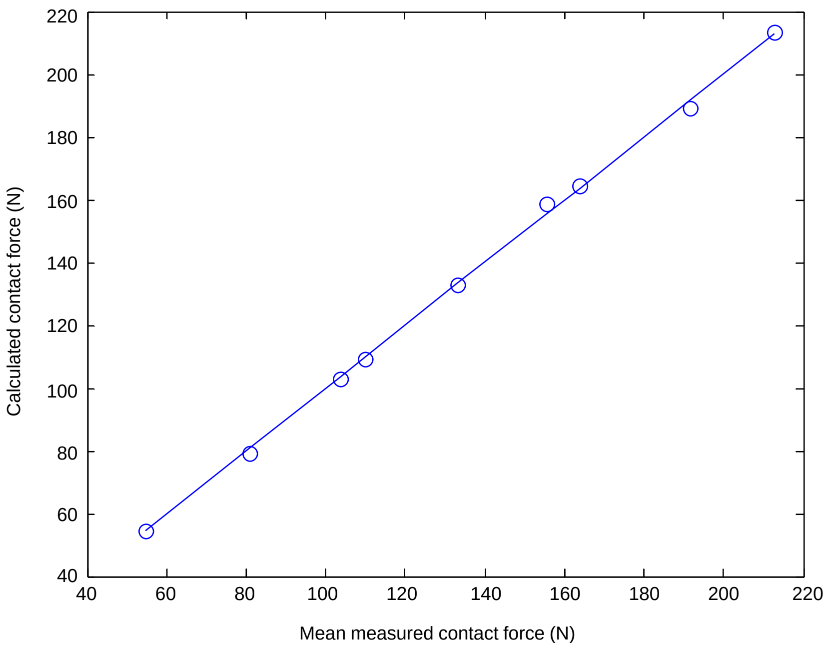

Fig. 4. Validation of the linear regression analysis on contact force for the 40 mm handle; $R^2 = 99.9\%$.

3.2. Hand–arm dynamic response measurements

The DPMI of the hand–arm system was measured using two levels of broadband random white noise excitation (8–1000 Hz, 2.5 and 5.0 m/s^2 frequency weighted) applied along the z_h axis of the basicentric coordinate system. The DPMI of the human hand arm is computed from

$$\mathrm{DPMI}(\mathrm{j}\omega) = \frac{G_{Fv}(\mathrm{j}\omega)}{G_{vv}(\mathrm{j}\omega)} - \mathrm{DPMI}_0(\mathrm{j}\omega), \tag{2}$$

where G_{Fv} is the cross-spectrum of the dynamic force and handle velocity, both measured at the driving-point, and G_{vv} is the auto-spectrum of the velocity measured at the handle. The term DPMI_0 represents the driving-point mechanical impedance of the handle and of the supporting structure alone, which is subtracted from the DPMI of the hand–handle system to account for the inertia effect of the handle and the supporting structure. The dynamic force is established by summing the signals from the two B&K 8200 force transducers, while the velocity is obtained by integrating the z_h component of the acceleration signal measured by the tri-axial accelerometer located inside the handle. The reported data on the DPMI of the human hand arm suggest that the apparent mass of the human hand reduces to a very small value at higher frequencies. The measurement of DPMI or apparent mass thus requires a highly sensitive and accurate measurement system. The system ability to measure small variations in the mass with high accuracy is thus investigated through measurement of the apparent mass of the 40 mm handle and that of the handle with a small mass of 42 g rigidly attached to it. The mass value obtained from the difference between the measured apparent masses of the handle with and without the added mass revealed a nearly constant mass and phase response close to zero, as shown in Fig. 5. These results suggest that the DPMI measurements are accurate in both magnitude and phase, noting that the mass magnitude has a variation of less than 8% over the entire frequency range, while the phase variation is close to zero. In contrast, the human hand–arm apparent mass magnitude is at least larger than 100 g in the frequency range of interest (8–1000 Hz).

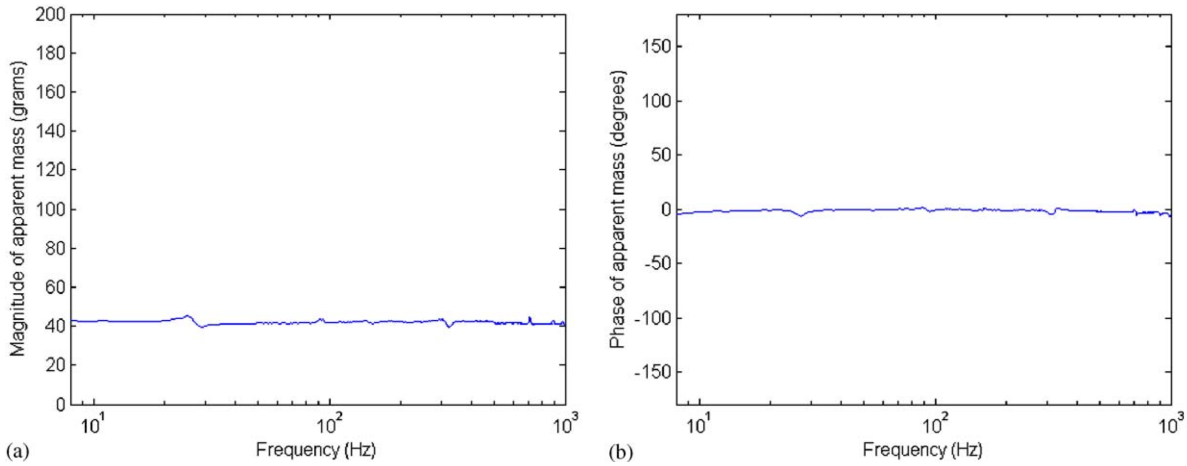

Fig. 5. Measured apparent mass magnitude and phase response of a 42 g mass on the 40 mm handle: (a) magnitude; (b) phase.

3.2.1. Influence of vibration magnitude on DPMI

The influence of vibration level on the DPMI response of the hand–arm system has been reported in a few studies, leading to somewhat contradictory conclusions. The measurements performed by Lundström et al. [18] showed that lower excitation amplitudes cause higher impedance magnitudes at low frequencies and lower impedance magnitudes at higher frequencies. Burström [6] found that the DPMI amplitude increases slightly with increase in the vibration level, and the increase is more pronounced in the frequency range above 200 Hz. In contrast, another study [5] found the influence of variations in vibration amplitude on the hand–arm DPMI as being insignificant. The data acquired in this study under two different magnitudes of vibration (frequency-weighted accelerations: 2.5 and 5.0 m/s^2) was analyzed to study the influence of excitation level on the DPMI. The mean DPMI magnitude and phase responses attained for seven subjects exposed to different levels of excitation and handle sizes are compared in Fig. 6, for constant levels of grip (30 N) and push (50 N) forces. The results generally show relatively small influence of the excitation amplitude on the DPMI magnitude and negligible effect on the phase response for all three handles. The effect on the magnitude response is negligible at frequencies above 100 Hz, specifically for the 40 and 50 mm handles, as shown in Fig. 6(a). The higher excitation amplitude yields a lower DPMI magnitude in the 30–100 Hz frequency range, and lower frequency corresponding to the peak magnitude response for all three handles, suggesting a softening effect of the hand and arm under higher excitation levels. The phase responses appear to be insensitive to excitation amplitude, irrespective of the handle size. The results also suggest nonlinear characteristics of the hand–arm system, specifically at lower frequencies, although the effect of excitation amplitude is relatively small.

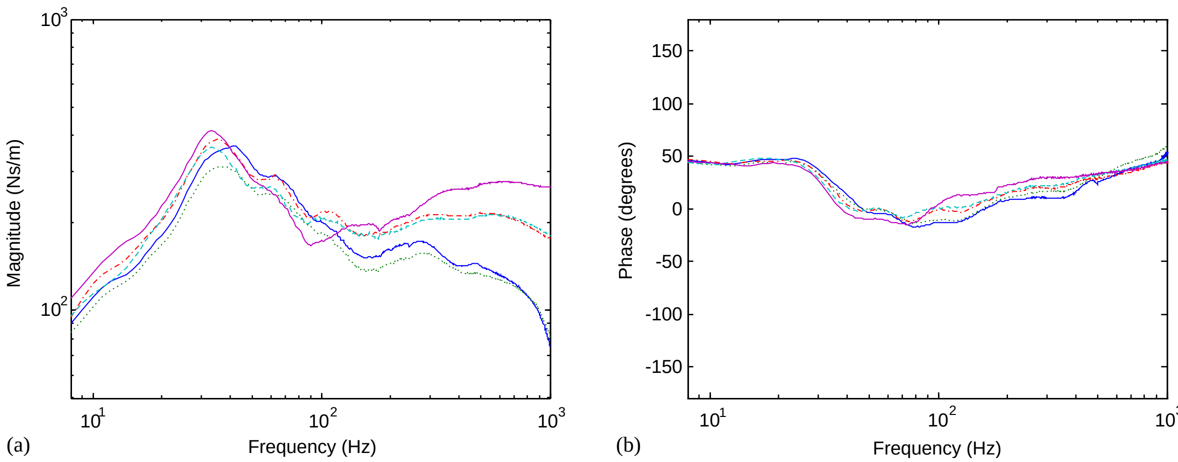

Fig. 6. Influence of excitation amplitude on the mean DPMI magnitude and phase responses measured under 30 N grip and 50 N push forces: (a) magnitude, (b) 40 phase (——, 30 mm handle, $a_{h,w} = 2.5\,m/s^2$;······, 30 mm handle, $a_{h,w} = 5.0\,m/s^2$;-·-·-·-·, 40 mm handle, $a_{h,w} = 2.5\,m/s^2$; – – –, 40 mm handle, $a_{h,w} = 5.0\,m/s^2$;——, 50 mm handle, $a_{h,w} = 2.5\,m/s^2$;- - - - -, 50 mm handle, $a_{h,w} = 5.0\,m/s^2$).

3.2.2. Inter-subject variability

Although the strong dependence of the biodynamic response of the human hand and arm on individual differences have been widely reported [6,19], the inter-subject variability of the data have been reported in only one study. On the basis of measurements performed on four male subjects, Gurram et al. [5] reported peak standard errors of 23% and 25%, respectively, in the DPMI magnitude and phase responses. Fig. 7 illustrates individual DPMI magnitude and phase responses of seven subjects corresponding to 30 N grip and 50 N push force, for all three handles. Despite considerable variations between individuals, both the magnitude and phase responses exhibit consistent trends. The DPMI magnitude responses of the hand–arm system consistently show the peak response occurring in the 30–40 Hz frequency range for all subjects and all three handles, which could likely be linked to the resonant frequency of the hand–arm system. Such a behavior has been noticed in several other studies [4–6,8,10,14], suggesting a resonance of the hand–arm system in the 30–50 Hz frequency range. The DPMI magnitude response tends to decrease, if not remain constant at higher excitation frequencies for all seven subjects. This trend is more pronounced for smaller handle sizes when compared to that for the larger handle. While such a trend has been reported in only a few studies [8,10], a number of reported studies have shown opposite trends with magnitude response, suggesting a rapid increase in magnitude with increasing frequency [5,6,18,20]. Although no definite explanation can be given to account for such a difference in trends at higher frequencies, it is suggested that differences in the handle design, measurement system and the dynamic characteristics of the experimental setup could lead to variations in response which would be more apparent in the higher frequency range.

Fig. 8 shows the coefficient of variation of the DPMI magnitude responses attained with all subjects corresponding to the center frequencies of the one-third octave bands for all three handles with 30 N grip and 50 N push force, and two different vibration excitation magnitudes. The coefficient of variation of impedance magnitude for the other force combinations showed similar trends. The peak variations in the magnitude response among subjects are observed in the 30–100 Hz frequency range for all three handles. The data obtained for the 30 mm handle also showed considerable variations in the magnitude response in the 300–400 Hz frequency range, irrespective of the excitation magnitude. The results show a peak standard error of approximately 28% under higher excitation level, which occurs in the vicinity of the hand–arm system resonance. Moreover, the data acquired with all three handles showed a similar order of magnitude for the peak standard error.

3.2.3. Influence of handle size on DPMI

Fig. 9 presents comparisons of the mean DPMI magnitude and phase responses attained with three different handles for different grip/push force combinations (10/25 N; 30/50 N; 50/75 N). The figures also show the mean, and lower and upper bounds of idealized values of DPMI magnitude and phase, as defined in ISO 10068:1998 [7]. The idealized values are considered applicable for handle diameters ranging from 19 to 45 mm, grip force from 25 to 50 N, and push forces lower or equal to 50 N. The results show that the DPMI response of the human hand and arm is strongly influenced by the handle diameter, while the effect depends upon the magnitudes of hand forces applied to the handle in a nonlinear manner. The peak DPMI magnitude tends to be higher for smaller diameter handle under lower hand forces, i.e. 10 N grip and 25 N push, when compared to those attained for larger handles. Higher levels of hand forces, however, yield an

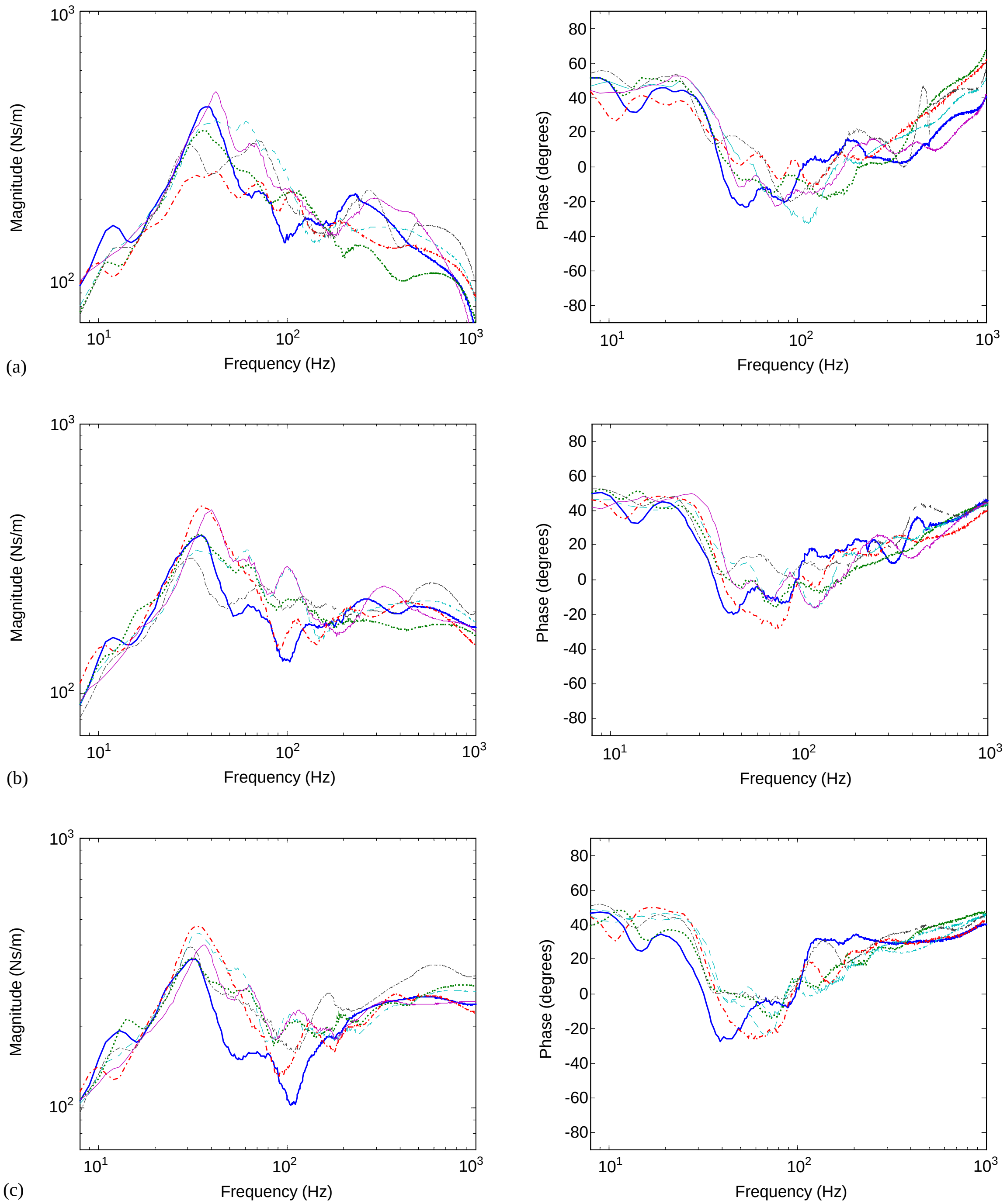

Fig. 7. Comparison of individual DPMI magnitude and phase responses measured for seven subjects under 30 N grip and 50 N push forces: (a) 30 mm handle, (b) 40 mm handle, (c) 50 mm handle ($a_{h,w} = 2.5\,m/s^2$).

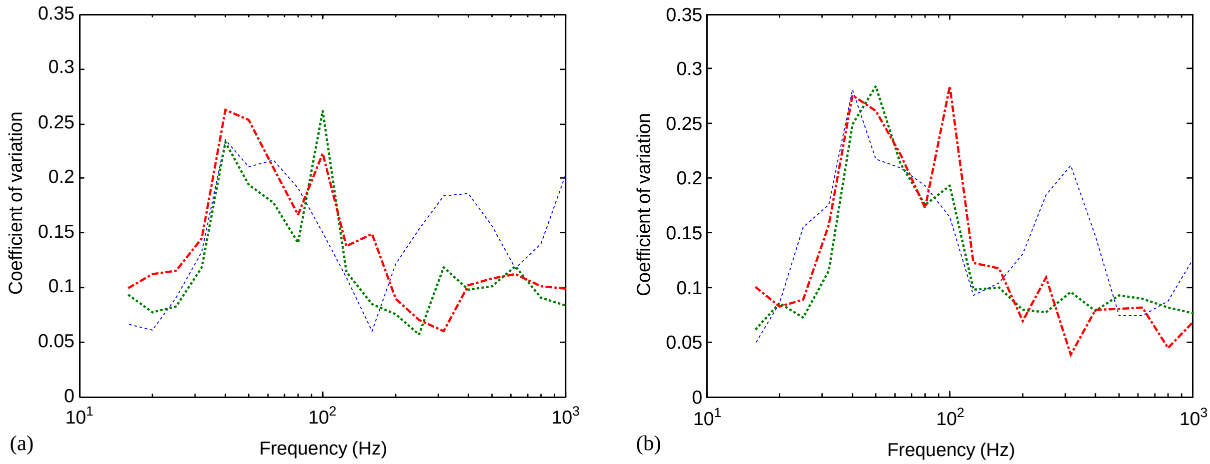

Fig. 8. Coefficients of variation of the mean DPMI magnitude of all seven subjects under two different levels of excitation for 30 N grip and 50 N push forces: (a) $a_{h,w} = 2.5\,m/s^2$; (b) $a_{h,w} = 5.0\,m/s^2$ (—, 30 mm handle; - - -, 40 mm handle; – -, 50 mm handle).

opposite trend, i.e. the peak DPMI magnitude increases as the handle diameter increases, as evident from Fig. 9(b) and (c). Moreover, the frequency corresponding to the peak magnitude decreases with increasing handle size. At low frequencies (below 25 Hz), the DPMI magnitude increases nearly linearly with frequency and tends to be higher for larger handles, irrespective of the hand force combination chosen in the study. The influence of handle size on the DPMI magnitude is most significant at frequencies above 125 Hz for all force combinations, which tends to be considerably higher with larger handle diameter. The handle diameter also has a significant influence on the DPMI phase, specifically in the 100–600 Hz frequency range, where the phase response is higher with increasing handle diameter. These results may be compared with those from one study which presented the measured dynamic compliance of the hand–arm system for two different handle diameters (19 and 38 mm) for a group of 75 foundry workers [14]. From the tabulated values of the compliance, it was shown that both the phase and magnitude varied upon the handle diameter, while no attempt was made to quantify the effect of the handle size.

Comparisons of the mean measured magnitude and phase responses with the idealized values suggest that the mean magnitude responses under low hand forces (10/25 N) lie within the lower and upper bounds defined in ISO 10068:1998 standard [7] only at frequencies below 200 Hz, while the mean phase responses are within the defined limits over the entire frequency range. Under this test condition, the mean magnitude response with the 30 mm handle is observed to be well below the lower bound of the standardized values at frequencies above 200 Hz. While the idealized values have been defined in the 10–500 Hz frequency range, they suggest that the DPMI magnitude increases with increasing frequency at frequencies above 100 Hz, similar to that of a mass. This trend is not evident from the mean responses obtained in this study, which generally shows decreasing magnitudes at higher frequencies. The mean responses attained under higher levels of hand forces show more important deviations from the bounds of the idealized values, as seen in Fig. 9(b and c). The most notable differences are observed in two frequency ranges: the

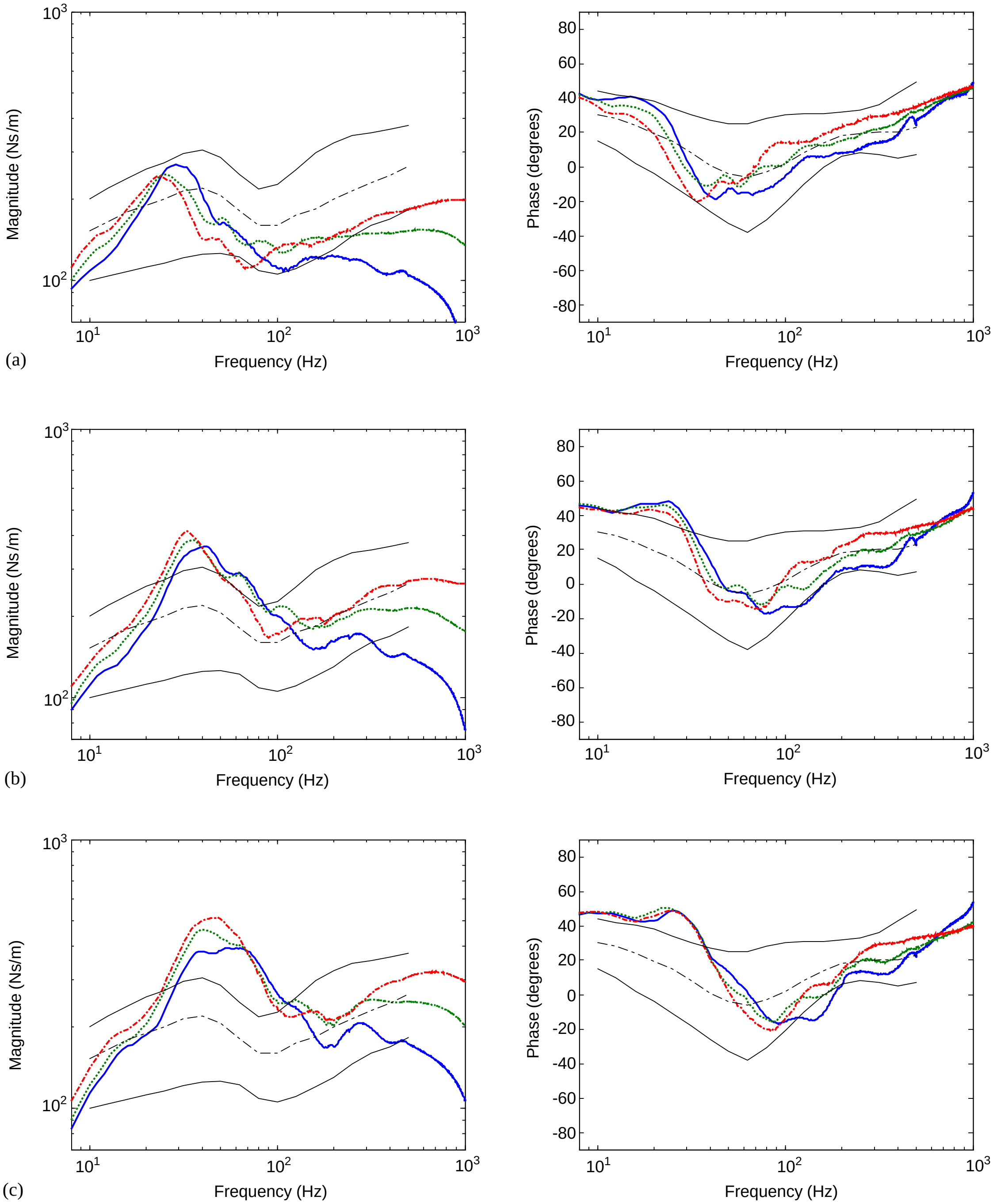

Fig. 9. Influence of handle size on the mean measured DPMI responses ($a_{h,w} = 2.5\,\text{m/s}^2$) and comparisons with mean and range of idealized values reported in ISO 10068:1998: (a) grip force = 10 N and push force = 25 N, (b) grip force = 30 N and push force = 50 N, (c) grip force = 50 N and push force = 75 N (—, 30 mm handle;- - -, 40 mm handle;– -, 50 mm handle; —, ISO 10068 limits;– -, ISO 10068 average).

first being located in the neighborhood of the fundamental frequency corresponding to peak magnitude, where both the magnitude and phase responses lie outside of the standardized bounds; the second being at frequencies above 200 Hz, where the magnitude responses tend to be below the lower bound, specifically for the 30 mm handle. The phase responses attained with all three handles, however, tend to lie close to the recommended limits in the second frequency range. The discrepancies between the measured and idealized DPMI responses could be attributed to many factors associated with the measurement systems and test conditions. The range of idealized values reported in ISO 10068 [7] have been attained from a synthesis of various data sets reported by different investigators using widely different test conditions and considerably different measurement systems. Furthermore, the synthesis involved many data sets that were acquired many years ago and most likely utilized less reliable systems for measurement of dynamic forces, specifically at higher frequencies where the apparent mass of the hand–arm system is known to be quite small.

3.2.4. Influence of grip and push forces on DPMI

The mean DPMI magnitude responses attained under vibration level $a_{h,w} = 2.5\,m/s^2$ and nine different combinations of grip (10, 30 and 50 N) and push (25, 50 and 75 N) forces are illustrated in Figs. 10(a–c), for handle sizes of 30, 40 and 50 mm, respectively. In general, these results suggest that at frequencies above 20 Hz, the DPMI magnitude tends to increase with increase in both the grip and push forces; the effect being more emphasized near the frequencies corresponding to peak responses. At frequencies below 20 Hz, the influence of grip and push forces appears to be negligible, where the DPMI magnitude increases nearly linearly with frequency. The peak magnitudes in general tend to be much higher under combinations of high grip and push forces. For the 40 and 50 mm handles, the peak DPMI magnitude corresponding to high grip/push forces (50/75 N, indicated as 50g75p) tends to be nearly twice that attained under low grip/push forces (10/25 N, indicated as 10g25p), as evident from Figs. 10(b) and (c). These results thus suggest that the combination of push and grip forces exerted by the hand has a considerable influence on the biodynamic response of the hand–arm system. This is in contradiction with the study of Bernard [9], which showed that the push force has little effect on the DPMI magnitude at frequencies above 100 Hz, and less than 10% variation in the 20–70 Hz frequency range. In addition, Jandák [10] found the effect to be negligible for push forces up to 100 N. However, many studies found that push and grip forces have considerable influence on the biodynamic response of the hand–arm system, which is in agreement with the results of the present study. For example, Riedel [3] found a strong effect of the coupling force on the biodynamic response of the hand–arm system, and Burström [6] concluded that an increase in push force leads to higher DPMI magnitude.

The influence of grip force on the mean DPMI response under a constant value of push force on the DPMI magnitude and phase responses attained with the 40 mm handle is shown in Fig. 11. While the results suggest only a minimal effect of variations in the grip force on the DPMI phase response, the important increase in the magnitude with increase in the grip force at frequencies between 25 and 80 Hz and above 200 Hz is clearly evident. Such a trend was also observed with the 30 and 50 mm handles considered in the study. The results further show that the fundamental frequency corresponding to the peak DPMI magnitude decreases with decreasing grip force, suggesting a softening effect of the hand–arm system. Increasing the push force yields

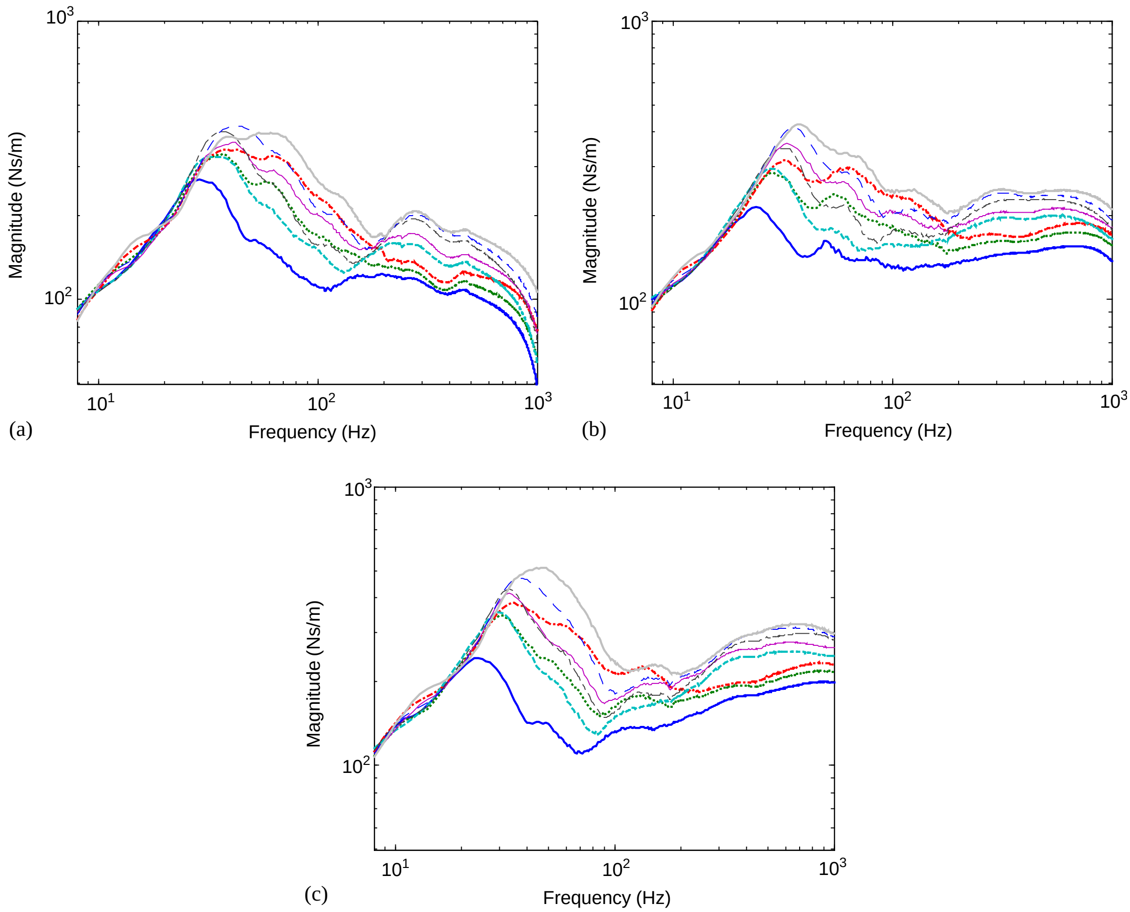

Fig. 10. Influence of grip and push force combinations on the DPMI magnitude ($a_{h,w} = 2.5\,\mathrm{m/s^2}$): (a) 30 mm handle, (b) 40 mm handle, (c) 50 mm handle (———, 10g 25p; ⋯⋯, 10g 50p; - · - · - ·, 10g 75p;- - -, 30g 25p; ———, 30g 50p; - - - - -, 30g 75p;– – –, 50g 25p;– -, 50g 50p; ———, 50g 75p).

considerably higher DPMI magnitude response in the 30–200 Hz frequency range, as shown in Fig. 12, for a constant level of grip force. The increase in the DPMI magnitude with increasing push force is much lower at frequencies above 200 Hz. A comparison of the results shown in Figs. 11 and 12 suggests that both the grip and push forces, when taken individually, have similar influence on the DPMI magnitude response at frequencies near and above resonance, i.e. 20–100 Hz, while the influence appears to be more important under variations in grip force at frequencies above 200 Hz. The DPMI phase response on the other hand appears to be more influenced by variations in the push force than in grip force.

3.2.5. *Relationship with coupling and contact forces*

From the results presented in Section 3.1, it has been shown that the total hand–handle contact force measured on different handles results from a linear combination of push and grip forces, where the contribution due to grip force is approximately three times larger than the push force.

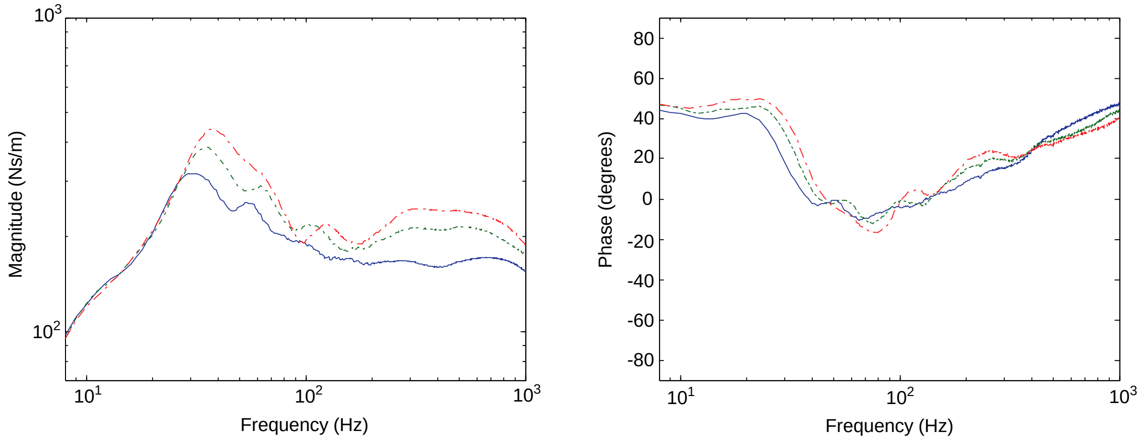

Fig. 11. Influence of the grip force on the DPMI (40 mm handle, 50 N push force, $a_{h,w} = 2.5\,\mathrm{m/s^2}$): (a) magnitude; (b) phase (—, 10 N grip;- - -, 30 N grip;– -, 50 N grip).

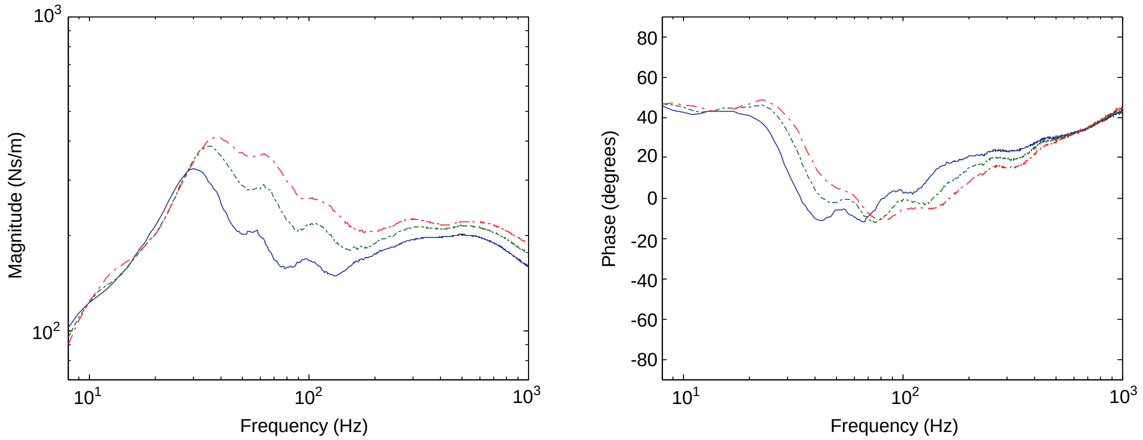

Fig. 12. Influence of the push force on the DPMI (40 mm handle, 30 N grip force, $a_{h,w} = 2.5\,\mathrm{m/s^2}$): (a) magnitude; (b) phase (—, 25 N push;- - -, 50 N push;– -, 75 N push).

In contrast, the working draft ISO/WD 15230 [13] defines the hand–handle coupling force as a direct summation of the push and grip forces. In an attempt to study the dependence of the DPMI magnitude on the hand–handle interface forces, regression analyses are performed to relate the measured coupling force and total contact force, derived from Eq. (1), with the mean DPMI magnitude, for various combinations of grip and push forces, and handle diameters. Figs. 13(a)–(c), illustrate the correlation coefficients obtained for the mean DPMI with respect to coupling and contact forces for the three handle sizes, respectively, and the entire range of grip and push forces considered in the study. The correlation coefficients are presented as a function of frequency, and plotted for center frequencies of one-third octave bands.

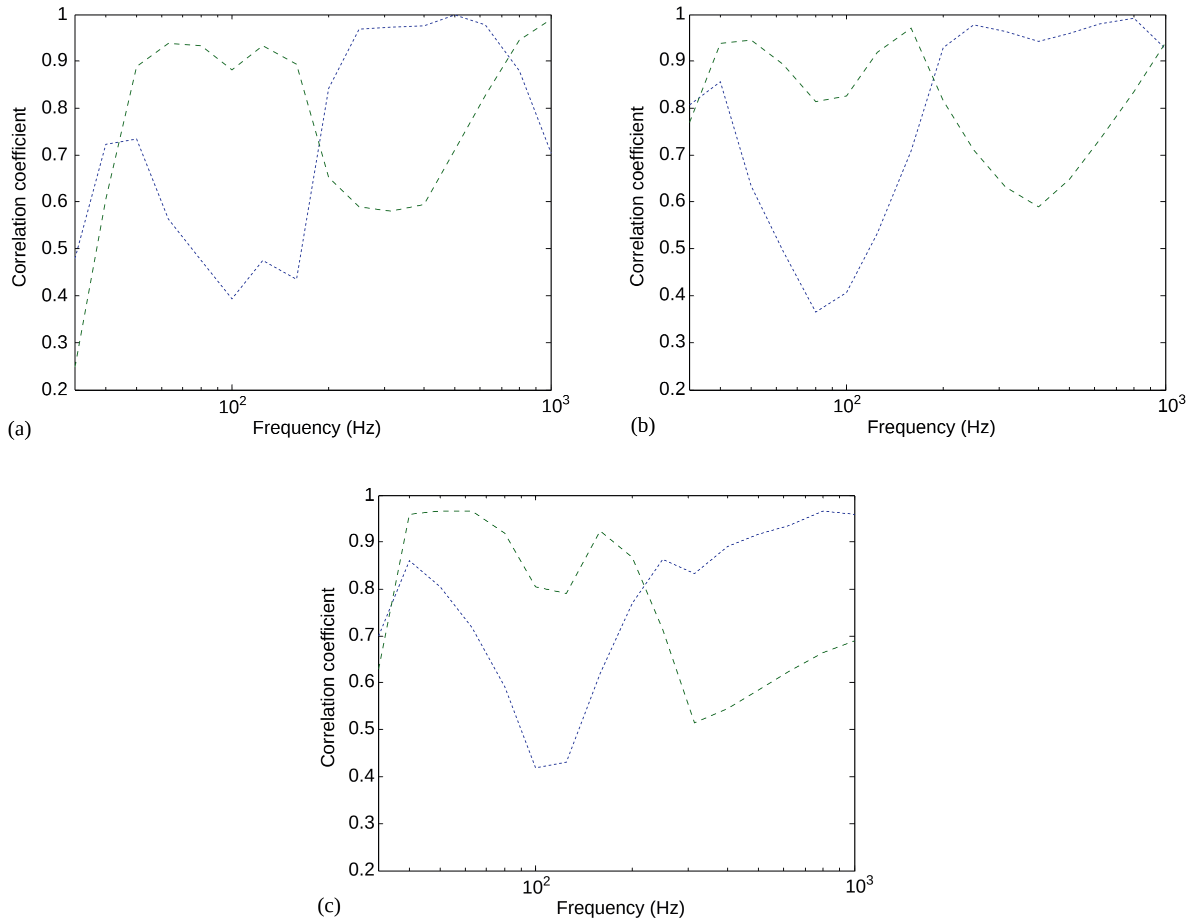

Fig. 13. Correlation coefficients derived for relations between the mean DPMI magnitude and the contact and coupling forces ($a_{h,w}$ = 2.5 m/s^2); (a) 30 mm handle, (b) 40 mm handle, (c) 50 mm handle (—, contact force;- - - -, coupling force).

These results suggest that the mean DPMI magnitude is more closely correlated with the coupling force at frequencies below 200 Hz, irrespective of the handle size. A better correlation with the contact force, however, is attained at frequencies above 200 Hz, for all the three handles. The strong correlation of the DPMI magnitude response with the coupling force at lower frequencies is perhaps attributed to its strong dependence on the push force in this frequency range, as seen in Fig. 12. This may further be attributed to the mechanical coupling of the entire hand–arm structure with the handle by the coupling force acting between the handle and the palm of the hand at lower frequencies below 200 Hz. The higher correlation with the contact force at higher frequencies is due to a strong dependence of the DPMI on the grip force, as seen in Fig. 11. At higher frequencies, the driving-point mechanical impedance is mainly caused by the skin tissues of the hand–arm system, where the grip force contributes far more than the push force, partly due to a larger contact area between the handle and the hand skin. The contact force, which increases in proportion to approximately three times the grip force, thus becomes the dominating factor at higher frequencies.

Table 2
Statistical significance analysis at discrete frequencies

	8 Hz	16 Hz	20 Hz	25 Hz	40 Hz	63 Hz	100 Hz
Excitation level	0.053	0.015	0.086	0.067	0	0	0.074
Handle size	0	0	0	0	0.062	0.338	0.021
Grip force	0.39	0.14	0.107	0.004	0	0	0.001
Push force	0.001	0.795	0.043	0.22	0	0	0
Excitation level: Handle size	0.018	0.058	0.02	0.018	0.141	0.183	0.132
Excitation level: Grip force	0.179	0.410	0.287	0.113	0.734	0.456	0.531
Handle size: Grip force	0.661	0.517	0.746	0.986	0.517	0.589	0.122
Excitation level: Push force	0.861	0.094	0.287	0.653	0.581	0.13	0.249
Handle size: Push force	0.171	0.904	0.651	0.183	0	0.072	0.605
Grip force: Push force	0.687	0.129	0.392	0.192	0.806	0.829	0.783

	160 Hz	250 Hz	400 Hz	630 Hz	800 Hz	1000 Hz
Excitation level	0.083	0.004	0.031	0.195	0.986	0.108
Handle size	0	0	0	0	0	0
Grip force	0	0	0	0	0	0
Push force	0	0.002	0.002	0	0	0
Excitation level: Handle size	0.115	0.005	0.373	0.099	0.077	0.532
Excitation level: Grip force	0.21	0.455	0.9	0.897	0.794	0.967
Handle size: Grip force	0.819	0.141	0.122	0	0	0
Excitation level: Push force	0.419	0.327	0.66	0.604	0.656	0.425
Handle size: Push force	0.215	0.112	0.562	0.653	0.975	0.169
Grip force: Push force	0.682	0.544	0.567	0.792	0.716	0.711

4. Statistical analysis

The statistical significance of four different parameters on the mean DPMI magnitude response of seven subjects corresponding to different discrete frequencies was further evaluated through multifactor ANOVA using the SPSS software. These included two levels of excitation (spectra: 2.5 and 5.0 m/s^2), three levels of handle diameter (handle: 30, 40 and 50 mm), three levels of push force (push: 25, 50 and 75 N) and three levels of grip forces (grip: 10, 30 and 50 N). Table 2 summarizes the results of the statistical analysis, 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 different parameters. It is shown that the influence of the excitation level on the impedance magnitude is significant in three distinct frequency ranges: at low frequencies (16 Hz), around the resonance (40 and 63 Hz) and at higher frequencies (250 and 400 Hz). However, the statistical significance of the influence of the excitation level upon the DPMI magnitude is weaker when compared to that of the other three parameters (handle size, grip force and push force). The influence of the excitation level over the DPMI magnitude can be further visualized in Fig. 6(a), for a specific combination of grip (30 N) and push (50 N) forces. The influence of the handle size is strongly significant over almost the entire frequency range except at 40 and 63 Hz, near the resonance frequency. The effect of varying the handle size upon the DPMI magnitude is further evident in Fig. 9, for the lower excitation level (2.5 m/s^2) and for three different combinations of grip and push forces. Finally, the influence of push and grip forces is strongly significant at all frequencies except at low frequencies below 20 Hz for the grip force, and between 16 and 25 Hz for the push force. This effect is also clearly shown in Figs. 10–12 for the lower excitation level (2.5 m/s^2). The results further show strong interactions between the handle size and the grip force at frequencies above 630 Hz, and between the handle size and push force near the resonance frequency (40 Hz). The interactions between the vibration level and the handle size is also observed to be significant at frequencies below 25 Hz and in the 250 Hz band. The interactions between the excitation level and hand forces, and between the hand forces (grip and push) are observed to be insignificant.

5. Conclusion

The influences of grip and push forces exerted on a vibrating handle, and handle size on the static contact force at the hand–handle interface and on the hand–arm dynamic driving-point mechanical impedance (DPMI) have been studied on a population of seven healthy male subjects using three different instrumented handles of 30, 40 and 50 mm diameter. The static contact force has been found to be a linear combination of grip and push forces, where the grip force contribution is three times larger than that of the push force. It is concluded that the grip force component is more important, specifically for the smaller diameter handle. The DPMI response was also found to vary considerably with variations in the grip and push forces combinations and handle size. An increase in either the grip or the push force resulted in higher peak magnitude of DPMI and the corresponding frequency, suggesting the stiffening of the hand–arm system.

The results of the ANOVA have further shown that the influence of all the main factors considered in the study; namely the grip and push forces, handle size and excitation level on the

DPMI response is statistically significant in various frequency bands. Furthermore, strong interactions were identified between the handle size and hand forces (grip and push) exerted on the handle.

The increase in DPMI magnitude with increase in grip and push forces was found to be better correlated with the coupling force, defined as the direct sum of both grip and push forces, at frequencies below 200 Hz, while at frequencies above, the correlation was better with the contact force for all three handles. These results suggest nearly equal importance of the grip and push forces at frequencies below 200 Hz, and mechanical coupling of the entire hand structure with the handle. At frequencies above 200 Hz, the biodynamic response of the hand–arm system is more strongly influenced by the grip force, which may be attributed to the skin tissue–handle interaction, and the higher contact area of the skin tissue and the handle.

The handle size was found to have a considerable influence on DPMI, particularly near the frequency of peak magnitude and at frequencies above 100 Hz, where the effect was observed to be quite considerable. Important influence was also observed on the phase response. The fact that the handle size has a clear effect on the biodynamic response of the hand–arm system suggests that it should be reported among the other extrinsic factors when reporting data on DPMI. The comparison of the measured data with the range of idealized DPMI data defined in the ISO 10068 standard has shown that important differences can arise at frequencies near the peak DPMI magnitude and above 300 Hz, even though the measurement conditions fall within the range of applicable conditions defined in the standard. The results also suggest that the biodynamic response of the human hand–arm is slightly nonlinear; increasing the excitation amplitude has the effect of reducing the DPMI peak amplitude and the corresponding frequency.

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