Industrial Health 2005, **43**, 485–494 **Original Article**

Estimation of Biodynamic Forces Distributed on the Fingers and the Palm Exposed to Vibration

Ren G. DONG*, Daniel E. WELCOME and John Z. WU

Engineering & Control Technology Branch, National Institute for Occupational Safety and Health, 1095 Willowdale Road, Morgantown, West Virginia 26505, USA

Received January 24, 2005 and accepted April 14, 2005

Abstract: The hand-tool coupling force in the operation of a vibrating tool is generally composed of applied force (AF) and biodynamic force (BF). There is wide interest in quantifying the coupling force. The objectives of this study are to develop an effective method for estimating the BF and to investigate its fundamental characteristics. Using the biodynamic response of the hand-arm system, such as apparent mass or mechanical impedance, and the acceleration that can be measured on vibrating tools, this study proposed an indirect method for the BF estimation. The BFs distributed on the fingers and the palm of the hand along the forearm direction (z_h-axis) in the operations of eighteen types of tool were estimated and used to identify the distributed BF characteristics. The results indicate that the BFs depend on both the tool vibration spectrum and the biodynamic properties of the hand-arm system. The dominant BF frequency component is usually at the same frequency as the dominant vibration frequency of each tool. The BF distributed on the palm (2–98 N) is much higher than that distributed on the fingers (1–30 N) at frequencies less than 100 Hz, but these biodynamic forces (2–22 N) are comparable at higher frequencies. The palm BF on several tools with relatively low dominant frequencies (≤ 40 Hz), especially in the resonant frequency range (16–40 Hz), is comparable with the applied palm force (50–100 N). Since the resonant frequency of the palm BF is also in the range of the dominant vibration frequencies of many percussive tools, the palm BF may be related to the disorders in the wrist-arm system. The BF on the fingers is likely to be closely related to the dynamic stresses and deformations in the fingers and it may thus be used to quantify the finger vibration exposure.

Key words: Hand-transmitted vibration, Mechanical impedance, Biodynamic force, Hand-arm vibration, Hand-arm vibration syndrome

Introduction

The operation of many powered hand tools such as rock drills, road breakers, grinders, chain saws, chipping hammers, etc. requires the application of significant hand forces (applied force) to control and guide the tools and to achieve the desired productivity. These tools are also known to generate high magnitudes of hand-transmitted vibration. The response of the hand-arm system to the vibration may generate a significant dynamic force at the interface between the hands and the vibrating surface. These two types of forces constitute the total hand-tool coupling force/pressure. A high coupling force may not only impede blood circulation[1], cause pain, discomfort, and other acute effects in the hand[2], but it can also impose high stresses on the other parts of the hand-arm system. The use of vibratory tools in combination with the forceful and repetitive hand actions may result in a greater incidence of various cumulative trauma disorders (CTDs) such as hand-arm vibration syndrome (HAVS) and carpal tunnel syndrome (CTS)[3]. Therefore, there is wide interest in the determination of the hand coupling force[4–6].

While it has been relatively easy to measure the applied

*To whom correspondence should be addressed.

force on non-vibrating tools, the measurement of the general coupling force, especially its dynamic component, on vibrating tools at workplaces remains a formidable research task. In order to help develop effective methods for measuring the coupling force on vibrating tools, an ISO standard on the definitions of the coupling force parameters and the general guidelines of their measurements has been proposed (ISO/CD 15230, 2004)[5]. A few recent studies have established the general relationships among the total contact force, the peak contact pressure, and the grip and push forces on cylindrical handles, as well as the effect of the handle size on the relationships[7, 8]. Another recent study has identified the effects of the hand and handle sizes on the distribution of the maximum voluntary grip force in two orthogonal axes on a cylindrical handle[9]. While the results from these studies should be used to improve the proposed ISO standard, further studies are required to improve the understanding of the coupling force, especially the dynamic component, so that the guidelines for the measurements can be further improved.

Several approaches have been used to measure the coupling force. One of them is to instrument the tool handle using strain gauges or force transducers[10–17]. However, the application of instrumentation to tool handles is usually tool-specific, inconvenient, and expensive. The handle instrumentation may also alter the dynamic properties of the handle. This may not be critical for a non-vibrating tool, but it may change the vibration pattern on the handle of a vibrating tool[17]. The instrumented handle should be sufficiently stiff to minimize this problem[17]. Instrumented adapters may also be used for the measurement without changing the original handle structure[17–19]. With the adapters, however, the hand contact area and coupling relationship may be changed. To identify the true coupling force, it is also necessary to eliminate the effect of the inertial force resulting from the mass of the force sensors, instrumented handle, or the adapter[20]. It may also be very difficult to determine the accurate value of such an inertia force in some cases because the handle or adapter may vibrate differently with and without the hand holding the handle[17]. While the applied push or pull force can be measured relatively easily using a force plate or similar devices, it has been difficult to directly measure the grip force at workplaces. The measurement of the biodynamic force at workplaces is an even more challenging task.

The recent developments of several new technologies have made it possible to overcome some of the above-mentioned confounding factors and technical difficulties. Wafer-thin, light, and flexible force pressure sensors are now available. They can be wrapped around the tool handle or incorporated into a work glove[7, 8, 21–23]. So far, however, such instrumentation installations have been shown to be expensive and/or fragile for many workplace environments. Some of these flexible sensors may also have significant hysteresis and non-linear behavior[23]. While such sensors may provide reasonable measurements of the pressure that is perpendicular to the contact surface, it is difficult to use such sensors to measure the tangential or friction force on the tool handles. These sensors have also been used to measure the dynamic forces[26, 27], but their reliability and accuracy have not been sufficiently proven. The further advancement of these technologies may lead to more convenient and reliable methods for the measurement. So far, however, while the applied grip, push, and contact forces on several vibrating tools have been reported from a few studies[6, 16, 23, 26], limited information on the biodynamic force is available[27, 28]. Thus, the fundamental characteristics of the biodynamic force have not been seriously investigated.

As an alternative approach, the present study proposed an indirect method for estimation of the dynamic component of the coupling force. It is based on the biodynamic response (BR), such as apparent mass (AM) or mechanical impedance (MI), and the tool vibration spectrum. The specific aims of this study are (i) to demonstrate this method using available experimental data; (ii) to investigate the fundamental characteristics of the biodynamic force distributed on the fingers and the palm of the hand, and (iii) to explore the potential applications of the biodynamic force.

Method

Theory

The apparent mass (AM) and the mechanical impedance (MI) are the most frequently used biodynamic response parameters. They are conventionally defined as

$$AM = \frac{F}{A} \quad \text{and} \quad MI = \frac{F}{V} \tag{1}$$

where F, A, and V are the biodynamic force, vibration acceleration, and vibration velocity at the hand-vibrating surface interface, respectively. In the frequency domain, each of the BRs defined in Eq.(1) can be obtained by performing a transfer function or transmissibility-like calculation. Specifically, they can be computed from:

$$Z(\omega) = \frac{G_{fm}(\omega)}{G_{mm}(\omega)} \tag{2}$$

where ω is the vibration frequency in rad/s, Z(ω) represents either of the BRs, G_{fm} is the cross-spectrum of force and dynamic motion (either acceleration for AM, or velocity for MI) and G_{mm} is the auto-spectrum of the motion. The biodynamic response parameters can be derived from each other. For example, when the mechanical impedance is available, the apparent mass can be calculated as follows:

$$AM(\omega) = MI(\omega) / j\omega \quad (3)$$

where $j = \sqrt{-1}$.

The apparent mass and the mechanical impedance can be measured in a laboratory experiment[17]. Using a vibration test system to provide the desired vibration source, an instrumented handle can be used to control the applied grip force and to measure the biodynamic force. The vibration is measured via a control accelerometer affixed to the handle to obtain the motion parameters for the BR calculation[20]. When the magnitudes of BR parameters and a tool vibration spectrum (A_{tool}) expressed in frequency domain are available, the biodynamic force acting at the hand-tool coupling location, $F_{tool}(\omega_i)$, at the i^{th} frequency can be calculated using the following formulas:

$$F_{tool}(\omega_i) = AM(\omega_i) \cdot A_{tool}(\omega_i) \text{ or}$$
$$F_{tool}(\omega_i) = MI(\omega_i) \cdot A_{tool}(\omega_i) / j\omega_i \quad (4)$$

The root-mean-square value of the biodynamic force can be calculated from:

$$F_{tool} = \sqrt{\sum_{i=1} [F_{tool}(\omega_i)]^2} \quad (5)$$

The human hand is a very flexible structure and it can adapt to very complicated geometry. The biodynamic force distributed at different locations of the hand could be very different and complicated, which may be important for fully assessing hand-transmitted vibration exposure and its health effects. Although the indirect method proposed in this paper can be generally applied to estimate the distribution of the biodynamic force at any interface between the human body and a vibrating surface, this study focuses on the biodynamic forces distributed on the fingers and the palm of the hand using a power grip on a cylindrical handle.

The cylindrical handle is frequently used on many powered hand tools. The applied force on such a handle is most frequently quantified by separately measuring the grip and push/pull forces[6–8, 14, 20]. Flexible pressure sensors can be used to measure the total contact force, and it can be used to calculate the grip and push/pull forces[5, 7, 8]. Similarly, the corresponding biodynamic forces can also be quantified in such a manner[14, 20]. As conceptually sketched in Fig. 1, the cylindrical handle can be evenly split into two parts at the centerline. The centerline divides the hand coupling force into the finger coupling force (F_{fapp} for finger applied force and F_{fdyn} for finger dynamic force) and the palm coupling force (F_{papp} for palm applied force and F_{pdyn} for palm dynamic force). While the finger coupling force represents the effect of the grip action or the combined grip and pull action, the palm coupling force reflects the effect of the push action or the combined grip and push action. A special instrumented handle has been developed by investigators at the National Institute for Occupational Safety and Health (NIOSH) and it has been used for the measurements of finger and palm biodynamic responses[14, 20].

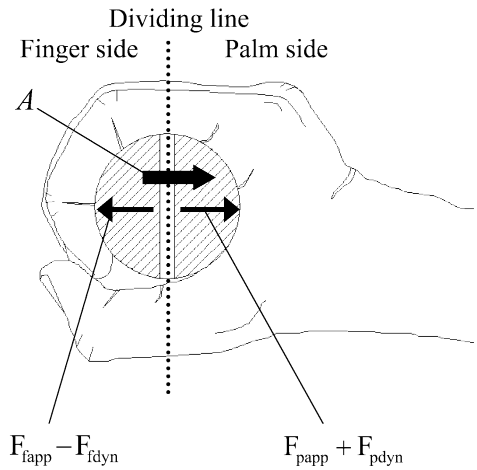

Fig. 1. Hand coupling forces and acceleration at the interfaces between the fingers and the handle, and between the palm and the handle.
F_{fapp}: static or applied finger force; F_{fdyn}: dynamic force acting on the fingers; F_{papp}: static or applied palm force; and F_{pdyn}: dynamic force on the palm; and *A*: handle vibration acceleration.

BR data and tool vibration spectra

To demonstrate the practical application of the proposed methodology and to understand the fundamental characteristics of the biodynamic force distributed on the fingers and the palm, this study used a set of mechanical impedance data measured at the fingers and the palm of the hand obtained from our earlier study of the biodynamic response[20]. Briefly, these BR data were measured using six subjects. Each subject took the same posture as that required for the ISO-standardized glove test (ISO 10819, 1996)[29]. With this test posture, the vibration input to the hand-arm system is in the z_h-axis[4] (along the forearm direction). Discrete sinusoidal vibrations with a constant-velocity (14 mm/s) at ten different frequencies (16, 25, 40, 63, 100, 160, 250, 400, 630 and 1,000 Hz) were used in the

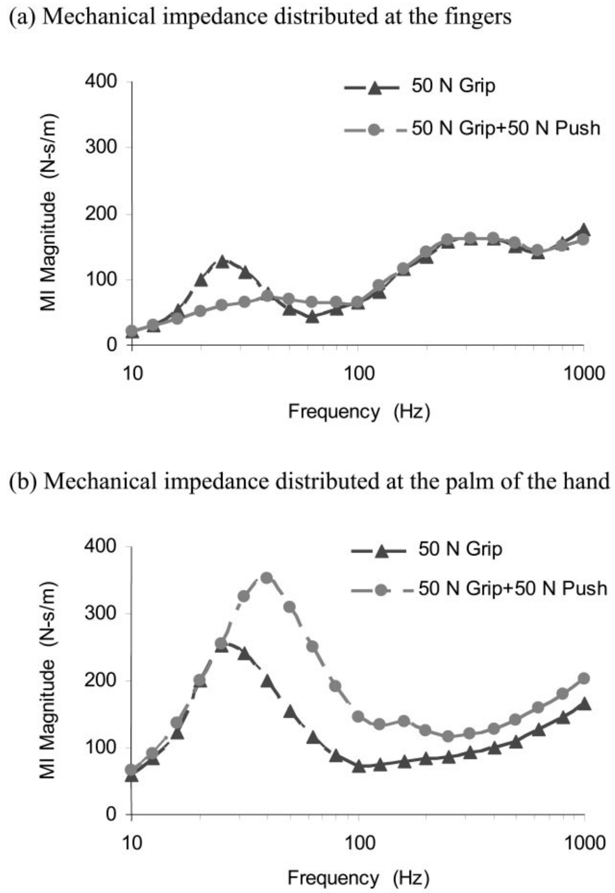

Fig. 2. Mechanical impedance of hand-arm system distributed at the fingers and the palm of the hand, which are estimated based on the data from a reported study[20].

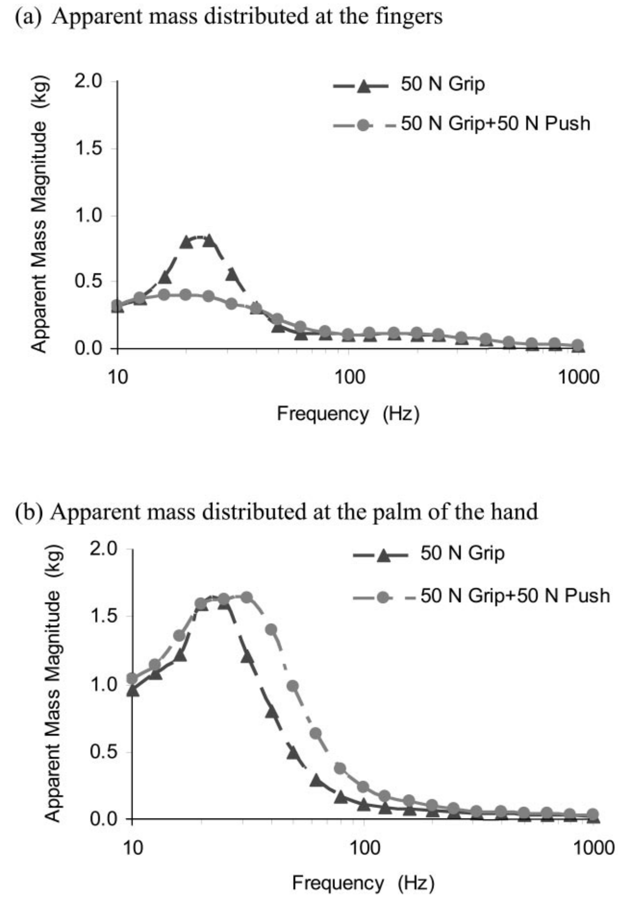

Fig. 3. Apparent mass of hand-arm system distributed at the fingers and the palm of the hand, which are calculated based on the data shown in Fig. 2.

experiment. In the present study, the missing values within the 1/3 octave band frequencies from 10 to 1,000 Hz were estimated using quadratic interpolation. The combined grip and push action may be the most frequently used action in the operation of many vibrating tools. The grip-only action may represent a special working condition. Hence, the data measured during two types of actions (50 N grip-only, and combined 50 N grip and 50 N push) were used. The mean values of the six subjects are plotted in Fig. 2. The major reason for choosing this set of data for the estimation is not only because it provides the distributed impedance but also because the summed impedance for the entire hand-arm system is very comparable with that measured using the vibration spectra measured on two typical vibrating tools (chipping hammer and grinder)[20, 30].

This study used eighteen tool vibration spectra reported from three studies[31–33], which include spectra measured on a rock drill, road breaker, chipping hammer, angle grinder, rotary file etc. The major vibration exposure direction on these tools is likely to be either on the z_h-axis[4] or the vibration magnitude is on this axis is comparable with that on any other axis. These spectra also represent a diverse selection of vibration characteristics of powered hand tools.

Results

Figure 3 shows the apparent mass values calculated using Eq.(3) from the mechanical impedance data shown in Fig. 2. The data indicate that the resonance of the hand-arm system in the z_h-axis[4] under the applied forces used in the BR measurement is in the range of 16 to 40 Hz. The resonance of the fingers under the combined grip and push action is not obvious. Increasing the palm force increases the resonant frequency and the magnitude of the apparent mass at frequencies higher than 25 Hz. The apparent mass generally diminishes with an increase in frequency beyond the resonant frequency range.

As examples, Fig. 4 shows the estimated biodynamic forces

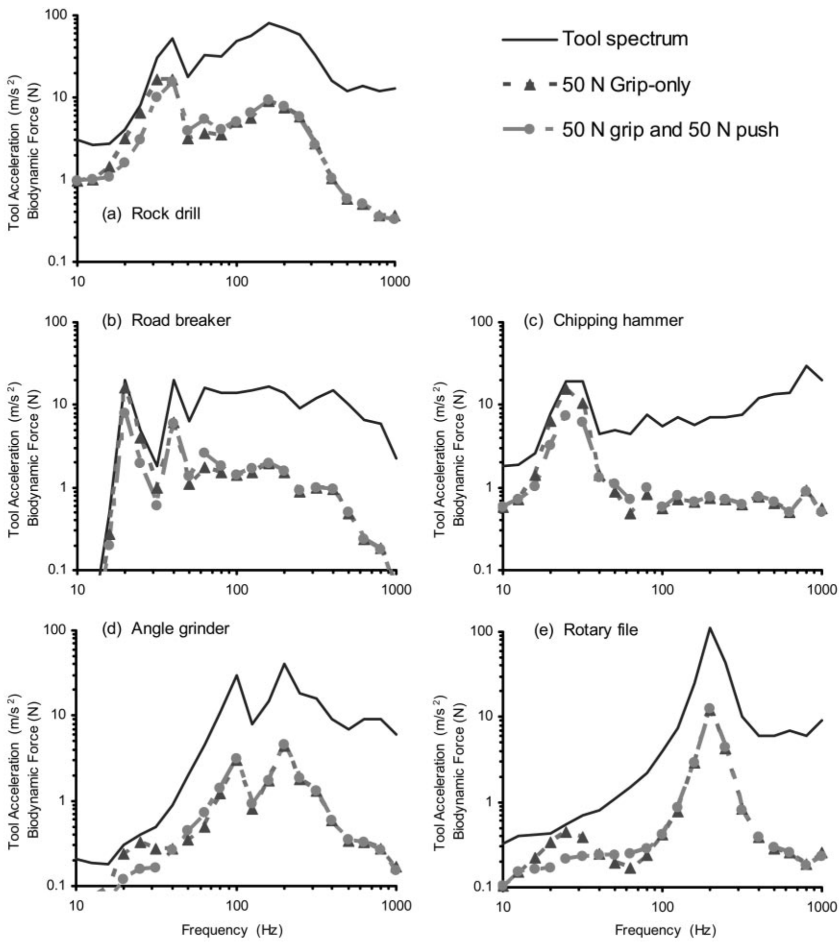

Fig. 4. Vibration spectra of the five tools (rock drill[31]), road breaker[33]), chipping hammer[32]), angle grinder[31]), rotary file[31])), and their corresponding biodynamic forces distributed at the fingers.

distributed at the fingers together with five tool vibration acceleration spectra. Since the accelerations at each 1/3 octave band frequency are expressed as root-mean-square (rms) values in the vibration spectra, the biodynamic forces are also rms values. As shown in Eq. (4), the apparent mass functions like a frequency weighting in determining the biodynamic force from the tool acceleration spectrum. The dominant biodynamic force is generally at the fundamental vibration frequency of each tool. The maximum finger peak force among the five tools is less than 20 N.

The predicted biodynamic force values distributed at the palm are presented with the tool vibration acceleration spectra in Fig. 5. Similar to the dynamic forces on the fingers, the dominant biodynamic force is also at the fundamental vibration frequency of each tool. The peak dynamic forces of the rock drill, road breaker, and chipping hammers are much higher than those of the two high frequency tools (angle grinder and rotary file). Although the peak acceleration on the rotary file is more than 100 m/s^2 at 200 Hz, the peak dynamic force is less than 20 N. On the other hand, the peak acceleration of the rock drill is 53 m/s^2 at 40 Hz, but the peak dynamic force is 74 N.

The comparisons of the finger and palm biodynamic forces shown in Figs. 4 and 5 indicate that the basic trends of these forces are similar to each other. However, they also clearly indicate that the biodynamic force on the hand at frequencies lower than 100 Hz is mainly distributed on the palm. At higher frequencies, the dynamic forces on the two parts of the hand are similar or comparable. These distribution characteristics are the same as those of the apparent mass or mechanical impedance[20]).

The rms values of the dynamic forces distributed on the fingers and the palm for the eighteen tools, together with their dominant frequencies, are listed in Table 1. The palm dynamic forces on the rock drill, road breaker, chipping hammer, and needle gun are comparable with the applied

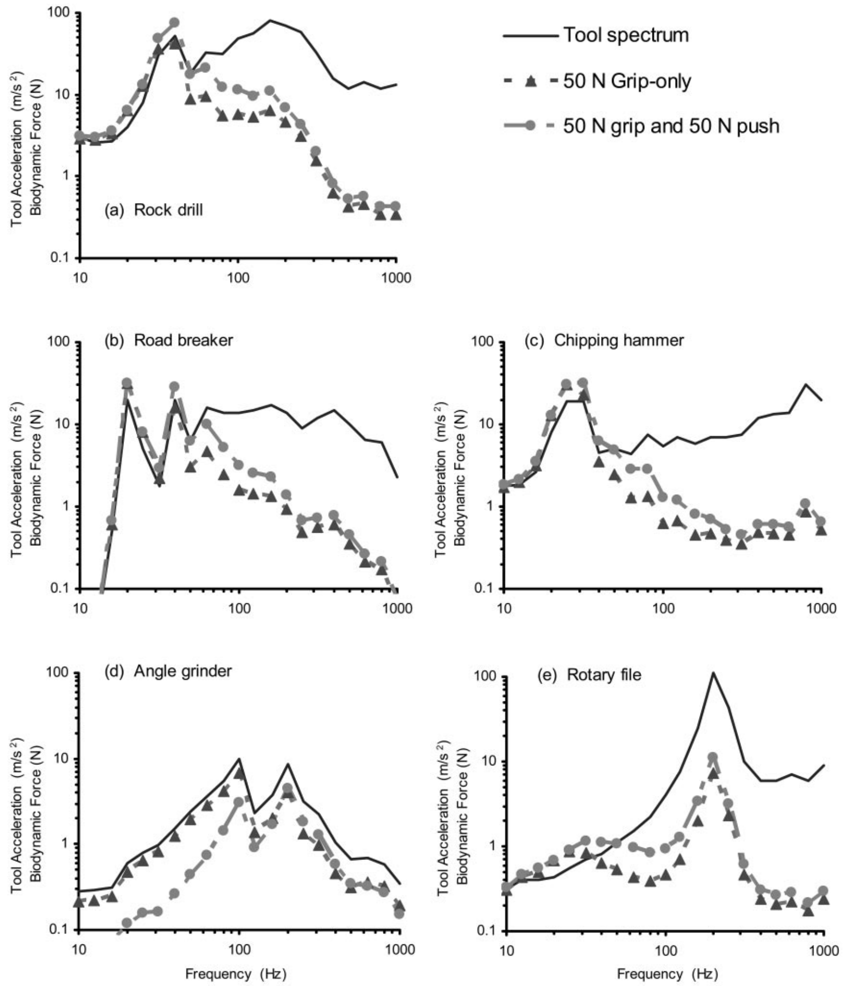

Fig. 5. Vibration spectra of the five tools (rock drill[31]), road breaker[33]), chipping hammer[32]), angle grinder[31]), rotary file[31])), and their corresponding biodynamic forces distributed at the palm of the hand.

palm forces (50 N for grip-only, 100 N for combined action). These tools have their dominant vibration frequencies at equal to or less than 50 Hz. The palm BFs on other tools with higher dominant frequencies are less than 20 N, except that on the non-anti-vibration chainsaw. In the combined grip and push action, the palm BF is generally more than two times higher than that acting on the fingers at the dominant frequency less than 100 Hz. The difference is smaller in the grip-only action but the palm BF is still the major component of the hand biodynamic force at frequencies less than 100 Hz. The difference between the finger and palm biodynamic forces generally decreases with a reduction in the dominant frequency.

Discussion

Depending on the purposes, available instruments, work conditions, and accuracy requirements of a study, different methods may be used to quantify the hand coupling force. This study proposed an alternative way to determine the biodynamic force. It can be used for the study of not only hand-transmitted vibration but also whole-body vibration. Since the measurement of vibration acceleration on a tool or a vehicle seat and the measurement of the biodynamic response in a laboratory have been developed reasonably well, it is much easier to estimate the biodynamic force than to measure it at workplaces. Theoretically, if the vibration spectra are reliable and the biodynamic response data are selected or measured appropriately, the estimated results can be representative and acceptable.

Table 1. Biodynamic force (BF) rms values of eighteen tools distributed on the fingers and the palm of the hand and the dominant vibration frequencies of the tools

Location and hand action type	Biodynamic Force (N)				Dominant Frequency (Hz)
	Grip-only		Grip + Push		
	Finger	Palm	Finger	Palm	
*Road breaker 1	11	24	8	28	16
***Road Breaker 2	18	37	11	46	20
**Chipping hammer 1	20	41	11	47	25
*Metal drill	3	7	2	9	25
*Impact wrench	9	19	7	28	31.5
*Nutrunner	6	13	4	17	31.5
*Rock drill	30	61	26	98	40
*Chipping hammer 2	8	15	9	27	50
*Needle gun	9	21	9	40	50
*Riveting gun	1	2	2	3	63
*Dolly w/rivet gun	5	8	5	14	63
* Pneumatic 7" vertical grinder	4	5	4	11	80
*Rand orbital sander	9	9	9	18	100
*Elec.9" angle grinder	6	6	6	10	100
*Pneumatic 5" straight grinder	4	7	5	13	100
*Non-AV chainsaw	12	15	12	22	125
*AV chainsaw	2	2	2	4	200
*Pneumatic rotary file	13	8	14	12	200

*Griffin[31]; ** Xu *et al.*[32]; and *** Tasker[33].

The apparent mass or impedance may be influenced by many factors such as vibration direction, vibration magnitude, hand and arm posture, type of hand action, applied hand force, handle shape and dimension, and individual anthropometrics[20, 34–36]. These factors also affect the biodynamic force. Because the hand BR is mainly distributed on the palm at frequencies less than 100 Hz, it may be acceptable to use hand BR to represent the palm BR to estimate the biodynamic force on tools that have the dominant vibration in this frequency range. A caution in the selection of the reported BR data for the prediction is that some of the data may not be reliable[36]. It is anticipated that the arm posture and abduction could significantly affect the response in this frequency range. To reasonably predict the biodynamic force, biodynamic responses should be measured under representative postures and vibration magnitudes as close as possible to the actual working conditions.

The estimated biodynamic force can be used to help develop an effective measurement strategy and practical method, select appropriate transducers, and perform adequate calibrations. For example, the average rms value of the palm biodynamic force at the dominant vibration frequency (40 Hz) of the rock drill is 74 N, as shown in Fig. 5. The time-history peak value must be much greater than this rms value. If some other frequency components are in phase with this dominant frequency component, the time-history peak value would be even greater. This is particularly true for many percussive tools. If the applied palm effective force is 100 N, it is estimated that the peak value of the coupling force could be higher than 200 N. At workplaces, the applied maximum force is likely to be greater than that used in this study. Hence, the actual peak coupling force is likely to be significantly higher than 200 N. The proposed standard (ISO/CD 15230, 2004)[5] recommends calibration of the force measurement device up to 200 N. This is not sufficient for measurement of the coupling force on the rock drill when the dynamic components are also of interest in a study. In any case, the transducers should be selected so that they can tolerate the high dynamic force. On the other hand, the biodynamic force on the high frequency tools such as the grinders and rotary file are usually not very high, as shown in Figs. 5(d) and 5(e) and Table 1. The biodynamic force acting on the fingers is also fairly low, as shown in Fig. 4 and Table 1. Therefore, it may not be necessary to consider a large force range for the measurement of the dynamic force on the fingers, especially in the operation of high frequency tools. Some capacitive pressure sensors may isolate a significant portion of the high-frequency vibration (>500 Hz) transmitted to the fingers and the palm. They may not be suitable for the measurement of the high-frequency biodynamic force. If only the applied force is of concern, or it is acceptable to use the proposed method to estimate the biodynamic component, the requirements of the instrumentation can be significantly reduced. This may be a practical option in field studies.

A major assumption of the proposed indirect method is that the biodynamic force changes linearly with the vibration magnitude. This assumption may be acceptable in a certain range of the vibration magnitude[35] but the response of the hand-arm system usually exhibits a nonlinear behavior[30, 37]. A study reported that the impedance magnitude and fundamental resonant frequency were generally reduced with an increase in the vibration magnitude[30], similar to that observed in whole-body vibration[38]. The magnitude of vibration used in the impedance measurement was likely to be different from those of the tools. Hence, the estimated results may have some errors. Nevertheless, since the impedance data used in this study are very comparable to those measured using the real tool spectra[20, 30], the possible errors should not be substantial. Further studies are required to determine the apparent mass as a function of vibration magnitude so that the accuracy of the force estimation can be improved. Besides, the apparent mass used in the estimation should be measured under the conditions (applied force, hand-arm posture, individual factors etc.) representative to those at workplaces.

Many injuries in the joints are caused from excessive stresses/strains and deformations in the joints[39]. A high level of the combined applied force and dynamic load may cause the excessive stresses and deformations and thus be harmful to the hand-arm system. At relatively low frequencies (≤ 40 Hz), the vibration can be effectively transmitted to the arm[40, 41]. Therefore, a large portion of the low frequency force acting on the palm can be effectively transmitted to the wrist, elbow, and shoulder. The resonance of the hand-arm system and the dominant vibration of many percussive tools such as rock drills, chipping hammers, jackhammers are all in this frequency range, as shown in Figs. 3 and 4. Therefore, the dynamic force, combined with the forceful action required in the operation of these tools, may result in a high incidence of the injuries and disorders in the wrist-arm system[3, 42–44]. The biodynamic force measured at the palm should be closely related to the stresses and deformations in the joints or the arm system. It may thus be a good vibration measure for studying the disorders in the wrist-arm system.

On the other hand, the dynamic stresses, deformations, and energy absorption in the fingers should be closely related to the biodynamic force measured at the fingers. It has been speculated that the energy absorption may be related to the etiology of the vibration-induced finger injuries or disorders[12]. It has also been speculated that the vibration-induced dynamic stresses and deformations are the essential mechanical stimuli that directly act on the tissues and they should be related to the etiology. Hence, the finger biodynamic force may be used as an alternative measure of the vibration exposure for studying finger disorders. The quantification of finger BF and the identification of its fundamental characteristics are the first step to test these hypotheses. The results of this study suggest that the rms value of the finger dynamic force on a high frequency tool is generally much less than the applied finger force. The effect of the dynamic force would be negligible on such a tool if it would have the same effect as that of the fingers-applied force. This is likely not the case because epidemiological studies indicate that many high frequency tools such as grinders can cause a high prevalence of vibration-induced white finger among workers[38], although the dynamic forces on such tools can be very low (e.g.: 4 to 6 N as listed in Table 1). Hence, the dynamic force should be treated differently from the applied force in risk assessment. The relationships between the biodynamic force and the disorders remain interesting topics for future studies.

Summary and Conclusions

This study proposed a convenient and efficient method for estimating the biodynamic force (BF). Based on the results and observations of this study, several conclusions are made as follows:

- The biodynamic force depends on both the tool vibration and the dynamic response of the hand-arm system. The peak component of the biodynamic force in the frequency domain is generally at the same frequency as the dominant vibration frequency of the tool.
- In the z_h-direction (along the forearm) exposure, the biodynamic force distributed on the palm is much higher than that distributed on the fingers at frequencies less than 100 Hz. At higher frequencies, the biodynamic forces distributed on the two parts of the hand are similar to each other.
- The biodynamic forces acting on the palm for the tools with relatively low dominant frequencies (≤ 40 Hz) are generally much higher than those for the tools with dominant high frequencies (≥ 100 Hz).
- Because the characteristics of the finger BF and palm BF have some significant differences and they are likely related to the stresses and deformation at different locations

of the hand-arm system, they should be quantified separately and applied in accordance with the goals and purposes of the studies in which they are used. While the finger BF may be used to quantify the finger vibration exposure, the palm BF may be used to study the disorders in the wrist-arm system.

Acknowledgement

The authors thank Mr. Chris Warren for his assistance in the study.

References

1) Welsh AJL, Griffin MJ (2004) Effect of vibration magnitude and push force on finger blood flow. In: Proceeding of the 10th International Conference on Hand-Arm Vibration. Las Vegas, USA.
2) Hartung E, Dupuis H, Scheffer M (1993) Effects of grip and push forces on the acute response of the hand-arm system under vibrating conditions. Int Arch Occup Environ Health **64**, 463–7.
3) NIOSH (1997) Musculoskeletal disorders and workplace factors: a critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back. 97–141, NIOSH Publication, U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health, Cincinnati, OH, USA.
4) ISO 5349-1 (2001) Mechanical vibration—Measurement and evaluation of human exposure to hand-transmitted vibration—Part 1: General requirements. International Organisation for Standardization, Geneva, Switzerland.
5) ISO/CD 15230 (2004) Definition and guidelines for the measurement of the coupling forces for operators exposed to hand-arm vibration. International Organization for Standardization, Geneva, Switzerland.
6) Riedel S (1995) Consideration of grip and push forces for the assessment of vibration exposure. Central Europ J Publ Health **3** (Suppl), 139–41.
7) Welcome DE, Rakheja S, Dong RG, Wu JZ, Schopper AW (2004) An investigation on the relationship between grip, push and contact forces applied to a tool handle. Int J Ind Ergon **34**, 507–18.
8) Aldien Y, Welcome D, Rakheja S, Dong R, Boileau PE (2005) Contact pressure distribution at hand-handle interface: role of hand forces and handle size. Int J Ind Ergon **35**, 267–86.
9) Edgren CS, Radwin RG, Irwin CB (2004) Grip force vectors for varying handle diameters and hand sizes. Hum Factors **46**, 244–51.
10) Chadwick EKJ, Nicol AC (2001) A novel force transducer for the measurement of grip force. J Biomech **34**, 125–8.
11) Li ZM (2002) The influence of wrist position on individual finger forces during forceful grip. J Hand Surgery-Amer **27A**, 886–96.
12) Lidström IM (1977) Vibration injury in rock drillers, chiselers, and grinders. Some views on the relationship between the quantity of energy absorbed and the risk of occurrence of vibration injury In: Proceedings of the International Conference on Hand-arm Vibration. 77–83, Cincinnati, OH.
13) Radwin RG, Yen TY (1999) Force dynamometers and accelerometers. In: The occupational ergonomics handbook. eds. by Karwowski W, Marras WS, CRC Press, Boca Raton, FL.
14) Dong RG, Schopper AW, McDowell TW, Welcome DE, Wu JZ, Smutz WP, Warren C, Rakheja S (2004) Vibration energy absorption (VEA) in human fingers-hand-arm system. Med Eng Physics **26**, 483–92.
15) McGorry RW (2001) A system for the measurement of grip forces and applied moments during hand tool use. Appl Ergon **32**, 271–9.
16) Kaulbars U (1996) Measurement and evaluation of coupling forces when using hand-held power tools. Cent Europ J Publ Health **4**, 57–8.
17) Dong RG, Rakheja S, Smutz WP, Schopper AW, Caporali S (2003) Dynamic characterization of the simulated tool handle and palm-adapter used for assessment of vibration performance of gloves. J Testing Evaluat **31**, 234–46.
18) Gillmeister F, Schenk T (2001) Hand-arm vibration and coupling force measurement with a new adapter. In: Proceeding of the 9th International Conference on Hand-arm Vibration. 9–18, Nancy, France.
19) Burström L, Lundstrom R (1998) Portable equipment for field measurement of the hand's absorption of vibration energy. Safety Sci **28**, 15–20.
20) Dong RG, Wu JZ, McDowell TW, Welcome DE, Schopper AW (2005) Distribution of mechanical impedance at the fingers and the palm of human hand. J Biomech **38**, 1165–75.
21) Bishu R, Wang W, Chin AA (1993) Force distribution at the container hand/handle interface using force-sensing resistors. Int J Ind Ergon **11**, 225–31.
22) Johansson L, Kjellberg A, Kilbom A, Hagg G (1999)

Perception of surface pressure applied to the hand. Ergonomics **42**, 1274–82.
23) Gurram R, Rakheja S, Gouw G (1995) A study of hand grip pressure distribution and emg of finger flexor muscles under dynamic loads. Ergonomics, **38**, 684–99.
24) Nikonovas A, Harrison AJL, Hoult S, Sammut D (2004) The application of force-sensing resistor sensors for measuring forces developed by the human hand. In: Proceedings of the institution of mechanical engineers part H. J Eng Med, **218**(H2), 121–6.
25) Feutry D, Lemerle P, Claudon L (2004) Design of a new instrumented glove for the measurement of the contact pressure distribution at the hand/handle interface. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.
26) Valentino M, Rapisarda V, Scalise L, Paone N, Santarelli L, Fenga C, Ross LG (2004) A new method for the experimental assessment of finger haemodynamic effects induced by a hydraulic breaker in operative conditions. J Occup Health **46**, 253–9.
27) Wasserman DE, Wasserman J, Ahn JI (2001) Instrumentation for measuring coupling forces of hand-held tools. J Sound Vib **35**, 22–5.
28) Wasserman J, Logston D, Wasserman D (2004) The use of a resistive pressure sensor to assess glove effects on tool transmitted vibration. In: Proceeding of the 10th International Conference on Hand-Arm Vibration. Las Vegas, USA.
29) ISO 10819 (1996) Mechanical vibration and shock—Hand-arm vibration—Method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand. International Organization for Standardization), Geneva, Switzerland.
30) Kihlberg S (1995) Biodynamic response of the hand-arm system to vibration from an impact hammer and a grinder. Int J Ind Ergon **16**, 1–8.
31) Griffin MJ (1997) Measurement, evaluation, and assessment of occupational exposures to hand-transmitted vibration. Occup Environ Med, **54**, 73–89.
32) Xu Z, Ding HC, Ding MP (1990) A study of dose-effect relationships for vibration induced white finger. In: Proceedings of the 5th International Conference on Hand-arm Vibration. 305–308, Kanazawa, Japan.
33) Tasker EG (1986) Assessment of vibration levels associated with hand-held roadbreakers. Scand J Work Environ Health **12**, 407–12.
34) ISO 10068 (1998) Mechanical vibration and shock—Free, mechanical impedance of the human hand-arm system at the driving point. International Organisation for Standardization), Geneva, Switzerland.
35) Burström L, Lundström R (1994) Absorption of vibration energy in the human hand and arm. Ergonomics **37**, 879–90.
36) Dong RG, Warren C, Welcome DE, McDowell TW, Wu JZ (2004) A comparison and evaluation of the reported mechanical impedance data of the human hand-arm system. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.
37) Lenzuni P, Lundström R, Burström L (2001) Frequency and magnitude functional dependence of absorbed power resulting from vibration transmitted to the hand and arm. In: Proceeding of the 9th International Conference on Hand-arm Vibration. 289–99, Nancy, France.
38) Griffin MJ (1990) Handbook of human vibration. Academic Press, London.
39) Taber LA (1995) Biomechanics of growth, remodeling, and morphogenesis. Appl Mech Rev **48**, 487–545.
40) Pyykkö I, Färkkilä M, Toivanen J, Korhonen O, Hyvärinen J (1976) Transmission of vibration in the hand-arm system with special reference to changes in compression force and acceleration. Scand J Work Environ Health **2**, 87–95.
41) Reynolds D, Angevine EN (1977) Hand-arm vibration, part II: Vibration transmission characteristics of the hand and arm. J Sound Vib **51**, 255–65.
42) Bovenzi M, Fiorito A, Volpe C (1987) Bone and joint disorders in the upper extremities of chipping and grinding operators. Int Arch Occup Environ Health **59**, 189–98.
43) Gemne G, Saraste H (1987) Bone and Joint Pathology in Workers Using Hand-Held Vibration Tools. Scand J Work Environ Health **13**, 290–300.
44) Malchaire J, Piette A, Cock N (2001) Associations between hand-wrist musculoskeletal and sensorineural complaints and biomechanical and vibration work constraints. Ann Occup Hyg **45**, 479–91.