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The relationships between hand coupling force and vibration biodynamic responses of the hand-arm system

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Abstract

This study conducted two series of experiments to investigate the relationships between hand coupling force and biodynamic responses of the hand–arm system. In the first experiment, the vibration transmissibility on the system was measured as a continuous function of grip force while the hand was subjected to discrete sinusoidal excitations. In the second experiment, the biodynamic responses of the system subjected to a broadband random vibration were measured under five levels of grip forces and a combination of grip and push forces. This study found that the transmissibility at each given frequency increased with the increase in the grip force before reaching a maximum level. The transmissibility then tended to plateau or decrease when the grip force was further increased. This threshold force increased with an increase in the vibration frequency. These relationships remained the same for both types of vibrations. The implications of the experimental results are discussed.

Practitioner Summary:

Shocks and vibrations transmitted to the hand–arm system may cause injuries and disorders of the system. How to take hand coupling force into account in the risk assessment of vibration exposure remains an important issue for further studies. This study is designed and conducted to help resolve this issue.

Keywords

Hand force; hand–arm vibration; hand-transmitted vibration; vibration risk assessment

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1. Introduction

Pneumatic hand tools such as sand rammers, road breakers, chipping hammers, riveting guns, and impact rock drills are used in construction, mining and manufacturing. As required by their functions, such tools generate shocks or impact vibrations. Part of the impact vibrations can be transmitted to the hand–arm system. Because the air actuation rates of these tools are usually in the range of 10–40 Hz, their fundamental vibration components are also in this frequency range (Dong et al. 2014; Griffin 1997). Coincidently, the major resonances of the human wrist–arm system are also primarily in this frequency range (Adewusi et al. 2010; Kihlberg 1995; Marcotte et al. 2005; Welcome et al. 2015; Xu et al. 2015). Vibrations at frequencies below 40 Hz can usually be effectively transmitted to the wrist, forearm and elbow; vibrations below 20 Hz can be further transmitted to the upper arm, shoulder, neck and head (Pyykko et al. 1976; Reynolds 1977; Welcome et al. 2015; Xu et al. 2017). These observations partially explain why vibrations are most strongly perceived in the hand–arm system in this frequency range (Miwa 1968; Morioka and Griffin 2006) and why a worker may complain of discomfort when operating low-frequency tools (Tominaga 1993). More importantly, prolonged and intensive exposure to impact vibrations may cause musculoskeletal disorders (MSDs) of the wrist–arm–shoulder substructures (Bovenzi, Fiorito, and Volpe 1987; Gemne and Saraste 1987).

Overexertion has been identified as one of the major factors associated with musculoskeletal injuries and disorders (NRC 2001). Forceful actions are required not only for guiding and controlling vibrating tools, but also for achieving their functions at some workplaces. The vibration exposure adds additional force to the hand–arm system (Dong, Welcome, and Wu 2005). These observations indicate that both the vibration exposure and the hand force should be taken into account when assessing the potential risk of injuries and disorders, especially among workers using impact tools. Probably for this reason, a standard on the measurement and evaluation of the applied hand forces during hand-transmitted vibration exposures has been established (ISO 15230 2007). In terms of their functions, the hand forces are divided into grip force, push/pull force, guide force, lift force and feed force. For risk assessment, the standard recommends the use of combined grip and push/pull forces, which is termed as coupling force. However, no specific method is recommended to take into account the hand forces in the current standard method for the risk assessment of hand-transmitted vibration exposures (ISO 5349–1 2001). This may be because the role of the hand forces is not sufficiently understood, and no reliable method has been established to include the hand forces in the risk assessment.

Due to the fact that the exact mechanisms of vibration-induced injuries and disorders have not been clearly understood (ISO 5349–1 2001), it is very difficult to determine the exact role of hand force in the development of vibration-induced injuries and disorders. However, it is reasonable to hypothesise that developments of such injuries and disorders are associated with biomechanical stresses and strains in the tissues induced from hand forces, vibrations and awkward postures (Dong et al. 2012), as they are among the essential factors that determine the injuries, remodelling and adaptation of the tissues and structures (Taber 1995; Fung 1996). Then, these factors can be quantified and synthesised to compute an exposure dose to study the dose-response relationships of specific health effects, which can be further used to develop the risk assessment method. In principle, the biomechanical stresses and strains in the tissues can be determined from the applied hand forces, input vibrations and hand and arm postures using various biomechanical methods. The applied forces and motions usually vary at much lower frequencies (<5 Hz) than the tool vibrations (>10 Hz) (ISO 10819 2013; ISO 15230 2007). The stresses and strains can thus be divided into two parts: non-vibration component and vibration component. While the former can be determined through studying the biomechanics of the hand–arm system subjected to the applied hand force and active motions (Chaffin, Andersson, and Martin 1999; Fung 1996), the latter is a passive response that can be determined by examining the system's biodynamic responses to vibration exposures. The current study focused the investigation on the vibration component.

Ideally, the vibration component should be quantified using stresses, strains or combinations of the two (Wu et al. 2006, 2010). Because it is very difficult to directly measure these detailed vibration responses *in vivo*, the vibration biodynamic responses of the hand–arm system have been frequently studied by measuring the vibration transmissibility on the system and/or the driving-point biodynamic response functions such as the apparent mass and mechanical impedance (Adewusi et al. 2010; Besa et al. 2007; Dong et al. 2013a; Griffin 1990; Kihlberg 1995; Marcotte et al. 2005). These frequency response functions can be used to estimate the vibration stresses and strains in the tissues through modelling studies (Wu et al. 2010). They can also be directly used to estimate the local forces and/or vibrations that can approximately represent the tissue loading environment. Therefore, these functions can be used to derive biodynamic frequency weightings (Dong et al. 2006b), which is an essential part of the overall frequency weighting for assessing the risk of vibration exposures (Dong et al. 2012). Because these frequency responses are functions of the hand force (Adewusi et al. 2010; Besa et al. 2007; Kihlberg 1995; Marcotte et al. 2005), the effects of the hand force on the physiological and health effects can at least be partially taken into account using the hand force-specific response functions to derive the biodynamic frequency weightings. Therefore, it is important to sufficiently understand the effect of the hand force on the biodynamic response functions and to characterise their direct relationships.

The reported biodynamic responses are usually expressed in the frequency domain. Although some studies have investigated the effects of hand force on the bio-dynamic responses (Adewusi et al. 2010; Kihlberg 1995; Marcotte et al. 2005), the direct relationships between the hand forces and biodynamic responses have not been clearly identified. Furthermore, the vast majority of the reported biodynamic responses were measured using random excitations, as it is an efficient excitation for the measurement of frequency response functions. Only a few studies used simulated tool vibration spectra to measure the response functions (Kihlberg 1995; Rakheja et al. 2002), which revealed that the response functions were not sensitive to the type of the input vibration. If this holds true, the response functions measured with the random excitation in laboratory experiments can be used to estimate the biodynamic responses from tool vibrations, or they can be used to derive location-specific biodynamic frequency weightings. The confirmation of this feature is very important for further biodynamic studies.

The specific aims of this study are threefold: (1) to identify the relationship between the grip force or coupling force and the vibration transmissibility on human arm structures (wrist, forearm and upper arm) for a given frequency in the range of 10 to 40 Hz; (2) to measure the vibration transmissibility on these arm substructures subjected to a random vibration under several combinations of hand forces, as well as the apparent mass at the palm of the hand; and (3) to enhance the understanding of the hand force effects of the response functions measured using these two types of vibrations.

2. Experimental method

Nine healthy male adults participated in this experimental study with informed consent. The age of the subjects ranged from 18 to 25, with the median age of 20. Their major anthropometries are listed in Table 1. The study protocol was reviewed and approved by the NIOSH Human Subjects Review Board.

2.1. Instrumentation and test set-up

As illustrated in Figure 1, this experimental study was conducted on a 1-D hand–arm vibration test system (Unholtz-Dickie, TA250-S032-PB). This study adopted the subject postures required for the standardised anti-vibration glove test (ISO 10819 2013). To make the instrumentation and measurement on the hand–arm system consistent for the subjects, the vibration was delivered to the right hand of each subject along the forearm direction (Z axis) through an instrumented handle (diameter: 40 mm; grip span: 110 mm). The handle was equipped with a tri-axial accelerometer (Endevco, 65–100) and two force sensors (Interface, SML-50) for measuring the acceleration input to the hand and the applied grip force, respectively. The selected force sensors are strain-gauge based and are not sensitive to thermal drift. The fundamental resonant frequency of the handle is about 900 Hz, which is sufficient for the purposes of this study. A force plate (Kistler, 9286AA) was used to measure the push force applied to the handle. A custom programme was created with LabVIEW software to display the applied and target grip and push forces on a computer monitor in front of the subject. As shown in Figure 2, three light-weight adapters (A: 13 g; B: 15 g; and C: 7 g), each equipped with a tri-axial accelerometer (Endevco, M35), were used to measure the vibrations transmitted to the wrist, forearm and upper arm, respectively. The adapters were secured in place using elastic cloth bandage wraps with a medium tightness comfortable for the subjects. This adapter method was examined and validated in a previous study (Xu et al. 2015). The measurements of the tri-axial accelerations on both the handle and adapters can avoid the difficulty of aligning the orientations of each accelerometer by evaluating the transmissibility of the total vibration – vector sum of the accelerations in the three directions (Xu et al. 2015). The total vibration method can also automatically take into account the possible vibrations in the X and Y directions (Dong et al. 2002), as well as the cross-axial responses on the hand–arm system. The vibration and grip force signals were input into a data acquisition and analysis system (B&K 3050/3053).

2.2. Test variables and procedures

The standard frequency weighting for the risk assessment of hand-transmitted vibration exposure approximately follows a reversed constant-velocity vibration curve (ISO 5349–1

2001). The biodynamic frequency weighting of the palm-wrist–arm also has a trend similar to the standard frequency weighting (Dong et al. 2006b). Therefore, this study used the constant velocity spectrum as a basis to compose the excitation spectra used in the experiments. Specifically, four discrete sinusoidal vibrations (10 Hz at 6.28 m/s^2, 16 Hz at 10.05 m/s^2, 25 Hz at 15.71 m/s^2 and 40 Hz at 25.13 m/s^2) were used as excitations in Experiment I, which share the same vibration velocity of 0.1 m/s. In Experiment II, a broadband random vibration spectrum ranging from 4 to 500 Hz was used as the excitation. The excitation spectrum includes a part of the spectrum (25–500 Hz) required for the standardised anti-vibration glove test (ISO 10819 2013). The remaining part is an extension of the standard spectrum from 25 to 4 Hz, with the same constant velocity as that (0.012 m/s) at 25 Hz in the standard spectrum.

In Experiment I, each subject was instructed not to apply any push force but to gradually increase the grip force from 0 to 150 N or his maximum grip strength if it is less than 150 N over a period of 30 s at an approximately constant rate (5 N/s). To help achieve the constant rate, a pacing programme was developed using LabVIEW software, which showed both the applied force and the desired force at every moment on a monitor (Figure 1). To assure no significant push force was applied, the push force was also monitored by a researcher. The subject was reminded to not apply any push force if a significant push force (>5 N) was observed. In this experiment, a total of 12 trials were completed (4 discrete frequencies × 3 replicates) for each subject. The test sequence of the four input frequencies was independently randomised among the subjects. The time histories of the accelerations and grip force were simultaneously measured at the sampling frequency of 4,096 Hz.

In Experiment II, each subject was tested under six randomised treatments: five grip-only actions (15 N, 30 N, 45 N, 60 N and 75 N) and one combined action (30 N grip and 50 N push). Three trials for each treatment were performed, and each trial lasted 20 s. In addition to vibration transmissibility, the apparent mass at the palm of the hand along the forearm direction was also simultaneously measured, which is the dynamic force at the palm-handle interface divided by the acceleration input to the palm (Dong et al. 2006a). The transmissibility and apparent mass were evaluated using B&K PULSE analyzer software, and the results were expressed in the one-third octave bands. While the directly measured apparent mass included the tare mass of the handle measuring cap, the tare mass determined from handle calibration tests (without hand coupling on the handle) was subtracted from the measured raw data to obtain the apparent mass at the palm of the hand (Dong et al. 2006a).

2.3. Calculations of vibration transmissibility

The time history of each acceleration measurement from Experiment I was used to calculate its root-mean-square (RMS) value for a given time duration (Δt), which was taken as the period of three sinusoidal vibration cycles for each frequency. Then, the total vibration or vector sum of the three axial accelerations measured at each location was calculated. The transmissibility was calculated by taking the ratio of the total vibration at each location and the total vibration measured at the handle. In Experiment II, the RMS acceleration spectra over 20 s for each of the predetermined grip forces were directly measured. These acceleration spectra were used to calculate the total vibration and transmissibility for each location.

2.4. Determination of the relationship between grip force and vibration transmissibility

In Experiment I, the time history of the force measured at the handle includes two components: the active grip force and the passive response force of the entire handle–palm-wrist–arm system. Because the frequency of the passive response force must be equal to that of the input vibration, this component can be removed by averaging the measured raw force (F_{Raw}) over the duration (Δt) for any number of full vibration cycles. In other words, the grip force ($F_{Grip\text{-}i}$) at any time (t_i) can be calculated from

$$F_{\mathrm{Grip}\_i} = \frac{\int_{t_i}^{t_i + \Delta t} F_{\mathrm{Raw}} \cdot dt}{\Delta t} \quad (1)$$

In this study, the average duration (Δt) was the same as that used for calculating the RMS values of the vibration accelerations. Because the force and motions were measured simultaneously in the experiment, and their calculations started at the same point in time, the grip force calculated using Equation (1) corresponds to the calculated vibration transmissibility. Then, their relationship was determined by plotting the resulting transmissibility values vs. grip force values. It should be emphasised that the grip force was not at any fixed value in Experiment I. For different trials, the starting point of the recording and the rate of increase of the force could not be exactly the same. As a result, the series of force values measured from one trial (e.g. 2.1, 5.4, 10.8, ……, 145 N) were usually different from those of another trial (e.g. 3.2, 5.6, 11.5, ……, 148 N). Without the same force basis, their corresponding transmissibility values cannot be directly averaged to determine the mean relationship for each subject or all the subjects. To overcome this difficulty, the relationship for each trial was fitted using a polynomial function; the resulting functions for all the trials were used to calculate the transmissibility values for a given force so that the mean transmissibility for the same force can be calculated.

For the random vibration exposure in Experiment II, the force-transmissibility relationship for each frequency was directly identified from the experimental data measured at discrete grip forces. The relationship was compared with that measured in the sinusoidal vibration exposure.

2.5. Statistical analyses

Whenever applicable, a general linear model for the analysis of variance (ANOVA) was used to determine the significance of the effects of test conditions (frequency, force, measurement location and trial sequence) on the dependent variables (transmissibility and apparent mass). Whenever necessary, stratified ANOVAs were also performed to determine the significance of the factors on the dependent variables in a specific frequency range. The ANOVAs were performed using SPSS statistical software (IBM SPSS Statistics, version 24). Differences were considered significant at the $p < 0.05$ level.

3. Experimental results

3.1. Results from experiment I

As examples, Figure 3 shows the relationship between the grip force (F) and the vibration transmissibility (T) measured at each of the three locations on the arm of a subject, together with their regression curves fit with a six-degree polynomial function ($T = a_0 + a_1F^1 + a_2F^2 + a_3F^3 + a_4F^4 + a_5F^5 + a F^6$; a_i – the coefficient for the ith term). The R^2-values of the regressions were in the range of 0.983–0.998. Several other functions (polynomial functions with less than six power degrees, logarithmic function and power function) were also tested for modelling the relationship, but their fits were not as good as the six-degree polynomial function. Therefore, this polynomial function was used for all the regression modelling applied in this study to calculate the mean relationship. While the maximum grip force designed for the experiment was 150 N, a subject might not reach this force value or go beyond it near the end of the measurement duration (30 s). As a result, the maximum grip force varied across each trial, as is also shown in Figure 3. The lowest maximum grip force among the trials was used as the ending point for the averaging process of the data in the following presentations.

To demonstrate the individual differences, Figure 4 shows the force-transmissibility relationships measured at the wrist under 16 Hz sinusoidal excitation with the nine subjects. Obviously, the relationship varies significantly among the subjects. Variability of subjects was considered a random factor in the statistical analyses of this study. Test data from all three replicate trials under each test conditions from the nine subjects were included in the statistical analysis.

Figure 5 shows the mean relationship between grip force and transmissibility. The force-transmissibility relationship strongly depended on the measurement location and the vibration frequency. However, the vast majority of them also had some common features: (i) the transmissibility at each given frequency increased with the increase in the grip force before reaching a maximum level; (ii) the transmissibility then tended to plateau or decrease when the grip force was further increased. Additionally, this transition force value increased with an increase in the vibration frequency. As also shown in Figure 5, there were intersections among some relationship curves. Statistical analyses confirmed that the interaction between the grip force and vibration frequency was significant ($F_{69,\ 7326} = 8.79$, $p < 0.001$).

3.2. Results from experiment II

Figure 6 shows the mean vibration transmissibility spectra of the nine subjects, which were measured with different hand forces while exposed to random vibration. At frequencies above 100 Hz, the transmissibility values are less than 0.22 at the wrist and less than 0.1 at the forearm and upper arm. Therefore, the transmissibility spectra of major interest for this study lie below 100 Hz, and the spectra in this frequency range were considered in the statistical analyses. Consistent with that observed in Experiment I, the vibration transmissibility was significantly affected by the applied hand force, measurement location and vibration frequency, as listed in Table 2. Increasing the grip force generally increased the peak frequency at the wrist and forearm, as shown in Figure 6(a, b); this shifted the entire transmissibility spectrum towards a higher frequency range. As a result, the response functions measured with different hand forces intersected each other. The statistical analysis confirmed that the interaction between the force and frequency was significant. Below the transition frequencies, the transmissibility for a lower grip force was generally higher than that for a greater grip force; however, this trend was reversed at higher frequencies. As shown in Figure 6(c), the force effect on the first peak frequency of the upper arm transmissibility was not obvious, but the transmissibility above 20 Hz generally increased with the increase in the grip force ($F_{5, 926} = 105.2$, $p < 0.001$).

As also shown in Figure 6, the transmissibility measured under the combined 30 N grip and 50 N push was very similar to that measured under the 75 grip-only condition at frequencies higher than 25 Hz. This is because the effective force at the palm under the combined action (80 N) is close to that of the 75 N grip-only action. However, this did not hold true below 25 Hz, as the transmissibility values measured at the wrist and forearm for the combined condition below this frequency were significantly lower than those for the 75 N grip-only condition ($F_{1, 626} = 34.7$, $p < 0.001$).

The relationships between grip force and vibration transmissibility for each frequency can also be determined from the random test data shown in Figure 6. For example, the transmissibility values on the wrist at 25 Hz for 15 N, 30 N, 45 N, 60 N and 75 N grip force were 1.02,1.43, 1.71, 1.78 and 1.88, respectively. For a direct comparison, the relationships for the four frequencies (10, 16, 25 40 Hz) derived from the random test data are plotted in Figure 7 (markers with thin lines), together with those measured under sinusoidal excitations (thick lines). Their basic trends are consistent. Their values are also comparable; in many cases, the data from these two experiments almost overlap.

Figure 8 shows the apparent mass measured at the palm of the hand, together with the mechanical impedance derived from the apparent mass (impedance = apparent mass × angular frequency) (Dong et al. 2013b). The basic shape of the apparent mass is similar to that of the transmissibility spectra measured on the upper arm shown in Figure 6(c), especially in the first resonant frequency range. The second resonance in the driving-point response functions can be more obviously observed in the impedance shown in Figure 8(b), which is more correlated with the resonance of the transmissibility spectra measured at the wrist shown in Figure 6(a). The comparison of Figures 6 and 8 also indicates that the effects of the hand force on these two types of frequency response functions were different. While increasing the effective palm force did not always increase the transmissibility, it increased the apparent mass or impedance at almost every frequency. The palm contact force (80 N) for the combined condition was the highest among the tested conditions; it corresponded to the highest level in the entire frequency range of concern in this study.

4. Discussion

For the first time, the direct relationship between grip force and vibration transmissibility of the wrist–arm system were determined in this study. The relationship, together with the driving-point response functions and vibration transmissibility of the system measured in this study, can be used to enhance the understanding of the biodynamic response of the system. They also provide useful information on how hand forces can be taken into account in hand-transmitted vibration risk assessments.

4.1. The effects of hand coupling force on the vibration biodynamic responses

The grip and push actions cause changes of the stiffness, damping and effective mass of the hand–arm system and the hand-handle coupling conditions. Because the bio-dynamic response functions are combined measures of these dynamic properties and conditions (Dong, Welcome, and Wu 2005; Dong et al. 2013a), these functions must be affected by the hand forces. The driving-point biodynamic response function depends on the dynamic force and acceleration acting at the interface between the hand and handle. Increasing the grip force increases both the stiffness and effective mass of the system as well as the coupling stiffness. This explains why increasing hand forces increased the apparent mass and impedance, as shown in Figure 8. The combined grip and push actions not only increased the palm contact stiffness but also brought about a greater effective mass from the upper arm. This explains why it corresponds to the highest apparent mass and impedance, as shown in Figure 8. Because more vibration can be effectively transmitted to the upper arm at frequencies below 25 Hz (Adewusi et al. 2010; Xu et al. 2017), the influence of the upper arm on the apparent mass was greater at the low frequencies than that at higher ones.

Different from the force effect on the apparent mass and impedance, the effects of the hand forces on the transmissibility are complex, as shown in Figures 5 and 6. This is because the effective mass of the system and the hand coupling stiffness affected by the hand forces have opposite effects on the resonant frequency of the system (Harris 1995). The final result depends on their combined effect. As shown in Figure 6, the resonant frequency was about 8 Hz under the 15 N grip force, and it is the same at the wrist, forearm and upper arm. This suggests that the entire hand–arm system moved approximately in phase in this resonance. When the grip force was increased to 30 N, the resonant frequency was increased to 16 Hz at the wrist and 12.5 Hz at the forearm. This suggests that the grip force primarily affected the hand coupling stiffness, as it is an essential factor that determines the resonant frequencies at these locations (Dong et al. 2007, 2008). Further increasing the grip force should have further increased the resonant frequencies, but the peak frequency at the forearm appeared to remain unchanged above 30 N. This may be partially because the change of the resonant frequency cannot be clearly expressed in the one-third octave bands spectra. This may also be because increasing the grip force increases the effective mass of the system involved in the response, which may reduce the effect from the increased coupling stiffness on the resonant frequency.

The grip force is generated primarily by the muscles in the forearm. Then, the grip action should not substantially affect the properties of the upper arm and its connecting tissues. If the fundamental resonance of the upper arm depends primarily on these biodynamic properties, the change of the grip force should not obviously affect the first resonant frequency of the upper arm. The results shown in Figure 6(c) support this hypothesis. This phenomenon is also consistent with that observed in a previous study (Xu et al. 2015).

As above-discussed, the combined grip and push actions must increase the effective mass of the system. Because the second resonant frequency depends largely on the effective mass and the palm contact stiffness (Dong et al. 2008), the resonant frequency of the transmissibility at the wrist (16 Hz) was lower than that in the 75 N grip only action, although the effective palm contact force (80 N) in the combined action is larger, as shown in Figure 6(a). This also affected the transmissibility on the forearm at frequencies below 25 Hz, as shown in Figure 6(b). Because the vibration transmitted to the upper arm decreases with the increase in frequency, the influence of the upper arm on the system response becomes less and less important when the frequency was above 25 Hz. Then, similar palm contact forces should correspond to similar transmissibility responses at the wrist and forearm. This explains why the transmissibility measured in the combined action was close to that measured in the 75 N grip action, as shown in Figure 6(a, b).

4.2. The effect of vibration type on the vibration transmissibility

The results of this study demonstrate that the relationship between the grip force and the transmissibility measured on the human arm under every sinusoidal excitation is very similar to that measured under the random excitation, as shown in Figure 7. Previous studies reported that the mechanical impedances measured under two different excitations were similar (Kihlberg 1995); additionally, it has been shown that glove transmissibility values measured with different excitations were similar (Rakheja et al. 2002; Welcome et al. 2012). Furthermore, previous results have shown vibration transmissibility measured on the surface of the human arm to be similar across two different levels of random excitations (Adewusi et al. 2010). These observations suggest that the vibration biodynamic response functions are largely independent of the test input vibrations. This further suggests that the vibration biodynamic responses of the hand–arm system can be reasonably predicted using these response functions for many cases when the vibration accelerations on tool handles are available. This supports the use of the biodynamic response functions to derive the biodynamic frequency weightings (Dong et al. 2006b, 2012).

4.3. Potential applications of the experimental data

The specific biodynamic method for taking into account the hand forces in risk assessments of human arm vibration exposures should depend on the type of vibration effect or disorder. If the vibration power absorption is associated with vibration-induced white finger (VWF), as hypothesised by some researchers (Cundiff 1976; Lidström 1977), the hand force-specific impedances shown in Figure 8(b) may be used to derive the biodynamic frequency weighting (Dong et al. 2006b, 2012). Dong et al. (2006b) demonstrated that the biodynamic frequency weightings derived from such impedances or those for the entire hand–arm system are very similar to the frequency weighting defined in the standard for risk assessment (ISO 5349–1 2001). If the current frequency weighting cannot reliably predict VWF, the biodynamic frequency weightings are unlikely to do a better job. For this reason, Dong et al. (2012) proposed to use the location-specific vibration power absorption to derive the biodynamic frequency weighting for each location. The experimental data presented in this paper cannot directly be used to derive such weightings, but they can be used to help develop a model of the hand–arm system to predict the location-specific impedances or vibration power absorptions (Dong et al. 2013a).

The vibration force is likely to be transmitted primarily through the joints and bones due to their high stiffness, but the vibration power absorption is likely to be dominant in the soft tissues of the system due to their high damping properties. Therefore, we hypothesise that joint injuries and bone damage are unlikely to be primarily related to the power absorption of the entire hand–arm system, but vibration-induced bone and joint problems should be more associated with the applied hand forces and the overall biodynamic forces induced from shocks and vibrations. Because the biodynamic forces can be directly estimated from the apparent mass and the vibration acceleration measured on a tool handle (Dong, Welcome, and Wu 2005), the hand force-specific apparent mass shown in Figure 8(a) may be used to derive the hand force-specific biodynamic frequency weightings to study the injuries and disorders of the joints and bones.

Some researchers have also hypothesised that the location-specific vibration power absorption is associated with vibration perception (Dong et al. 2012; McDowell et al. 2007). Furthermore, vibration may also influence muscle functions (Martin and Park 1997; Radwin, Armstron, and Chaffin 1987). We also hypothesise that the local tissue vibration power absorption may play an important role in determining such a physiological effect. While it is currently difficult to accurately quantify the local power absorption, the location-specific vibration acceleration may be used to approximately represent the local power absorption. Then, the hand force-transmissibility relationship shown in Figure 5 and the hand force-specific vibration transmissibility spectra shown in Figure 6 can be used to derive the hand force-specific biodynamic frequency weightings to study these vibration effects.

4.4. Major limitations of this study

The biodynamic response functions may vary with many factors. While it is very difficult to consider all the possible combinations of these factors in the experiments, this study only took into account some combinations of hand forces, vibration frequencies and vibration types in the experiments. The hand–arm postures and vibration directions may significantly affect the responses (Adewusi et al. 2010; Dong et al. 2013a). Only one posture and one vibration direction were considered in this study. The measured data may not accurately represent the system responses for the working postures that are largely different from that used in this study and the vibration exposure not primarily along the forearm direction. The number of subjects used in this study was also limited. Hence, the applications of the results presented in this paper require special caution if the working conditions and individual anthropometry are substantially different from the experimental conditions used in this study.

5. Conclusion

This study found that the effects of hand forces on the biodynamic responses depend on the specific type of response, vibration frequency and location on the arm. Increasing the force acting at the palm of the hand increases the palm apparent mass or impedance. This feature suggests that the hand force can be taken into account when quantifying the vibration exposure by deriving a frequency weighting based on the palm force-specific apparent mass if the vibration-induced injury or disorder is associated with the applied hand forces and the biodynamic forces.

The hand forces affect the vibration transmissibility on the system in a complex manner. The experimental results confirm that increasing the hand forces generally increases the resonant frequencies of the wrist and forearm, but the applied forces do not have substantial effects on the resonant frequency of the upper arm in the force range considered in this study. At a fixed frequency, the transmissibility increases with an increase in the grip force until the force reaches a certain value. Then, the transmissibility starts to reduce marginally or remains more or less the same when the grip force is further increased. Additionally, this transition force value increases with increases in the vibration frequency. The experimental results also demonstrate that the vibration transmissibility on the human palm–wrist–arm system does not change substantially with any change in the vibration excitation. This feature suggests that the local tissue vibrations in the system can be estimated using the vibration transmissibility measured in the laboratory when the vibration accelerations of tool handles are available. If a vibration-induced physiological effect or health effect is associated with the local tissue vibration, the hand force-specific transmissibility may be used as a basis to derive the required force weighting and biodynamic frequency weighting for quantifying the vibration exposure to study the health effects.

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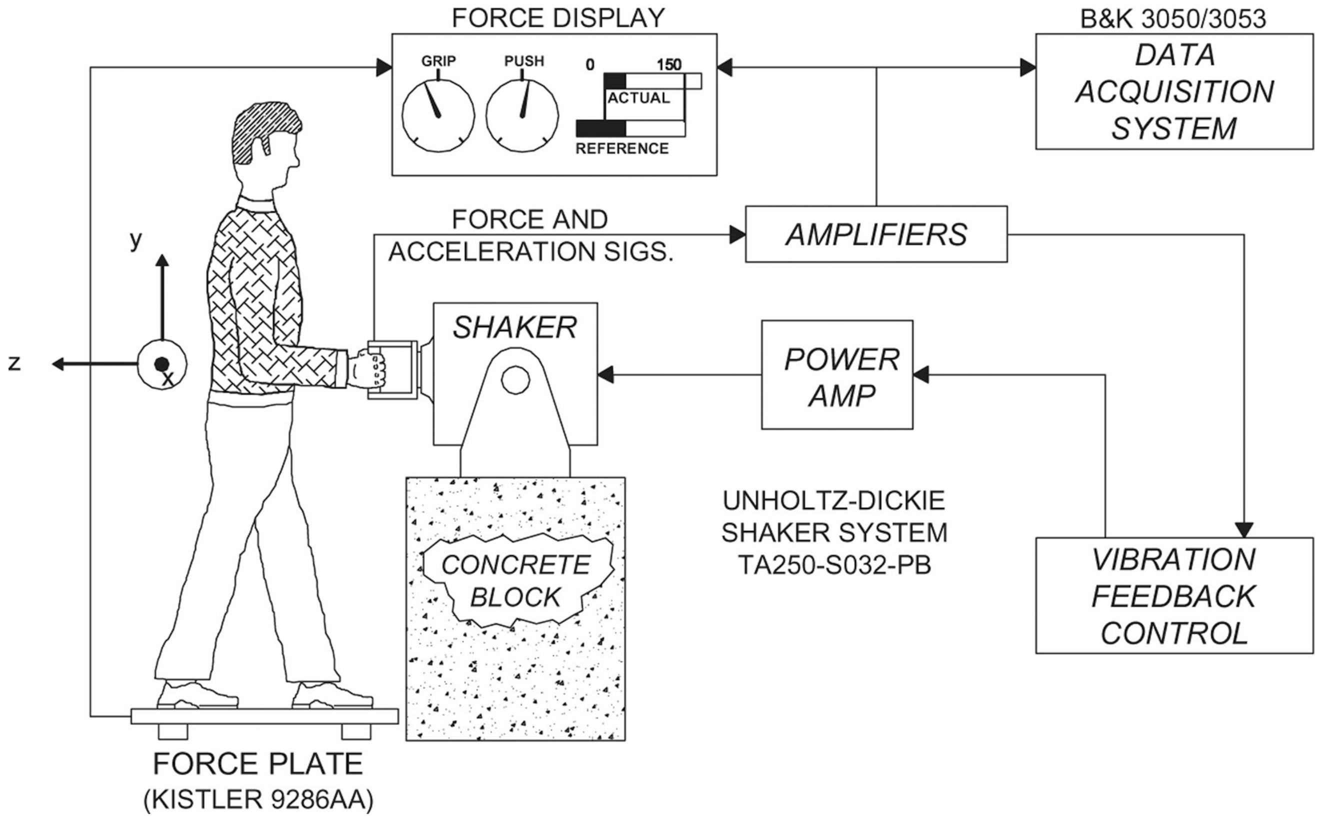

Figure 1.
The test set-up that includes a closed-loop controlled 1-D hand-arm vibration test system, a vibration and response measurement system and grip/push force measurement and display systems.

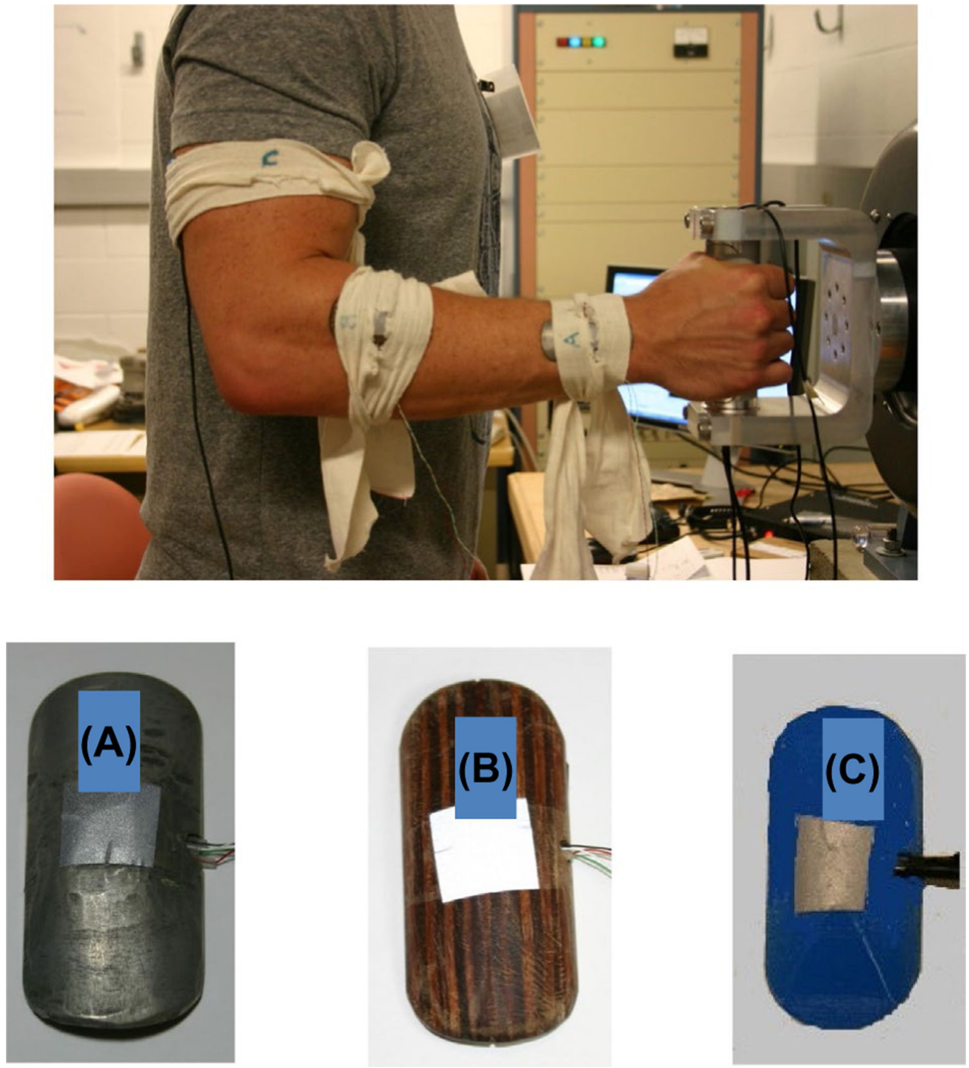

Figure 2.
A view of a subject employing the prescribed posture and gripping the instrumented handle of the 1-D hand-arm vibration test system, with three measuring adapters (A, B and C) wrapped at the wrist, forearm and upper arm.

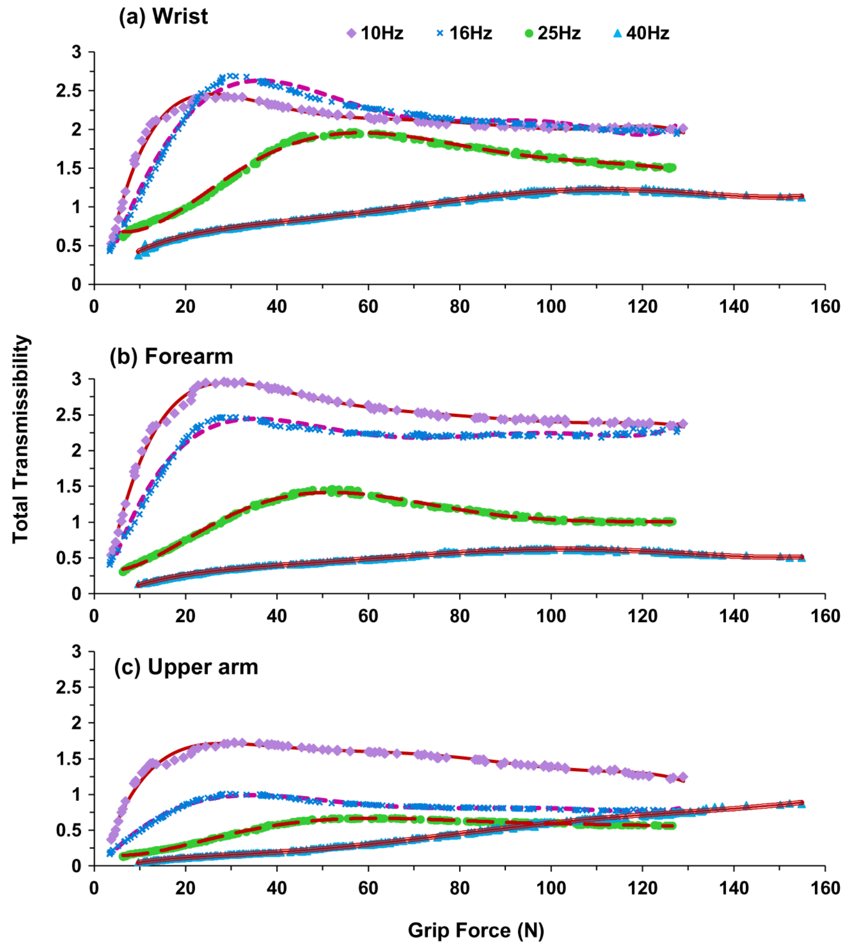

Figure 3.

Examples of the force transmissibility relationships determined from the experimental data (dotted lines) measured in a trial with a subject, together with their regression curves (continuous lines): (a) wrist; (b) forearm; (c) upper arm.

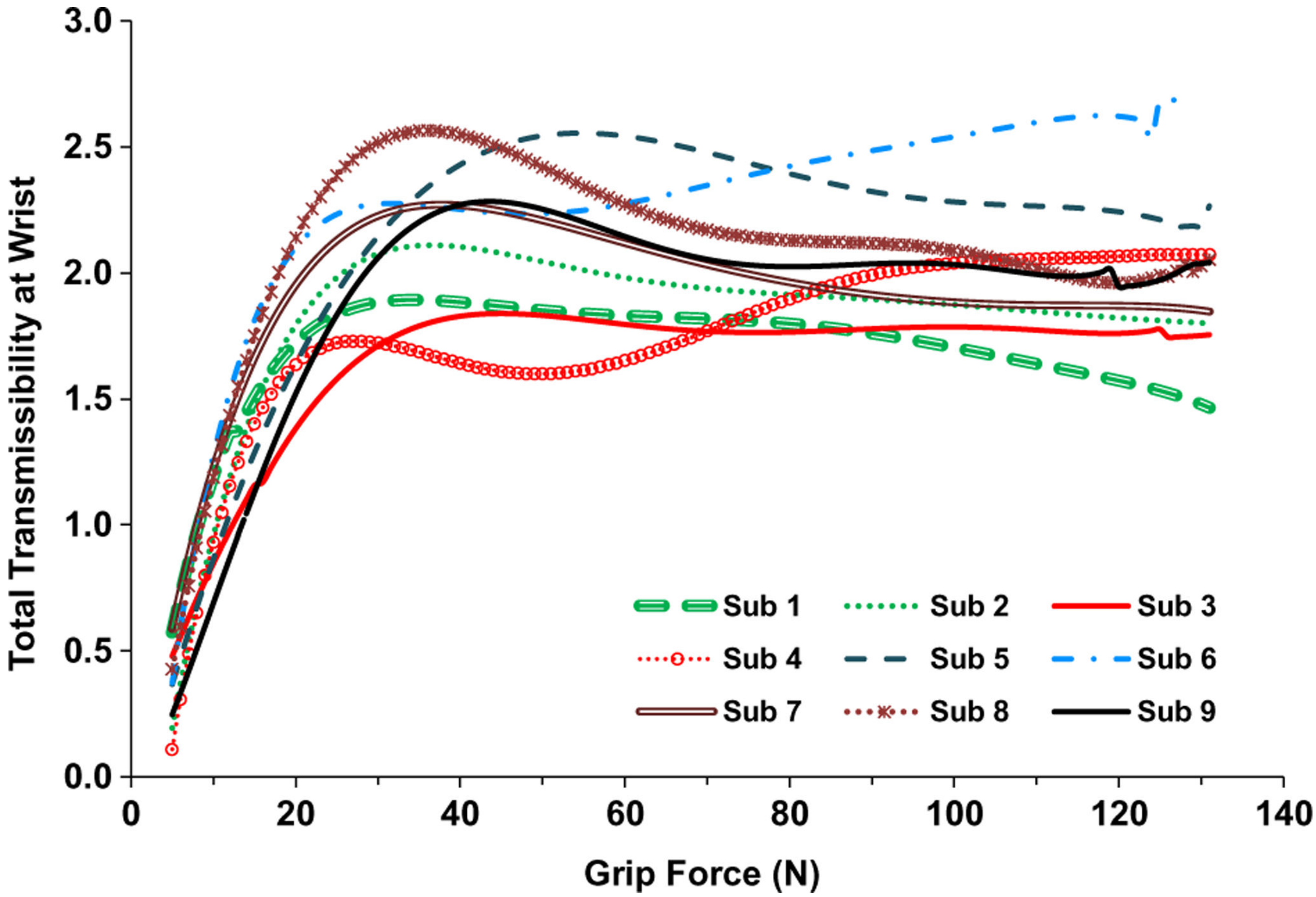

Figure 4.
Variations of the force transmissibility relationships at the wrist at 16 Hz among the nine study participants.

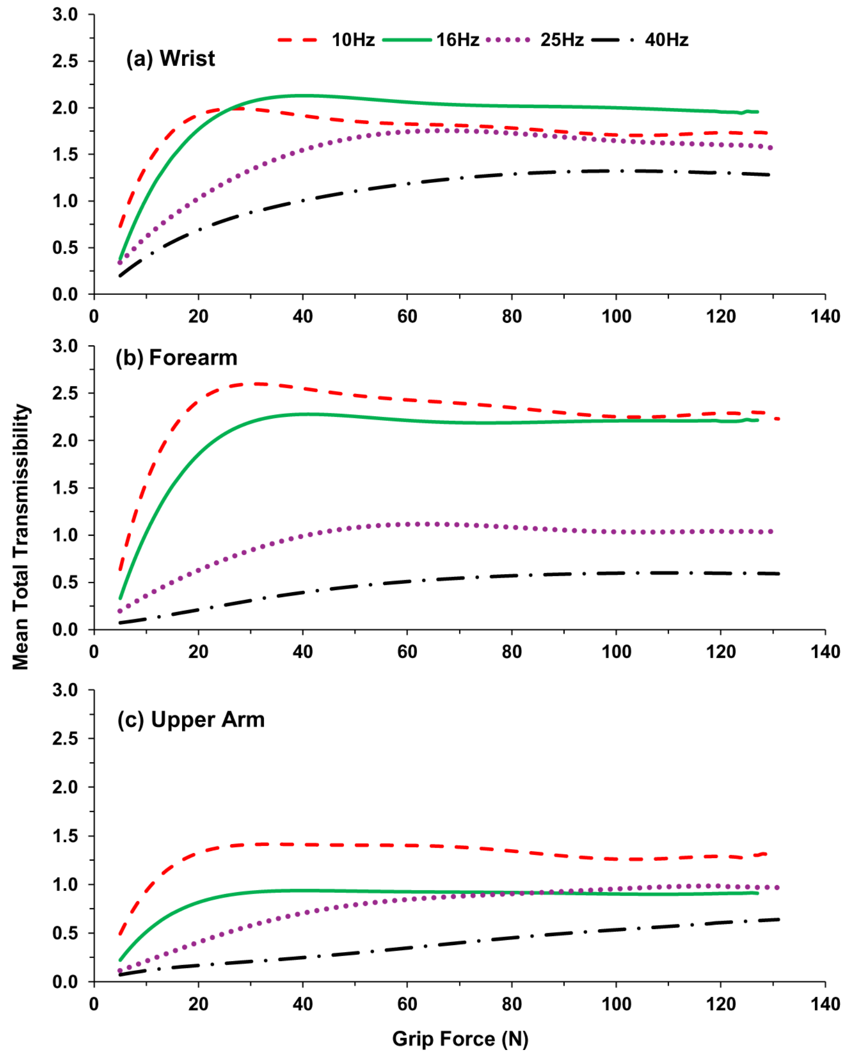

Figure 5.

The mean relationship between grip force and vibration transmissibility measured with nine subjects: (a) wrist; (b) forearm; (c) upper arm.

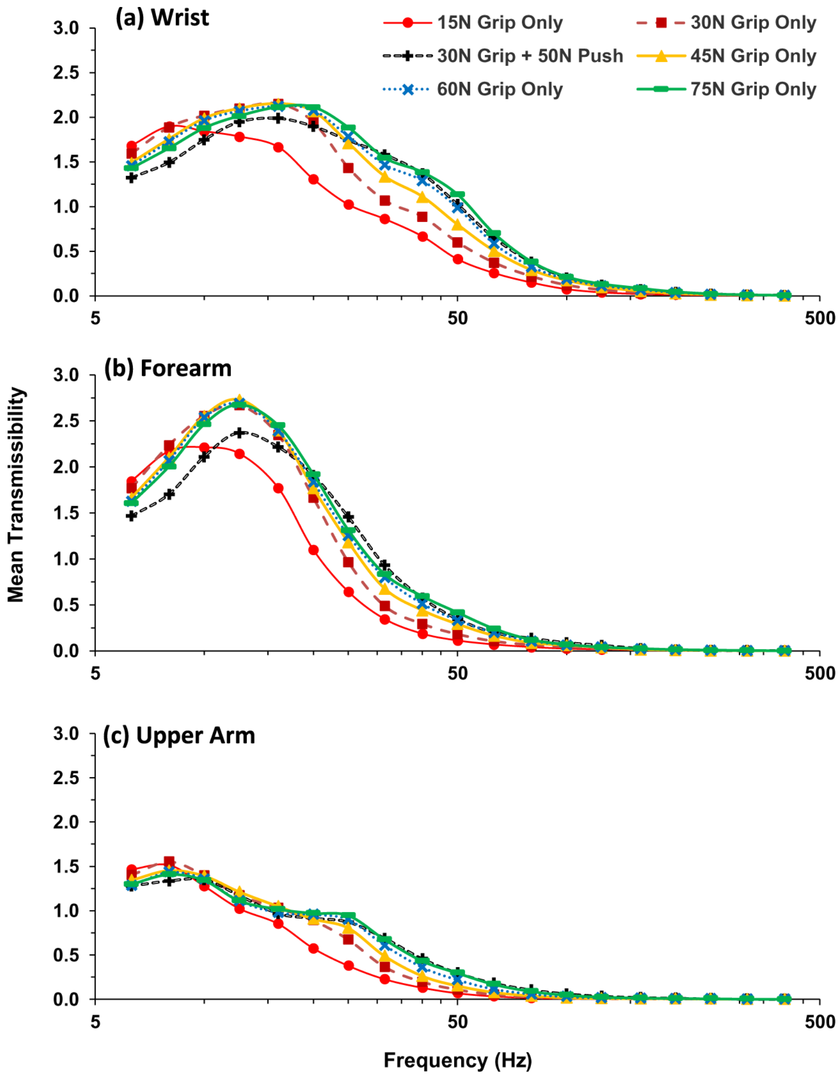

Figure 6.

The mean vibration transmissibility of the nine subjects measured at different hand forces: (a) wrist; (b) forearm; (c) upper arm.

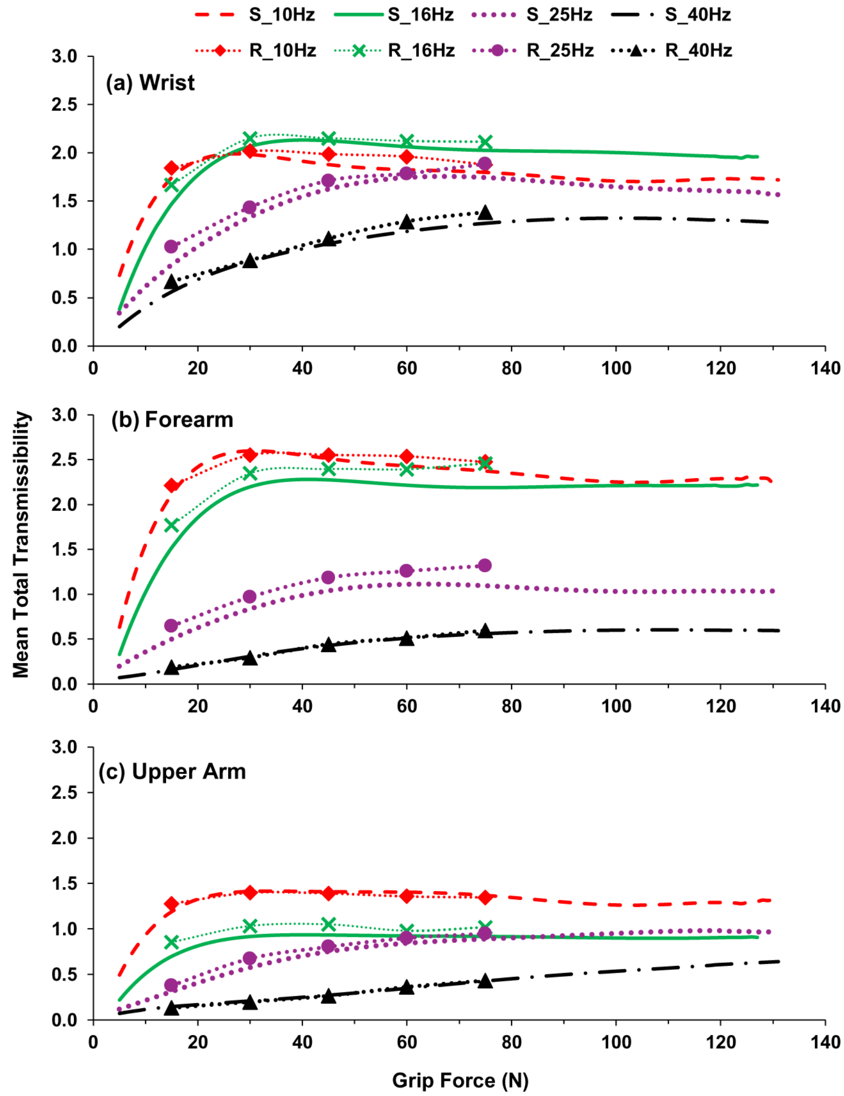

Figure 7.

Comparisons of the hand force-transmissibility relationships measured with sinusoidal (**S**) and random (**R**) vibrations: (a) wrist; (b) forearm; (c) upper arm.

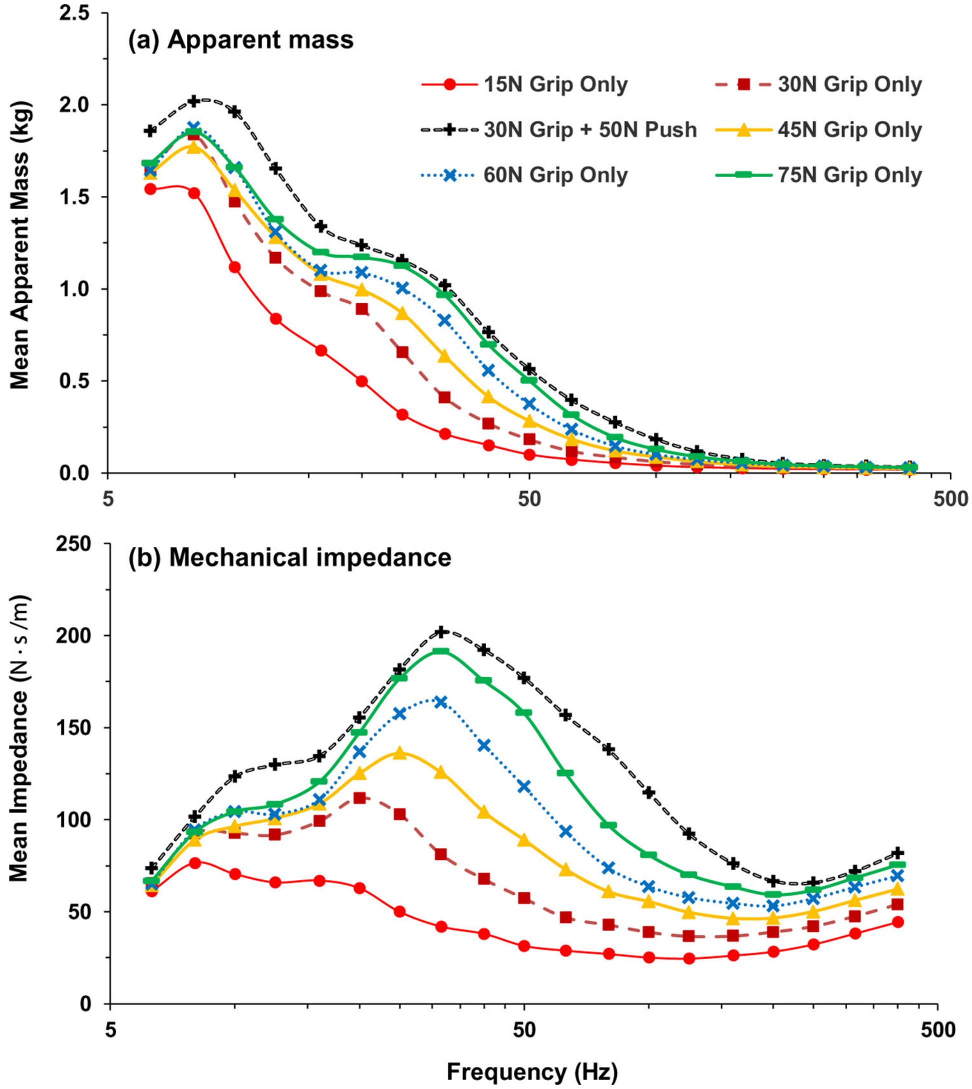

Figure 8.

The mean driving-point response functions of the nine subjects measured at the palm of the hand at different hand forces: (a) apparent mass; (b) mechanical impedance.

Table 1.

Subject anthropometry (hand length = tip of middle finger to crease at wrist; hand circumference measured at the metacarpals; forearm volume was measured using a water displacement method)

Experiment I/II					
Subject	**Height (cm)**	**Weight (kg)**	**Hand length (mm)**	**Hand circumference (mm)**	**Forearm volume (ml)**
1	181.5	78.1	187	218	1560
2	176.8	69.3	179	193	1180
3	177.5	136.7	193	231	2465
4	175.5	67.9	195	215	1240
5	183.5	110.4	188	240	1965
6	168.5	51.3	179	190	963
7	183.5	63.8	182	193	1125
8	174.75	93	185	206	1620
9	189.5	86.4	206	212	1870
Mean	179.0	84.1	188	211	1554
SD	6.2	26.3	9	17	484

Table 2.

ANOVA table for vibration transmissibility measured at the subjects' wrist, forearm and upper arm for six different hand coupling forces in experiment II.

	Degree of freedom	Sum square	Mean square	*F* value	Pr (> *F*)
Subject	8	81.8	10.2		
Location	2	453.8	226.9	1060.9	< 0.001
Trial	2	0.0	.000	.0027	0.9973
Force	5	57	11.4	80.7	< 0.001
Frequency	11	2309.5	210.0	1486.8	< 0.001
Force × Frequency	55	86.1	1.6	11.1	< 0.001
Error	5748	811.7	0.14		