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An Evaluation of the Methods for Deriving Representative Frequency Response Functions of the Human Whole-body System

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Abstract: The biodynamic response functions of the human whole-body system measured with subjects participating in an experiment are commonly arithmetically averaged and used to represent their mean response functions in many studies. The reported means were further averaged to form the reference means for standardization and various applications. The objectives of this study are to clarify whether this response-based averaging process could significantly misrepresent the characteristics of the original functions, and to explore appropriate methods for deriving representative functions. A set of reported mechanical-equivalent models for 12 subjects was used to derive the vertical and fore-and-aft cross-axis response functions expressed in apparent mass. The response-based average was directly compared with the response derived from a property-based derivation method. This study found that the response-based average could differ from the property-based mean response by more than 30%, especially in the fore-and-aft cross-axis response functions. This study also theoretically demonstrated that the discrepancies result from the non-linear relationship between the apparent mass and the properties of a dynamic system. Therefore, the discrepancies depend on the variability of the subjects' dynamic properties. Practically, the discrepancies in the vertical response could be reduced to an acceptable level (e.g., <10%) if a sufficient number of subjects with similar body weights are selected or grouped in the measurement. However, it is very difficult to reduce the discrepancies in the fore-and-aft cross-axis to such a level. While more demanding than the response-based method, the property-based method is theoretically more reliable for deriving the representative response functions for each axis.

Key words: Biodynamic response, Averaging method, Whole-body vibration, Modeling of whole-body vibration exposure

Introduction

The vibration-induced biodynamic response of the human whole-body system can be expressed in many forms such as vibration-induced stress, strain, power absorption, force, and motion. The biodynamic response is important for understanding vibration-induced psychophysical responses and health effects, for helping to develop more effective anti-vibration devices, and for improving the methods used to assess the risks associated with whole-body vibration exposure[1–4]. The dynamic response is most frequently studied by examining the driving-point frequency response functions such as apparent mass and mechanical impedance and the vibration transmissibility functions on the body[2–4]. Because these response functions are individual-specific, and they usually vary in a large range[5–8], it is frequently desired to derive representative response functions for a group of subjects, such as those participating in a given study. The unweighted arithmetic average is usually used for such a representation. The reference mean functions recommended in an international standard (ISO-5982, 2001)[2] were synthesized by further averaging several sets of reported means[3]. Presented computer models of the whole-body system are also usually developed or validated based on such averages[2, 3]. However, a few researchers have indicated that such a response-based averaging could significantly misrepresent the response functions[9–11]. For example, it could artificially increase the number of resonant peaks and reduce the principal resonance value[9–11]. These observations cast some doubt on the validity of this conventional mean derivation method.

Alternatively, the representative response function can be derived from a biodynamic property-based approach[8–11]. With this approach, dynamic properties of each subject are estimated using a mechanical-equivalent model that can be constructed based on the response function, the vibration transmissibility, or both of these biodynamic measures. Then, the biodynamic properties of the representative virtual subject are determined by computing averages for each of the properties of all subjects participating in the study. The response functions derived from the mechanical-equivalent model with the averaged properties are used to represent the study population's response functions.

Whereas the response-based averaging method is simple and

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can be easily applied by most researchers, the property-based derivation method can be time-consuming and technically difficult, especially when a complex model structure is required. The simpler response-based method is certainly the first choice if the results generated by these two approaches are similar. For example, the inter-subject and intra-subject variations of the biodynamic responses measured under the same testing conditions in the same laboratory are usually greater than 10% in the resonance frequency range[5–8]; the variations of the inter-laboratory mean data are also usually greater than 10%[3]; hence, a percent difference of less than 10% between the two approaches at some frequencies is unlikely to be important for many practical applications. Although issues with the response-based method have been raised[9, 11], it is unclear whether the specific averaging discrepancies are beyond an acceptable level. It is also unclear how such potential discrepancies can be reduced by taking some feasible measures in study designs or during data processing in the study of the whole-body biodynamic response. Therefore, a more comprehensive understanding of these potential discrepancies and their influencing factors is required.

The objectives of this study are to clarify whether the conventional response-based averaging process could significantly misrepresent the characteristics of the original responses, to identify the major influencing factors of response-based averaging misrepresentations, and to explore appropriate procedures or methods for deriving a representative biodynamic response. A methodology for a systematic analysis of the response-based averaging method has been proposed and used to examine the averaging effects in the derivation of representative response functions of the human hand-arm system[10]. The basic procedures of this methodology were applied in the current study. Similar to those in the previously reported study, the hypotheses tested in the current study were as follows: (a) the response-based averaging process could introduce some errors in deriving the mean response functions, but the significance of the misrepresentations depends on the specific biodynamic characteristics of individual response functions; (b) because the human body is usually heavily damped, the misrepresentations produced by the response-based averaging method are not substantial in the major vibration modes of concern; (c) misrepresentations can be controlled to an acceptable level if the number of subjects selected based on certain criteria is sufficiently large; and (d) the conventional response-based averaging method could be problematic in some cases, but it is acceptable if properly applied under certain conditions.

Methods

Fundamental concept and basic approach

The driving-point frequency response functions such as apparent mass, mechanical impedance, and dynamic stiffness of the human body are mathematically defined as the driving-point responding force divided by the input acceleration, velocity, and displacement, respectively. They are very similar to the definitions of mass based on Newton's second law, the viscous damping of an energy absorber, and the stiffness of a spring, respectively. The vibration transmissibility function is also a ratio of the responding motion and the motion input to the body. If the human body is treated as a linear system for a given test condition, as is usually the case in the mechanical-equivalent modeling of the human body, all these response functions are independent of any input excitation, or they are exclusively dependent on the biodynamic properties of the human body. Therefore, it is very reasonable to generally define a representative response function as the response of a virtual subject who exhibits the average biodynamic properties (e.g., the mass, damping, stiffness, and their distributions and connections) of all subjects who participated in an experiment, as proposed in a previous study[10]. The method based on this definition is termed as the biodynamic property-based derivation method in this study.

With this definition, the critical issue for determining the representative response functions becomes how to quantify the biodynamic properties of the virtual subject. An efficient approach is to take the mean values of the properties of the subjects participating in a study as those of the virtual subject. Therefore, it is necessary to quantify the biodynamic properties of each subject. However, for many practical reasons, it is not feasible to directly measure the biodynamic properties of each local tissue or body part of each human subject participating in a study. Alternatively, the overall biodynamic properties of the human body can be estimated using the mechanical-equivalent approach based on the measured frequency response functions, which was the approach used in the current study.

Also based on this definition, the difference between the response-based mean function and the property-based mean function can be considered as the error of the response-based averaging method. However, if we would compare the experimentally-measured mean with the property-based modeling mean, the error cannot be clearly identified because of the coupling effects of the response-based averaging effects and the modeling residuals. Therefore, we examined the difference between the modeling response-based mean and the modeling property-based mean. Specifically, the model for each individual was first determined using the mechanical-equivalent approach. Using the modeling responses of all the subjects, the response-based mean was calculated. With the modeling properties of all the subjects, the mean properties of the virtual subject were calculated, which were further used to calculate the property-based mean. Because the response-based mean and the property-based mean are from the same models, their difference must exclusively reflect the arithmetic averaging effects.

Generation of error functions

The specific comparison procedure usually involves four steps[10]. As the first step, the mechanical-equivalent models for the subjects can be developed based on the experimentally-measured biodynamic responses of the subjects. For the purpose of the present study, the subject models presented in the recent study by Nawayseh and Griffin[12] were directly used, which saved the work of the first step. The reported model structure is shown in Fig. 1, and the parameters of the individual subject models are listed in Table 1. This set of models was used to simulate the vertical response and the fore-and-aft cross-axis response. The associated equations of motion are expressed as follows:

$$\begin{bmatrix} M_3 & 0 & 0 \\ 0 & M_1+M_2+M_3 & M_2 e\sin\alpha \\ 0 & M_2 e\sin\alpha & J \end{bmatrix}\begin{Bmatrix} \ddot{z}_3 \\ \ddot{x}_1 \\ \ddot{\theta} \end{Bmatrix}+\begin{bmatrix} C_{3z} & 0 & C_{3z}e\cos\alpha \\ 0 & C_{1x} & 0 \\ C_{3z}e\cos\alpha & 0 & C_2+C_{3z}e^2\cos^2\alpha \end{bmatrix}\begin{Bmatrix} \dot{z}_3 \\ \dot{x}_1 \\ \dot{\theta} \end{Bmatrix}$$
$$+\begin{bmatrix} K_{3z} & 0 & K_{3z}e\cos\alpha \\ 0 & K_{1x} & 0 \\ K_{3z}e\cos\alpha & 0 & K_2+K_{3z}e^2\cos^2\alpha \end{bmatrix}\begin{Bmatrix} z_3 \\ x_1 \\ \theta \end{Bmatrix}=\begin{Bmatrix} K_{3z}z_b+C_{3z}\dot{z}_b \\ 0 \\ e\cos\alpha(K_{3z}z_b+C_{3z}\dot{z}_b-M_2\ddot{z}_b) \end{Bmatrix}. \quad (1)$$

The apparent mass response was calculated using these equations[12]. The results were expressed in the frequency domain.

As the second step, the representative virtual subject model was developed by taking the averages of the biodynamic properties of the individual models. Specifically, each parameter of the virtual subject model (P_{i_Mean}) was calculated from

$$P_{i\_\mathrm{Mean}}=\frac{1}{n}\sum_{j=1}^{n}P_i \quad (2)$$

where the P_i is the corresponding parameter value of the model for each subject, and n is the number of subjects

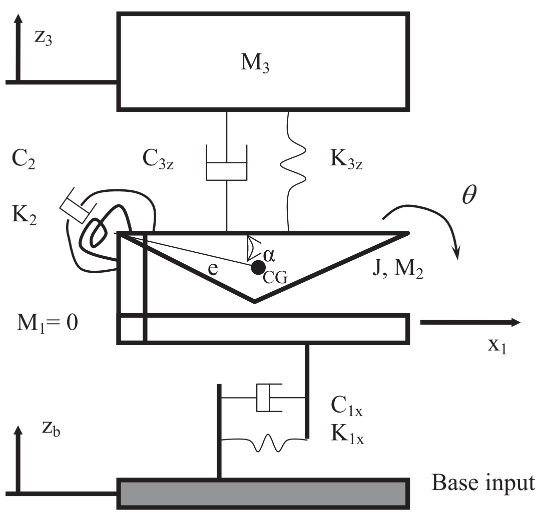


Fig. 1. A model of whole-body system for simulating the vertical biodynamic response and the fore-and-aft cross axis biodynamic response reported by Nawayseh and Griffin[12].

considered in the average. The property-based mean apparent mass ($M_{\mathrm{Mean\_Property}}$) was calculated using this virtual subject model.

As the third step, the response-based average ($M_{\mathrm{Mean\_Response}}$) of the individual subject modeled responses (M_{k}) determined in the first step was calculated using the following formula:

$$M_{\mathrm{Mean\_response}}(\omega)=\frac{1}{n}\{\sum_{k=1}^{n}M_{k\_\mathrm{Real}}(\omega)+j\sum_{k=1}^{n}M_{k\_\mathrm{Imaginary}}(\omega)\} \quad (3)$$

Finally, the discrepancies (ΔM) between the property-based means and the response-based means were evaluated from

$$\Delta M(\omega)=|M_{\mathrm{Mean\_property}}(\omega)-M_{\mathrm{Mean\_response}}(\omega)| \quad (4)$$

Statistical analyses

To help analyze the role of the number of subjects in the response-based averaging process, the error functions expressed in Eq. (4) for all the possible combinations of 2, 4, 6, 8, 10, and 12 subjects out of the 12 study subjects were created. These error functions were used to identify the maximum error (ΔM_{i_Max}) for each combination of subjects. The root-mean-square (RMS) value of each error function (ΔM_{i_RMS}) in the frequency range of concern (0.5 to 10 Hz) was also calculated. The maximum error at each frequency (ΔM_{ω_Max}) among the combinations for each given number of subjects was also identified.

In addition to the number of subjects, the peak frequency distribution and the sharpness of the resonance responses have also been identified as major factors that could influence discrepancies between the response-based means and the property-based means[10]. The roles of these response curve characteristics were also examined in the current study by performing several correlation analyses among the above-mentioned error parameters and the characteristics of the individual subject response functions. In this study, the major characteristics of each apparent mass were represented using the maximum resonance peak frequency (f_{Max}) shown in Fig. 2 and a measure of sharpness of the maximum peak (ξ). The former was used to assess the distribution of the peak frequencies of each combination of subjects by evaluating their standard deviations in the correlation analyses. The latter was used to reflect the

Table 1. Model parameters of the 12 subjects reported by Nawayseh and Griffin[12]

Parameter		Subject											
Symbol	Unit	S12	S2	S11	S3	S4	S7	S10	S9	S6	S8	S1	S5
M_1	kg	0	0	0	0	0	0	0	0	0	0	0	0
M_2	kg	23	24	24	21	16	20	24	17	20	17	26	14
M_3	kg	64	45	43	43	44	39	35	42	37	36	26	35
J	kg·m^2	9.41	0.12	0.21	0.18	0.14	0.08	0.13	0.13	0.17	0.51	0.29	1.14
K_{1x}	N/m	38990	32887	32545	69002	33170	37212	19457	49202	29561	44320	26024	41203
K_2	N·m/Rad	12409	76	162	90	41	67	31	49	145	186	142	414
K_{3z}	N/m	52602	44264	37923	74587	48193	64479	21967	40155	36458	35845	25631	40549
C_{1x}	N·s/m	469	551	744	1132	694	660	514	758	636	1167	2879	558
C_2	N·s/m	127	7	14	1	4	5	7	1	11	4	2	14
C_{3z}	N·s/m	936	406	445	1135	787	409	149	786	296	545	344	679
E	meter	0.49	0.07	0.09	0.06	0.09	0.06	0.07	0.06	0.09	0.1	0.07	0.28
α	Rad	1.32	0.99	0.98	1.35	1.33	0.96	0.61	1.27	0.93	1.25	1	1.39

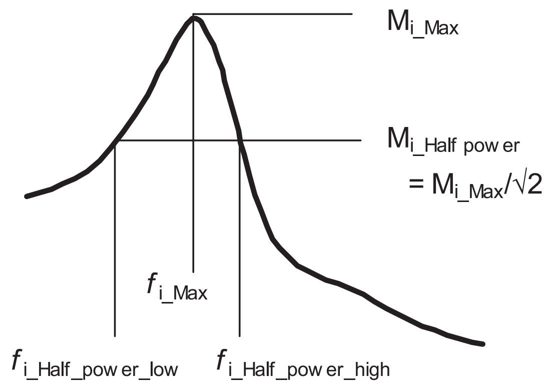


Fig. 2. Illustration of the i^{th} subject's maximum peak response (M_{i_Max}), maximum peak frequency (f_{i_Max}), and half power magnitude ($M_{i\_Half\_power}$) and frequencies ($f_{i\_Half\_power\_low}$, $f_{i\_Half\_power\_high}$).

damping properties of each apparent mass, and it was thus termed as the peak damping factor in this study and evaluated from

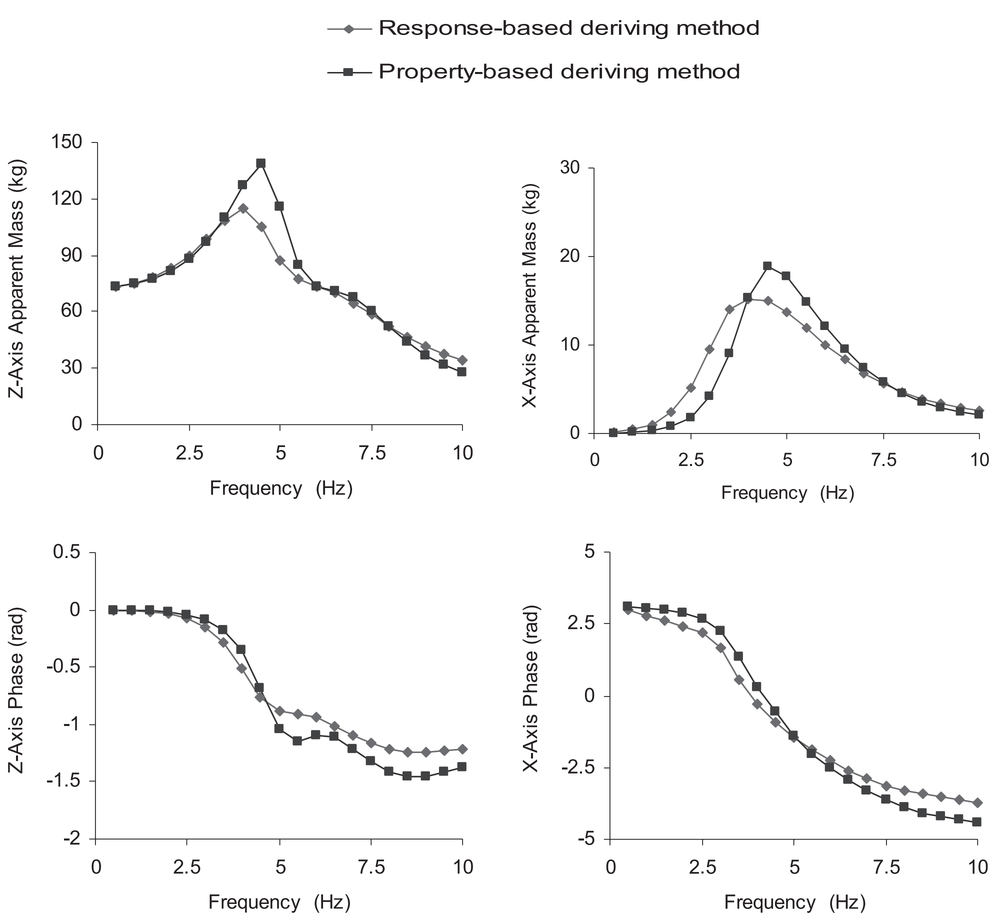
$$\xi_i = \frac{M_{i\_Max} - M_{i\_Max}/\sqrt{2}}{f_{i\_Half\_power\_high} - f_{i\_Half\_power\_low}} \tag{5}$$

where $f_{i\_Half\_power\_high}$ is the high-end frequency at which the response is equal to the half-power value ($Mi\_Max/\sqrt{2}$) of the peak response, and $f_{i\_Half\_power\_low}$ is the low-end half-power frequency. These parameters are also illustrated in Fig. 2. The mean values of the peak damping factors of each combination of subjects were used in the correlation analyses.

Results

As an example, Fig. 3 shows the comparisons of the apparent mass responses derived from the two methods for two subjects (S7 and S12). In the vertical direction (z-axis), the larger differences occur mainly in the resonance region (3 to 6 Hz). In the fore-and-aft cross-axis (x-axis), the larger differences occur in a wider frequency range. The phase differences are also evident in a larger frequency range.

Figure 4 shows the effect of the number of subjects on



(a) Vertical Response (b) Fore-and-aft cross-axis response

Fig. 3. Comparison of the two types of responses derived with a two-subject combination (S7 and S12).

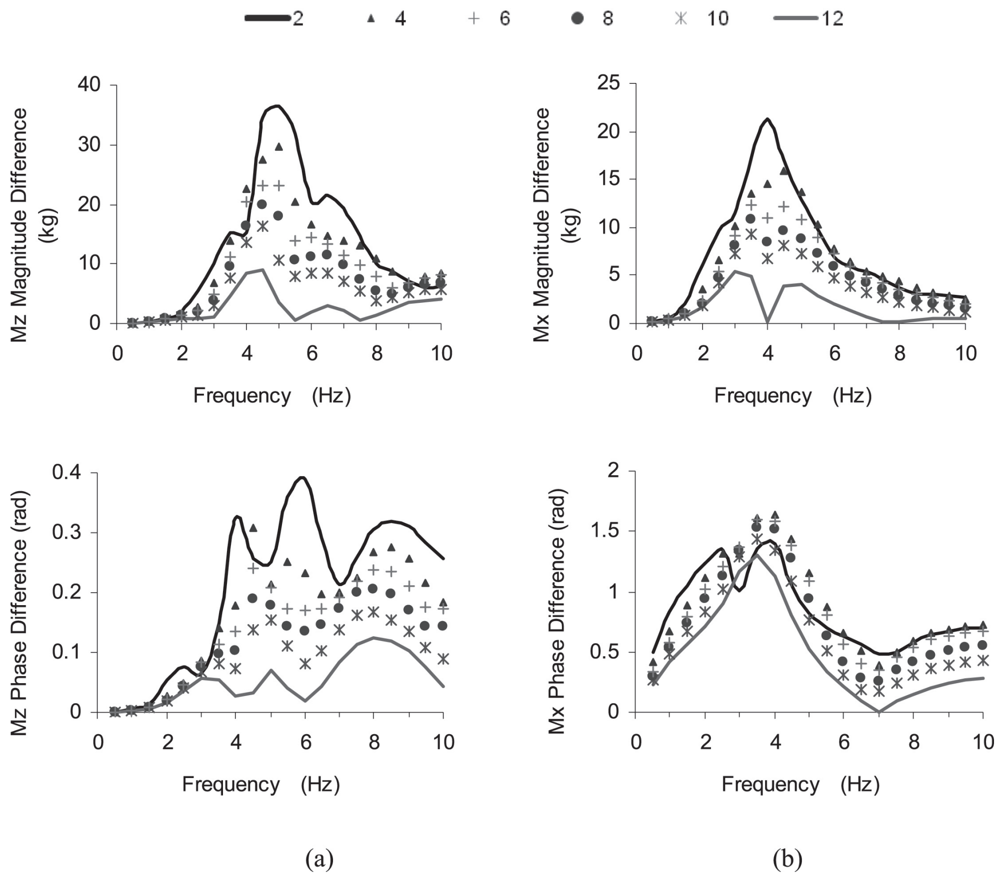


Fig. 4. The effects of the number of subjects on the maximum discrepancies: (a) in vertical response; and (b) in fore-and-aft cross-axis response.

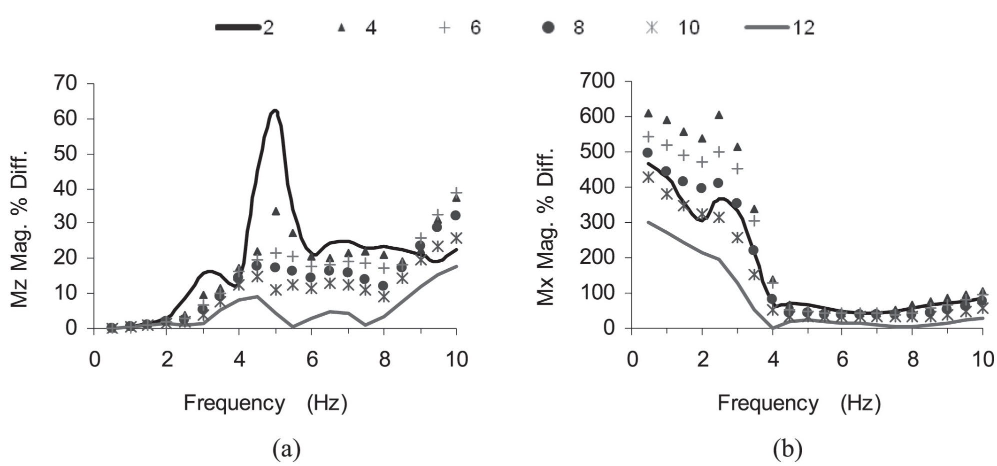


Fig. 5. The effects of the number of subjects on the maximum percent differences: (a) in vertical response; and (b) in fore-and-aft cross-axis response.

$\Delta M\omega_{\_Max}$ or the maximum difference between the response-based average and the property-based average at each frequency. Except in some cases, the maximum difference at each frequency generally decreases with the increase in the number of subjects. However, the increase in the number of subjects does not obviously reduce the phase differences exhibited in the fore-and-aft cross-axis, especially in the frequency range of 3 to 5 Hz.

Figure 5 shows the maximum percentage differences in the vertical and cross-axis response magnitudes. In the vertical direction, the maximum difference identified in the 12 subject combination is less than 10% at frequencies below 8.5 Hz. However, the maximum percentage differences in the fore-and-aft cross-axis responses below 4 Hz are substantial, regardless

Table 2. Characteristics of the apparent mass responses of the 12 subjects derived from the models reported by Nawayseh and Griffin[12)]

Parameter		Subject											
Symbol	Unit	S12	S2	S11	S3	S4	S7	S10	S9	S6	S8	S1	S5
M_{Total}	kg	87	69	67	64	60	59	59	59	57	53	52	49
f_{Max_Z}	Hz	4.02	4.25	4.07	5.89	4.53	5.51	3.67	4.41	4.30	4.74	4.97	4.74
f_{Max_x}	Hz	3.46	3.87	4.05	3.48	4.18	4.56	3.42	4.57	4.22	4.68	5.45	4.99
ξ_Z	kg/Hz	45.68	23.76	24.44	10.15	14.31	12.08	22.60	10.80	21.48	15.86	14.33	11.82
ξ_x	kg/Hz	6.50	8.83	6.73	9.30	4.68	3.42	5.19	6.16	6.52	3.34	3.38	5.65

M_{Total}: the total effective mass of a subject=M_1+M_2+M_3. f_{Max_Z}: the frequency of the maximum peak on z-axis. f_{Max_x}: the frequency of the maximum peak on x-axis. ξ_Z: the peak damping factor on z-axis. ξ_x: the peak damping factor on x-axis.

Table 3. Results of the correlation analyses: the response characteristics of six-subject combinations vs. the response-based averaging error measures

Subject Combination Characteristic	Correlation Coefficient (*r*-value)							
	Mz Magnitude Error		Mz Phase Error		Mx Magnitude Error		Mx Phase Error	
	RMS	Max	RMS	Max	RMS	Max	RMS	Max
f_{Max_Z} SD	0.29*	0.29*	0.24*	0.03	0.28*	0.19*	0.05	0.04
f_{Max_x} SD	0.01	–0.02	–0.10	0.00	0.01	0.02	0.18*	0.18*
ξ_z Mean	0.52*	0.62*	0.40*	0.57*	–0.06	0.30*	0.82*	0.80*
ξ_x Mean	0.13*	0.13*	0.04	0.03	0.22*	0.29*	0.12*	0.14*
M_{Total} SD	0.52*	0.63*	0.39*	0.49*	0.07	0.45*	0.92*	0.93*
M_{Total} Max	0.59*	0.73*	0.44*	0.52*	0.02	0.44*	0.97*	0.97*

*p<0.001.
Error RMS: the root-mean-square value of the averaging discrepancies in the frequency range of 0.5 to 10 Hz.
Error Max: the maximum discrepancy in the frequency range of 0.5 to 10 Hz. Because C_6^{12}=924, the correlation is significant at the level of p<0.001 when r>0.11.

of the number of subjects. This is because these responses are small at low frequencies, as shown in Fig. 3.

Table 2 lists the parameters used to characterize the special features of the apparent mass response for each of the 12 subjects. The associations among these parameters and the discrepancies between the response-based averages and the property-based averages can be assessed using the correlation coefficients listed in Table 3. The *r*-values indicate that the standard deviation (SD) of the maximum peak frequency for the z-axis among the subjects (f_{Max_z} SD) is generally correlated with the differences in the two averaging methods in both z- and x-directions. However, the SD of the maximum peak frequency for the x-axis among the subjects (f_{Max_x} SD) is generally very poorly correlated with the averaging differences. The mean peak damping factor for the z-axis (ξ_z Mean) is a much stronger indicator than either the mean peak damping factor for the x-axis (ξ_x Mean) or the distribution of the peak frequencies. The SD of the total effective mass values is also strongly correlated with the z-axis averaging discrepancies because the effective mass is strongly correlated with the z-axis peak damping factor (*r*-value=0.83, p<0.001), as evaluated using the data listed in Table 2.

As also listed in Table 2, the peak damping factor for the z-axis response for subject S12 (45.68 kg/Hz) is much larger than that for any other subject. The above-mentioned correlation relationship suggests that the elimination of this subject in the derivation of the representative response could reduce the averaging differences, although this obviously decreases the number of subjects considered in the derivations. This is demonstrated in the comparisons shown in Fig. 6. The above correlation relationship also suggests that the use of subjects with small differences among their effective total mass values could also reduce averaging discrepancies. This is demonstrated in Figs. 7 and 8, which show the comparisons of the difference for the selected six subjects and the maximum difference for all possible six-subject combinations. In Fig. 7, the selected subjects are S1, S6, S7, S8, S9, and S10, and their total effective mass values range from 52 to 59 kg with a SD of 3.2 kg and a coefficient of variation (CV) of 5.7%. In Fig. 8, the selected subjects are S2, S3, S4, S7, S10, and S11, and their total effective mass values range from 59 to 60 kg with a SD of 4.3 kg and a CV of 6.9%. At such mass variation levels, the errors resulting from the response-based average method are obviously smaller than the worst case.

Discussion

Systematic deficiency of the response-based averaging method

The results of this study clearly show that there are some differences between the response-based mean apparent mass and the property-based mean apparent mass. This indicates that the apparent mass does not change linearly with the linear variation of the dynamic properties of the human body, although the body could be treated as a linear system in

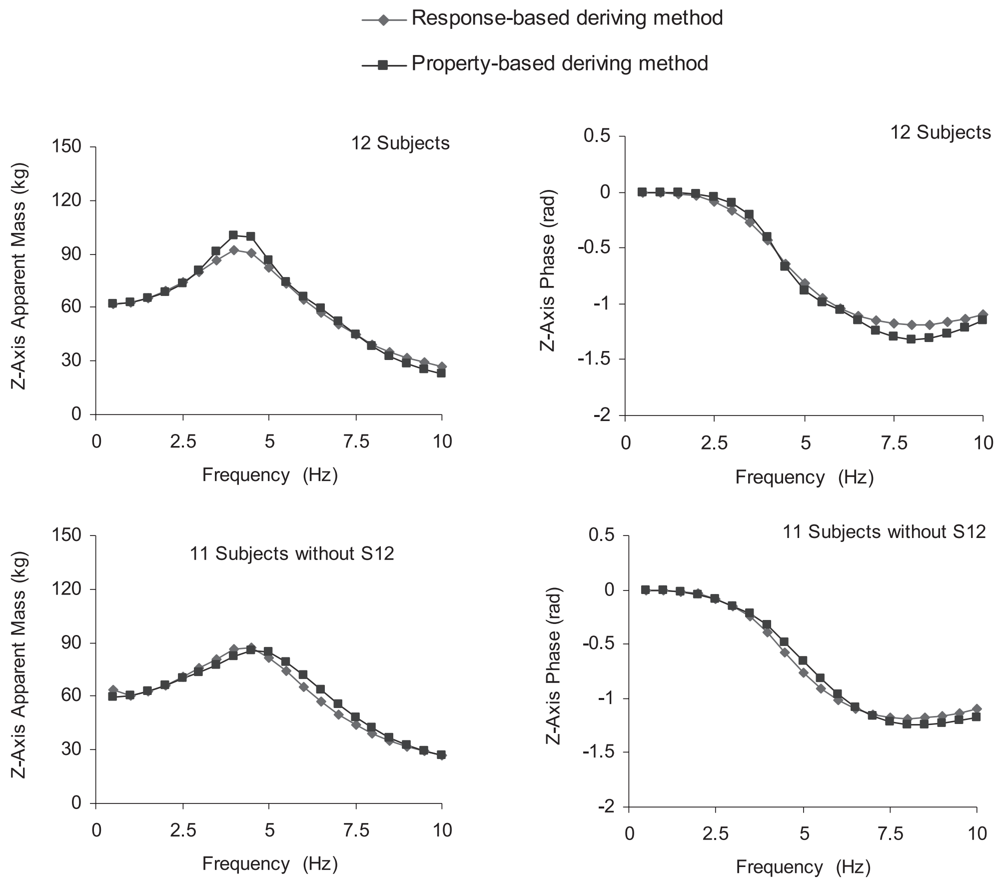


Fig. 6. Comparison of the two types of responses on z-axis with and without S12.

the modeling study. However, the response-based averaging method cannot reflect the non-linear aspects because the unweighted arithmetic average is a linear process or operation. This is a systematic deficiency of the response-based averaging method.

This problem can be further understood by considering a single degree-of-freedom (1-D) model shown in Fig. 9(a), which has also been used to simulate the vibration response of the human whole body system[5)]. The non-linear relationship between the apparent mass (M_A) and the dynamic properties (m, c, and k) of this model can be expressed as follows:

$$M_{\mathrm{A}} = \frac{(k + j\omega \cdot c)\cdot m}{k - m\omega^2 + j\omega \cdot c} \tag{6}$$

where ω is the frequency in Rad/s, and $j = \sqrt{-1}$.

For demonstration purpose, the apparent mass magnitudes of the model with two different sets of assumed parameters were calculated using Eq. (6). The results are plotted in Fig. 9 (b), together with those derived using the response-based and property-based methods from the original response functions. As expected, the resonance frequency and peak value derived from the property-based method are between those of the two original functions (Set 1 and Set 2). However, the response-based averaging method dramatically alters the basic shape of the original functions; it not only reduces the resonant peak but also increases the number of resonance peaks. This means that the response-based mean function does not appropriately reflect the 1-D structure; it is not repesentative of the basic dynamic characteristics of the orignial system.

Significance of the response-based averaging effects

The substantial averaging effects shown in Fig. 9 (b) were not clearly evident in the real data used in this study. This is because the biodynamic properties of the human subjects participating in the experiment did not vary as much as that assumed in the demonstration. However, the effects of the arithmetic average on the peak reduction and the function distortion were clearly observed. In some cases, the errors could be more than 30%, especially in the fore-and-aft cross-axis response functions, as shown in Figs. 3, 4, and 5. Therefore, some cautions are required when the conventional response-based averaging method is used to derive a representative mean response function.

Approaches for minimizing the response-based averaging effects

The results of this study also indicate that the misrepresentations of the response-based method in the fore-and-aft cross-axis response are not strongly associated with either the distribution of the major peak frequencies or the major peak damping factor, as indicated in Table 3. Increasing the number of participating subjects can reduce the averaging discrepancies, but this may not be sufficiently effective either, especially for

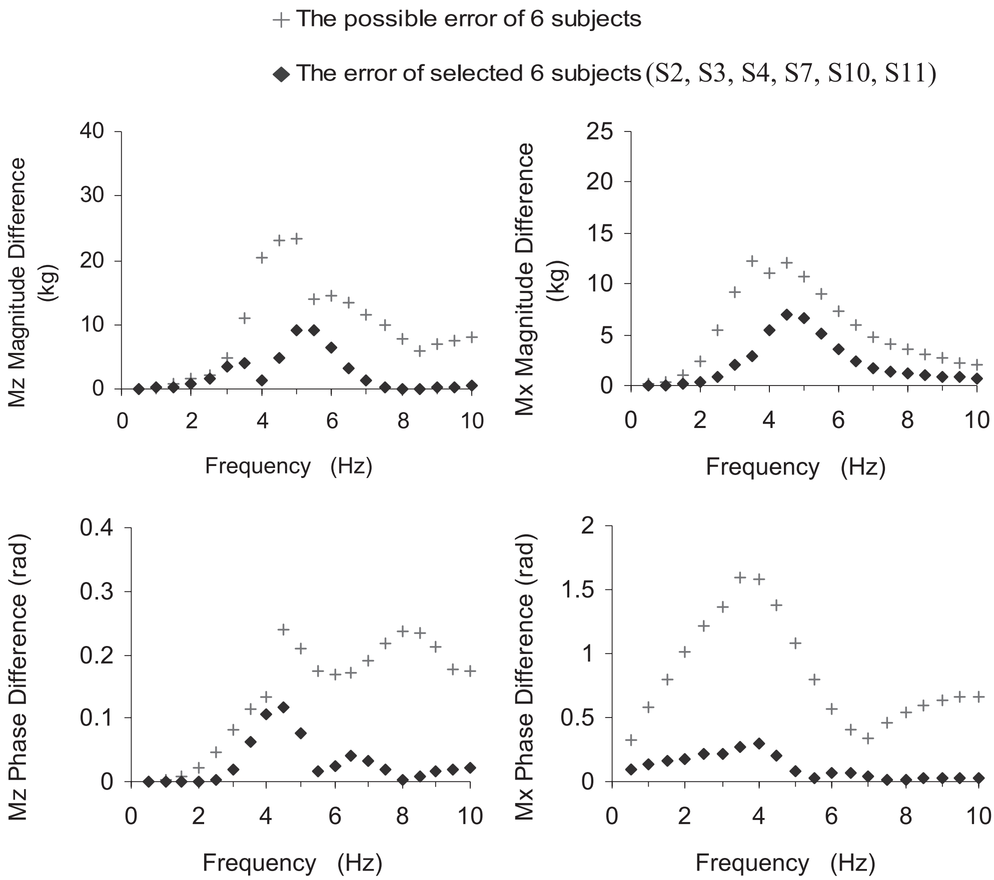


Fig. 7. Comparisons of the possible maximum averaging discrepancies of six-subject combinations and the averaging discrepancies of the selected six subjects with similar effective total mass value (from 52 to 59 kg for S1, S6, S7, S8, S9, and S10, as listed in Table 2).

the phase angle differences, as shown in Figs. 4 and 5. These observations suggest that it could be very difficult to develop practical study designs and/or data processing techniques that could reduce these averaging discrepancies to an acceptable percentage (e.g., <10%). The property-based derivation method seems to be the best choice for deriving the representative fore-and-aft cross-axis response if such a response is important in the study or its applications.

On the other hand, the number of participating subjects, the distribution of the peak frequencies of the responses, and the damping characteristics of the peaks are among the major factors that could significantly influence response-based averaging misrepresentations in the vertical response, as demonstrated in Table 3 and Figs. 4 and 5. These factors can thus be considered to help reduce the potential for misrepresentations when the response-based average method is used to derive the representative vertical biodynamic response. The first practical measure is to use a sufficient number of subjects in the response measurement. However, this does not mean that simply adding additional subjects to the study will always reduce response-based averaging discrepancies, as shown in Fig. 6. As a second measure, the participating subjects can be selected or grouped in terms of their body weights in the measurement or during data processing, as was done in some studies[3, 8] and in the standardization[2]. This is because the total effective mass (which is strongly associated with body weight) could be correlated with the peak damping factor which can strongly influence averaging discrepancies. As shown in Figs. 7 and 8, discrepancies between the response-based method and the property-based method could be controlled to very low levels by taking these measures. However, these correlations cannot guarantee low levels of discrepancies in all cases. As the most reliable measure, the distribution of the peak frequencies can be used to approximately predict differences between the two methods; this response-curve parameter can be evaluated after the individual response functions of the subjects are measured. In that regard, the results of this study may be used as references for such predictions. If the potential level for averaging discrepancies remains uncertain or is likely to be at a high level, the property-based derivation method should be used.

Applications of the property-based method

The property-based method may be particularly useful for predicting a representative response function when the availble sets of data are limited. For example, a particular experiment might be limited in its consideration of postures or vibration magnitudes; in these cases, the property-based method can be used to predict the response function of an intermediate condition between two postures or vibration magnitudes. For such

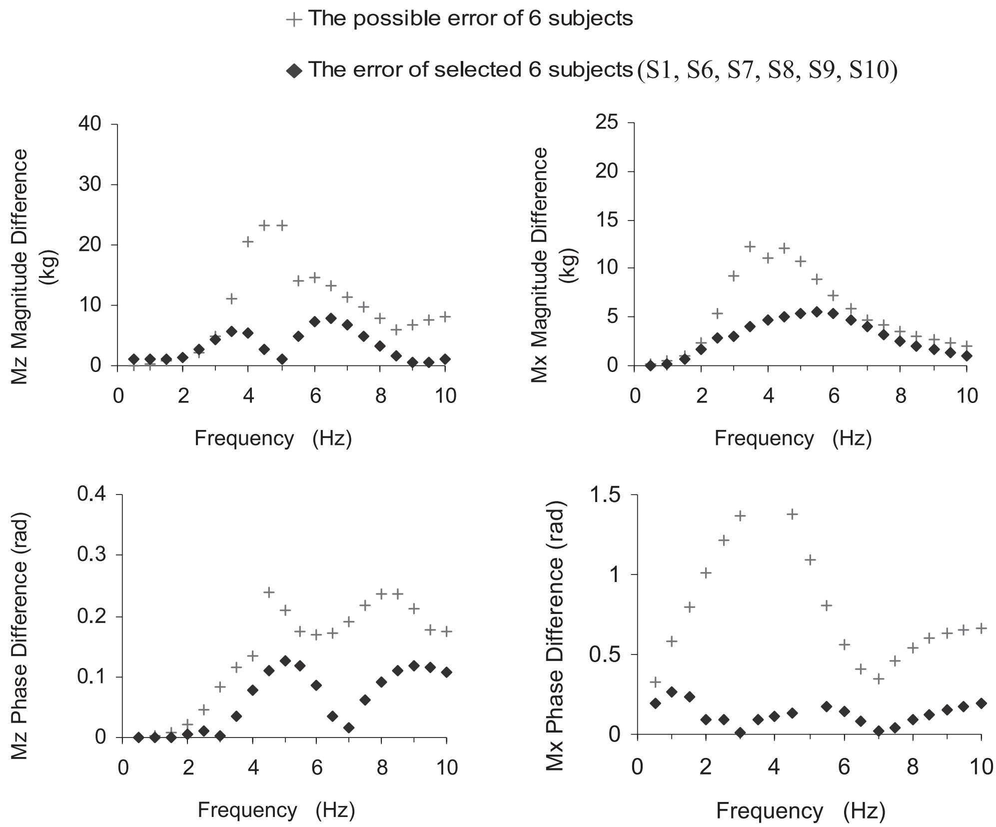


Fig. 8. Comparisons of the possible maximum averaging discrepancies of six-subject combinations and the averaging discrepancies of the selected six subjects with similar effective total mass value (from 59 to 69 kg for S2, S3, S4, S7, S10, and S11, as listed in Table 2).

applications, a non-linear interpolation of the property values may also be used if more than two points are measured. The avialable data from different laboratory for some test conditions could be very limited. The property-based method can be used for the synthesis of the mean response function, even if only two sets of data are avaialabe.

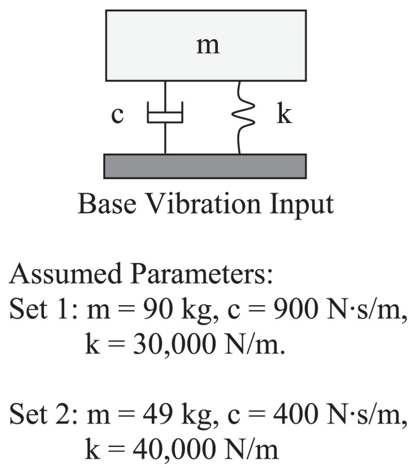
Finally, it should be noted that the relibility of the property-based derivation method depends on the accuracy of the mechanical-equivalent modeling. In reality, no model can exactly replicate the original system or perfectly fit a measured response function. However, it is possible to select a model that has a better representation of the experimental data in the application of the property-based method.

Conclusions

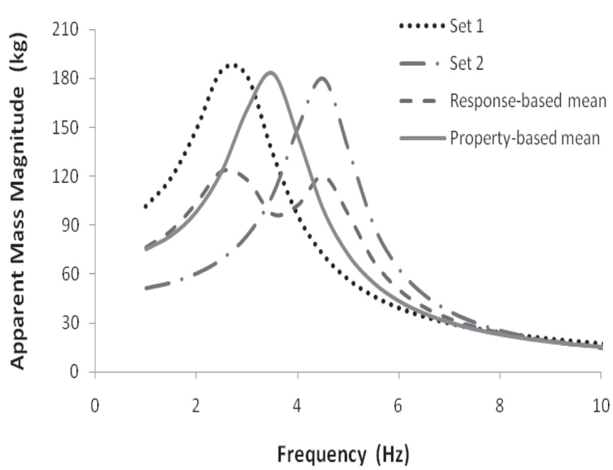
This study confirmed that there are some discrepancies between the response-based average apparent mass and the property-based average apparent mass of a set of human subjects. The discrepancies could be greater than 30%, especially in the fore-and-aft cross-axis response functions. The discrepancies generally depend on the number of subjects, the resonant frequencies of the individual response functions, and their damping characteristics. This study also demonstrated that the discrepancies result from the non-linear relationship between the apparent mass and the properties of a dynamic system. Because the response-based averaging method cannot take into account the non-linear relationship, it could introduce some systematic errors in the linear arithmetic average of the individual response functions, depending on the variability of the subjects' dynamic properties. If the subjects are grouped in terms of their body weights, and a sufficient number of subjects is considered in each group, the discrepancies can be greatly reduced to an acceptable level (e.g., <10%) in the vibration excitation direction. However, this approach may not work very well in the fore-and-aft cross-axis. On the other hand, the property-based method can take into account the non-linear relationship by considering the mean properties of the subjects in the process. Therefore, while more demanding than the response-based method, the property-based method is generally a more reliable method for the derivation of representative frequency response functions of the human whole-body systems.

Disclaimers

The content of this publication does not necessarily reflect the views or policies of the National Institute for Occupational Safety and Health (NIOSH), nor does mention of trade names, commercial products, or organizations imply endorsement by the U.S. Government.



(a)



(b)

Fig. 9. A single degree-of-freedom model of the whole-body and the comparisons of the apparent mass magnitudes calculated with two different sets of parameters and those derived from the response-based and property-based methods.

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