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Biodynamics of the human body under whole-body vibration: Synthesis of the reported data

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ABSTRACT

Identification of most probable ranges of biodynamic responses of the human body exposed to whole-body vibration is essential for developing effective integrated human-machine system design tools, improved vibration mitigation devices and frequency-weighting for exposure assessment. The international standard, ISO-5982 (2001), defines such ranges for very limited conditions, namely for body seated without a back support and exposed to vertical vibration. The reported data on biodynamic responses of the seated and standing human body exposed to whole-body vibration along different directions and the associated experimental conditions are systematically reviewed in an attempt to identify datasets that are likely to represent comparable and practical postural and exposure conditions. Syntheses of datasets, selected on the basis of a set of criterion, are performed to identify the most probable ranges of biodynamic responses of the human body to whole-body vibration. These include the driving-point biodynamic responses of the body seated with and without a back support while exposed to fore-aft, lateral and vertical vibration and those of the standing body to vertical vibration, and seat-to-head vibration transmissibility of the seated body. The proposed ranges are expected to serve as reasonable target functions in various applications involving coupled human-system dynamics in the design process, and potentially for developing better frequency-weightings for exposure assessments.

Relevance to the industry: Identification of most probable biodynamic responses of the seated and standing human body exposed to whole-body vibration is essential for developing anthropodynamic manikins, integrated human-machine system design tools for improved vibration mitigation devices and frequency-weighting for exposure assessment. This study derives ranges of biodynamic responses of the body seated with and without the back support, and those of the standing body. The ranges would serve as the target response functions for: (i) designs of anthropodynamic manikins for assessment of vibration isolation effectiveness of coupled seat-occupant system; (ii) development of human body models, which are vital for quantifying the vibration-induced stresses in different joints and for deriving integrated human-machine system design tools; and (iii) identification of alternate frequency weightings for assessment of vibration exposure.

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1. Introduction

Biodynamic responses of human body in different standing and sitting conditions have been widely measured under whole-body vibration (WBV). The measures are most often expressed in terms of force–motion relations at the driving-point, namely, mechanical impedance, apparent mass and absorbed power, and flow of vibration through the body, such as seat-to-head and body segments vibration transmissibility. The measured biodynamic responses have been used to identify mechanical-equivalent properties of the exposed human body and critical frequency ranges associated with resonances of different body segments (e.g., Coermann, 1962; Suggs et al., 1969; Mertens, 1978; Dupuis and Zerlett, 1986; Panjabi et al., 1986; Sandover, 1982; Donati and Bonthoux, 1983; Kitazaki and Griffin, 1998; El-Khatib et al., 1998) to understand the potential injury mechanisms (e.g., Liu et al., 1998; Hinz et al., 2002; Magnusson et al., 1993) and for deriving frequency-weightings for exposure assessments (e.g., Meister et al., 1984; Mansfield and Griffin, 1998; Lundström and Holmlund, 1998; Rakheja et al., 2008), and to help developing and validating continuum and discrete distributed-parameter models (e.g., Von Gierke and Coermann, 1963; Suggs et al., 1969; Fairley and Griffin, 1989; Mertens, 1978; Fritz, 2005; Pankoke et al., 2001). These

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biodynamic models can be further used to help quantify and understand the distributed joint forces, tissue stresses, and strains that may be directly related to the vibration-induced injury and disorder mechanisms (e.g., Fritz, 2000, 2005; Pankoke et al., 2001; Hinz et al., 2002), to help design better seats and anti-vibration systems (e.g., Stein, 2003; Paplukopoulos and Natsivas, 2007; Kruczek and Stribrsky, 2004; Rakheja et al., 2002a; Sachse et al., 2003; Pernica, 1990); and to construct anthropodynamic manikins for assessing vibration isolation performance of suspension seats, as an attractive alternative to the use of human subjects in the standardized seat assessment method (ISO-7096, 2000).

The effectiveness of biodynamic models and the manikins strongly relies on representative biodynamic responses of the body. The need to identify the range of biodynamic response of the human body to vibration was identified over 2 decades ago. The ISO-5982 (1981), ISO CD 5982 (1993) and ISO-7962 (1987) standards have proposed driving-point mechanical impedance (DPMI) and seat-to-head transmissibility (STHT) magnitude and phase characteristics of the human body based on the averaging of various data sets reported by different investigators. The synthesis included datasets generated under vastly different conditions, such as standing and sitting postures with feet supported and hanging. These early standards did not differentiate between the two postures, which are known to yield considerably different biodynamic responses (Paddan and Griffin, 1998). The proposed values were thus found to deviate considerably from the datasets reported under conditions considered applicable in many exposure situations, such as vehicle driving. Boileau et al. (1998) performed a synthesis of reported data to define ranges of DPMI and STHT characteristics in the 0.5–20 Hz range under particular conditions applicable to vehicle driving. These included: human subjects sitting erect without a back support with feet supported and vibrated, and exposed to vertical vibration with magnitude equal to less than 5 m/s^2. The results of the study were subsequently adapted in the ISO-5982 (2001), which has served as the basis for developing mechanical-equivalent biodynamic models of the seated body and anthropodynamic manikins. The idealized ranges of mechanical impedance magnitude and phase, defined in the current standard, were based on 8 and 7 datasets, respectively, reported in 6 different studies, while the STHT magnitude and phase ranges were defined from 4 to 3 datasets, respectively.

The ranges of biodynamic responses in terms of DPMI magnitude and phase have also been defined by the German Institute for Standardization, which are considered applicable for both standing and sitting human subjects exposed to vertical vibration (DIN 45676, 1992). The standard defines the mechanical-impedance values for three body masses (55, 75 and 98 kg), where the 75 kg values were taken as the mean values defined in ISO-5982. The biodynamic responses of seated subjects of 55 and 98 kg body mass were derived from the measured data acquired for 18 and 14 subjects, respectively, exposed to harmonic vertical vibration (rms acceleration weighted in accordance with ISO-2631-1 = 1.49 m/s^2 or less) dominant in the 1–6 Hz frequency range. Despite the somewhat comparable ranges of conditions, considerable differences between the two standardized values could be observed. A number of recent studies have also shown substantial differences between the standardized values and the measured data, which are attributed to differences in the experimental conditions considered (Patra et al., 2008; Rakheja et al., 2002b; Maeda and Mansfield, 2005).

The applicability of biodynamic mechanical-equivalent models and anthropodynamic manikins seem to have met limited success thus far. While some of the studies on seats with biodynamic models and manikins have shown good agreements with the data acquired from the seat-human system under particular conditions and body mass (e.g. Gu, 1999; Mansfield and Griffin, 1996; Huston et al., 1998; Toward, 2000; Cullmann and Wölfel, 2001; Lewis, 2005), others have identified substantial limitations of the current models and manikin designs. Only limited efforts have been made to assess the performance of models and manikins under ranges of representative conditions. The suitability of two prototype manikins for assessing vibration isolation effectiveness of different suspension seats was evaluated in a recent study by Nelisse et al. (2008), which involved subjects and manikins configured to three different body masses (55, 75 and 98 kg) as per the ISO-7096 guideline. The study concluded that the manikins provided an overestimate of isolation effectiveness of seats, when compared to those with human subjects, while the SEAT values of the low natural frequency (<2Hz) seats coupled with manikins were comparable with those of the seats loaded with equivalent rigid mass. Considerable differences between the results predicted from vertical human-seat models and laboratory-measured data have also been shown (Wei and Griffin, 1998; Tchernychouk et al., 2000). These differences in part may be attributed to: (i) limited applicability of biodynamic model and thus the manikin in the vicinity of the experimental conditions associated with the target response used for identifying the model, namely, the body mass, sitting posture, magnitude of vibration; (ii) assumption of linear response of the seated body; (iii) lack of consideration of contributions of the body coupling with elastic seats, since the measurements have been invariably performed with rigid seats, although a recent study has reported the driving-point responses of body seated on a soft seat (Hinz et al., 2006a).

The quality of both the biodynamic models and the manikins could be considerably enhanced by defining more reliable ranges of biodynamic responses of the seated body. The ranges of idealized values defined in ISO-5982 (2001) were based on datasets reported prior to 1998, while a number of datasets have been reported in the recent years under more representative and comparable experimental conditions. A synthesis of the data including the recently reported ones can help define more reliable ranges of the biodynamic responses. Furthermore, the initial efforts made in defining the idealized ranges need to be enhanced for broadening their applicability for standing subjects, different vibration directions, and sitting with back support. Considerable exposure to vertical vibration of standing subjects in many situations have been documented, such as high speed boat or craft operator, which necessitate the design of vibration attenuating floors (Akers, 2004). A large number of work vehicles transmit significant magnitudes of fore-aft and lateral vibration, which are either comparable or exceed those in the vertical direction (Kumar et al., 2001; Bovenzi et al., 2002; Rehn et al., 2005). A few recent studies have explored means of controlling horizontal vibration by considering biodynamic models of the body (Stein et al., 2007a; Fleury and Mistrot, 2006), since exposure to large magnitudes of horizontal vibration could cause greater shear forces in the lumbar spine (Fritz, 2005). Moreover, the biodynamic responses of the seated body are greatly influenced by the back support condition. The vertical biodynamic responses of the body seated against vertical and inclined back supports have been reported in a few studies (Fairley and Griffin, 1989; Boileau and Rakheja, 1998; Mansfield and Griffin, 2002; Wang et al., 2004), which could be applied to define the ranges under back supported sitting conditions.

In this study, the ranges of biodynamic responses under different postures and vibration directions are defined on the basis of syntheses of available data. In particular, the reported data are synthesized to define ranges of (1) apparent mass and seat-to-head vibration transmissibility of seated human body exposed to vertical vibration with and without a back support; (2) apparent mass characteristics of seated body exposed to fore-aft and lateral vibration; and (3) apparent mass characteristics of standing human body exposed to vertical whole-body vibration. The experimental conditions associated with the reported data sets are carefully examined and selection criteria are defined so as to select datasets considered applicable under conditions considered representative of the work situations.

2. Selection of datasets and conditions

The biodynamic responses of the standing and sitting body are strongly influenced by the vibration (magnitude and frequency), and anthropometric and posture-related factors. Reported studies on biodynamic responses have employed a wide range of experimental conditions, which are reviewed so as to select datasets under conditions representative of the workplace. The studies reporting biodynamic responses of seated and standing body with different postures and exposed to vibration along different translational directions were initially considered. The biodynamic responses of the standing body have been generally evaluated under vertical vibration, while the responses to horizontal vibration are addressed in a very few studies (e.g. Starck et al., 1991). The synthesis of datasets on standing body biodynamics is thus limited to vertical vibration alone.

For the seated body, the mechanical impedance or apparent mass data reported under fore-aft (x), lateral (y) and vertical (z) vibration are considered, while those on seat-to-head vibration transmissibility are limited to vertical vibration alone due to only a few datasets reporting the transmission of horizontal vibration. A few selected datasets were initially analyzed to determine their 'grand mean' using two approaches: (i) based on magnitude data alone; and (ii) based on the magnitude as well as phase data. The two approaches resulted in quite comparable mean responses. The synthesis thus included data sets reporting either magnitude alone or both the magnitude and phase.

Only a few studies have investigated the gender effect on the measured biodynamic responses. Some of these have concluded insignificant gender effect on the biodynamic responses to vibration (Mertens, 1978; Parsons and Griffin, 1982), while others have suggested strong gender effect (Laurent, 1996; Lundström et al., 1998). Other studies have suggested small differences in the biodynamic responses of male and female subjects only at higher frequencies (Mansfield et al., 2001; Wang et al., 2004). Griffin et al. (1978) showed that male subjects exhibit greater seat-to-head vibration transmission than females in the 1.25–4 Hz range, while an opposite trend was observed at higher frequencies. The datasets reporting the biodynamic responses of the female subjects are excluded from the synthesis due to their very small number. The datasets reporting the mean responses of male and female subjects, however, are included. Considering that the gender effect is generally small, well within the expected variations among the reported datasets, the resulting synthesis could be considered representative of the biodynamic responses of male as well as female subjects within the range of chosen body mass range.

The reported biodynamic response data and the associated experimental conditions were thoroughly reviewed in order to select datasets reported under comparable and representative conditions. For this purpose, selection criteria comprising the ranges of experimental variables and test were formulated. Irrespective of the sitting posture and direction of vibration, the data satisfying these conditions were considered for the synthesis, which included: (i) datasets reporting either the magnitude or the magnitude and phase of the biodynamic response function; (ii) datasets derived using adult subjects with body mass ranging from approximately 55–110 kg; (iii) datasets reported under either sinusoidal or random vertical vibration within the 0.5 to 20 Hz frequency range, while those under horizontal vibration were limited up to 10 Hz; (iv) datasets acquired under vibration of magnitude below 5 m/s^2 (peak as stated in the current standard), while those reported in the vicinity of 1 m/s^2 rms acceleration were preferred, which is considered to be more representative of vehicle vibration and the nonlinear effects of vibration magnitude tend to diminish beyond this level (Matsumoto and Griffin, 1998b; Mansfield and Griffin, 2000; Wang et al., 2004); (v) datasets acquired with clearly defined subject population, while those reporting a single subject data were carefully examined. Few studies have shown comparable AM responses to both sinusoidal and random vibration of comparable magnitudes (Mansfield and Maeda, 2005b; Boileau and Rakheja, 1998). The data reported under both types of excitation have thus been considered. The magnitudes of vibration corresponding to each selected dataset are expressed in rms acceleration (m/s^2), unless stated otherwise.

Various studies reporting the biodynamic responses of the seated and standing subjects are initially identified, which would satisfy the selection criteria completely or in-part. Multiple datasets could be obtained from the majority of the studies corresponding to different postures and vibration magnitudes. Additional specific criterion is subsequently applied to select datasets under comparable and representative conditions for different posture and vibration directions, which are described in the following subsections. The studies have reported either mean or median values of the responses of the subject populations considered. The median values of the selected datasets and body mass are considered close to the mean values, assuming symmetric distribution. The synthesis of selected datasets thus includes both the reported median and mean datasets.

2.1. Studies reporting driving-point biodynamic responses of seated body under vertical vibration

A total of 45 studies reporting the driving-point biodynamic responses of the seated body under vertical vibration were initially identified. Table 1 summarizes the selected studies together with the associated experimental conditions. Wide variations in the experimental conditions employed in different studies are clearly evident, although very similar measurement and analyses methods are used. The vast majority of the studies report multiple datasets under different sitting and back support conditions. The datasets satisfying the selection criteria are selected from those studies corresponding to the concerned sitting posture and vibration magnitude. The earlier studies generally reported the driving-point biodynamic responses in terms of mechanical impedance (MI) under sinusoidal vibration, while the more recent studies present apparent mass (AM) under broad-band random vibration. The reported impedance data were expressed in the form of apparent mass using the relation:

$$M(j\omega) = \frac{1}{j\omega} Z(j\omega) \tag{1}$$

where $Z(j\omega)$ is the complex mechanical impedance corresponding to frequency ω and $M(j\omega)$ is the complex apparent mass and $j = \sqrt{-1}$

Additional selection criteria are defined by considering the posture and vibration-related factors affecting the driving-point responses of the seated body, namely, the back support, the feet supports, sitting posture (tense, relaxed or slouched), and magnitude of vibration. The datasets reported for seated body with feet hanging are excluded, since the responses with feet-hanging sitting postures are significantly different from those with feet supported

Table 1
Summary of experimental conditions employed in studies reporting driving-point biodynamic responses of seated human body to vertical vibration.

Author(s)	*n* (gender)	Mass (kg) (mean)	Feet condition	Sitting conditions		Excitation			Function Reported
				Posture	Back support	Type	Frequency (Hz)	Magnitude[a] (m/s^2 rms)	
Coermann (1962)	8 (M[1])	70–99.5 (86.2)	Not supported	Erect relaxed	None	sine	1–20	Up to 0.5 g peak	Median MI[3] magnitude and phase
Edwards and Lange (1964)	2 (M)	77.7–84 (81)	Not supported	Upright	None	Sine	1–20	0.2, 0.35, 0.5 g peak	MI magnitude and phase (individuals)
Vykukal (1968)	4 (M)	68–83 (75.8)	Not supported	NR[6]	NR	sine	2.5–20	0.4g peak (1, 2.5, 4 g bias)	MI magnitude and phase (n=1)
Vogt et al. (1968)	10 (M)	NR (80)	Supported Stationary	Erect	NR	sine	2–15	0.5g peak (1, 2, 3 g bias)	MI magnitude and phase
Suggs et al. (1969)	11 (M)	58–90 (73.6)	supported	Upright	None	sine	1.75–10	1.25 mm peak displacement	Mean MI magnitude and phase
Miwa (1975)	20 (M)	50–76 60.8)	Not supported	Erect Relaxed	None	sine	3–200	0.1 g rms	Mean MI magnitude and phase
Mertens (1978)	6(M) 3(F)	57–90 (66.8)	Not supported	Upright	NR	sine	2–20	0.4 g rms (1 to 4 g bias)	Mean MI magnitude and phase
Sandover (1982)	6 (M)	52.7–87.2	Supported	Erect	None	Random	1–25	1	Individual AM[4] magnitude and phase
Donati and Bonthoux (1983)	15(M)	49–74 (62.9)	Supported	Upright Hands on SW	None	Random sine	1–10	1.6	Mean MI magnitude and phase
Fairley and Griffin (1983)	1 (M)	63	Supported	Normal	None	Random	0.25–20	1.0	AM magnitude & phase
Meister et al. (1984)	6 (M)	63–86 (72)	Supported	Erect- hands on SW	NR	sine	2, 4, 8 and 16	Two levels at each frequency	MI magnitude .
Fairley and Griffin (1986)	8 (M)	57–85 (71.8)	Supported	Normal	None	Random	0.25–20	0.25–2.0	Individual AM magnitude and phase
Hinz and Seidel (1987)	4 (M)	56–83 (71.2)	Supported	Erect	NR[5]	sine	2–12	1.5 and 3.0	Mean AM magnitude and phase
Fairley and Griffin (1989)	24 (M[1]) 24(F[1]) 12(C[1])	NR (63.1[5])	Supported Stationary & vibrated	Erect & tense	None	Random	0.25–20	1.0	Mean normalized AM magnitude
Mansfield, 1994	12 (M)	60–85 (68.3)	Supported	Upright	None	Random	0.5–20	0.25–2.5	Individual AM magnitude
Holmlund et al. (1995)	30	54–93 (70)	Supported	Erect & Relaxed	None	Sine	2–100	0.5	Mean normalized MI magnitude and phase
Seidel et al. (1996); cited in Boileau et al. (1998)	11(M) 14(M)	60–70 70–80	Supported	Upright	None	Random	0.5–20	<1.4	Mean MI magnitude
Matsumoto and Griffin (1998b)	8 (M)	63–83	Not supported	Normal	None	Random	0.5–20	1.0	Individual AM magnitude and phase
Kitazaki and Griffin, (1998)	8 (M)	NR (74.6)	NR	Normal, Slouched	None	Random	0.5–30	1.7	Mean normalized AM magnitude
Wu et al. (1998)	6 (M)	58–73 (64.2)	Supported	Erect	None	Random	0.5–20	1.0 and 2.0	Mean AM magnitude and phase
Boileau et al. (1998a)	6 (M)	70–81 (75.4)	Supported	Erect, relaxed, slouched	None Vertical Inclined-14°	Sine Random	0.625–10	1, 1.5, 2.0 weighted	Mean MI magnitude and phase
Holmlund (1999)	3 (M)	74 (74)	In-vehicle	Erect Relaxed	None	Field	1–20	NR	Individual MI magnitude
Mansfield and Griffin (2000)	12 (M)	60–85 (68.3)	Supported	Upright	None	Random	2–20	0.25–2.5	Median normalized AM[4] magnitude
Holmlund et al. (2000)	15(M) 15(F)	55–92 (74) 54–93 (66)	Supported	Erect Relaxed	None	sine	2–100	0.5, 0.7, 1.0, 1.4	Mean MI magnitude and phase
Nawayseh (2001)	12 (M)	57–106 (74.6)	Unsupported & Supported	Upright – 4 thigh support	None	Random	0.25–25	0.125, 0.25, .625, 1.25	Median AM magnitude and phase
Mansfield et al. (2001)	11(M) 13(F)	72–96(81) 54–79 (67)	Supported stationary	Upright	None	Random	2–20	0.5, 1.0, 1..5	Median AM magnitude
Rakheja et al. (2002b)	12(M) 12(F)	58–100 (78.5) 48–111 (64)	Supported	Relaxed	Automotive 13° pan, 24° backrest	Random	0.5–40	0.25, 0.5. 1.0	Mean AM magnitude and phase

(*continued on next page*)

Table 1 (*continued*).

Author(s)	*n* (gender)	Mass (kg) (mean)	Feet condition	Sitting conditions		Excitation			Function Reported
				Posture	Back support	Type	Frequency (Hz)	Magnitude[a] (m/s^2 rms)	
Matsumoto and Griffin (2002a)	8(M)	64–87 (73)	Supported	Upright –Tense buttock	None	Random	2–20	0.35–1.4	Median normalized AM magnitude and phase
Matsumoto and Griffin (2002b)	8 (M)	63–83 (72)	Not supported	Upright	None	Random	0.5–20	0.125–2.0	Median normalized AM magnitude and phase
Mansfield and Griffin (2002)	12(M)	NR (75.4)	Supported	Upright	None Vertical	Random	1–20	0.2, 1.0, 2.0	Normalized AM magnitude & individual phase
Hinz et al. (2004)	23 (M) 22 (F)	58–106 (NR) 51.5–84 (NR)	Supported	Relaxed	Automotive. 16° pan, 16° backrest	Random	1–35	0.3 weighted	Mean normalized AM magnitude and phase
Nawayseh and Griffin (2004)	12 (M)	62–106 (77.2)	Unsupported & supported	Upright – 4 thigh supports	Vertical	Random	0.25–20	0.125, 0.25, 0.625, 1.25	Median AM magnitude
Wang et al. (2004)	13 (M) 14 (F)	47.4–110.5 (70.8)	Supported	Upright-Hands on lap & SW	None Vertical Inclined	Random	0.5–40	0.5, 1.0	Mean AM magnitude and phase
Maeda and Mansfield (2005)	12 (M)	NR (65.8)	Supported	NR	None	Random	1–20	1.0	Median AM magnitude and phase
Mansfield and Maeda (2005a)	12 (M)	NR (63.8)	Supported	Upright/ twisted	None Vertical	Random	1–20	0.4	Median normalized AM magnitude
Mansfield and Maeda (2005b)	12 (M)	NR (65.8)	Supported	Upright	None	Random sine	1–40	1.0 .2–.5 weighted	Median normalized AM magnitude and phase
Kim et al. (2005)	5 (M)	89.8–98.7 (80.7)	Supported	Upright	None	Random	1–50	1.0	Mean AM magnitude and phase
Nawayseh and Griffin (2005a)	12 (M)	65–103 (76.5)	Supported	Upright – 4 pan angles	Vertical	Random	0.5–15	0.125, 0.25, 0.625	Median AM magnitude
Mansfield and Maeda (2006)	15 (M)	NR (64.3)	Supported	Upright	None Vertical	Random	1–20	0.4, 0.8	Median AM magnitude (phase for vertical back)
Huang and Griffin (2006)	14 (M)	NR (70.3)	Supported	Various postures	None	Random	0.5–20	0.25, 2	Median normalized AM magnitude and phase
Hinz et al. (2006b)	13 (M)	61.3–103.6 (79.3)	Supported	Upright –Hands on bar	None	Random	0.25–30	0.25, 1.0, 2.0	Mean AM magnitude
Mansfield et al. (2006)	12 (M)	NR(79.1)	Supported	Upright	None vertical	Random	2–20	1.0	Median AM magnitude
Mansfield and Maeda (2007)	15 (M)	NR(64.3)	Supported	Upright	None vertical	Random	1–20	0.4, .8	Median AM magnitude
Patra et al. (2008)	9 (M) 9 (M) 9 (M)	50–60 (55.7) 70–80 (75.2) 93–107 (98)	Supported	Upright Hands on lap & SW[7]	None Inclined	Random	0.5–20	0.5,1.0, 2.0	Mean AM magnitude and phase for 3 mass groups
Wang et al. (2008)	12(M)	66.4–99.6 (77.3)	Supported	Relaxed Hands on lap &-SW	None Vertical Inclined	Random	0.5–15	0.5,1.0, 1.5	Mean AM magnitude and phase

M – male, F- female, C -children; MI – Mechanical impedance; AM – Apparent mass; Estimated; NR-Not reported; SW – Steering wheel.
[a] Magnitude in m/s^2 rms unless stated

(Nawayseh and Griffin, 2004). Moreover, the feet hanging posture is not considered representative of the vehicle driving.

The vast majority of the studies have reported the responses without a back support, while the back support affects the seated driving-point responses considerably (Wang et al., 2004; Mansfield and Maeda, 2005a; Boileau and Rakheja, 1998; Mansfield and Griffin, 2002). The datasets reported for none and vertical or inclined back supports are thus synthesized separately. The datasets corresponding to upright erect and relaxed postures alone are selected, which are most commonly reported and considered representative of vehicle driving. The position of the subjects hand may also affect the responses, although the vast majority of the studies consider hands in lap or resting on the knees. The hands placed on a steering wheel or a bar may affect the responses only with back supported postures (Wang et al., 2004), while the effect is significant when an automotive seat geometry is used, which is attributable to low seat height, lower vibration magnitude and substantial backrest inclination, in the order of 24° with respect to the vertical axis (Rakheja et al., 2002b). The datasets reported for both hands position are thus retained for the no back support condition, while those for the back support condition are limited to either vertical or slightly inclined backrests (≤12°) with hands in lap. A few earlier studies have investigated the biodynamic responses of the seated body under different levels of gravity (Vykukal, 1968; Vogt et al., 1968; Mertens, 1978). The data reported under normal gravity are retained in these cases.

In view of the above and the general selection criteria, a large number of datasets are excluded from the synthesis. These include: (i) datasets reported for feet unsupported posture or not vibrated or not clearly identified (Coermann, 1962; Edwards and Lange, 1964; Vykukal, 1968; Vogt et al., 1968; Miwa, 1975; Mertens, 1978; Matsumoto and Griffin, 1998b, 2002b; Kitazaki and Griffin, 1998); (ii) datasets involving children (Fairley and Griffin, 1989); (ii) datasets reported for automotive postures (Rakheja et al., 2002b; Hinz et al., 2004); (iv) datasets not reporting the total body mass (Fairley and Griffin, 1989); (v) studies involving only one subject (Fairley and Griffin, 1983); (vi) studies reporting individual subjects responses (Mansfield, 1994; Holmlund, 1999); although exceptions were made in cases where the mean data could be easily obtained from the individual data (Fairley and Griffin, 1986; Sandover, 1982); and (vii) studies reporting responses at a few discrete frequencies (Meister et al., 1984). Among the remaining 29 studies some of the datasets reported by same authors under comparable conditions were found to be very similar. Only one of these datasets was thus retained in the synthesis. This resulted in exclusion of dataset reported by Mansfield and Maeda (2005a, 2006) for back unsupported and supported postures, respectively.

A total of 33 and 26 datasets in magnitude and phase, respectively, were considered to satisfy the selection criteria for the back unsupported condition. For the vertical and inclined back support, a total of 15 and 10 datasets in magnitude and phase were identified. These included multiple datasets reported by: (i) Donati and Bonthoux (1983), Hinz and Seidel (1987), Boileau et al. (1998) under sinusoidal and random vertical vibration, denoted hereafter as '-sine' and '-random', respectively; (ii) Seidel (1996) for body mass in 60–70 and 70–80 kg ranges, denoted as '60–70' and '70–80', respectively; (iii) Wang et al. (2004) for mean body mass of 70 and 75 kg, denoted as '70' and '75'; (iv) Patra et al. (2008) for mean body mass of 55, 75 and 98 kg, denoted as '55', '75' and '98' respectively; and (v) Holmlund et al. (2000) for erect and relaxed sitting posture, denoted as 'E' and 'R', respectively (Table 2). Although the individual body masses were not reported in a few of the selected studies (Mansfield and Griffin, 2002; Maeda and Mansfield, 2005; Mansfield and Maeda, 2005b; Huang and Griffin, 2006), these were retained since adult subject populations were considered. Attempts were made to include the datasets reported under excitations in the vicinity of 1 m/s^2 rms, when available.

Table 2
Selected datasets on driving-point biodynamic responses of seated human body to vertical vibration (Back not supported and Back supported).

Author(s)	Excitation		
	Type	Frequency (Hz)	Magnitude (m/s^2 rms)
	No back support		
Suggs et al. (1969)	Sine	1.75–10	1.25 mm peak displacement
Sandover (1982)	Random	1–25	1.0
Donati and Bonthoux (1983)	Random	1–10	1.6
Fairley and Griffin (1986)	Random	0.25–20	1.0
Hinz and Seidel (1987)	Sine	2–12	1.5
Holmlund et al. (1995)	Sine	2–100	0.5
Seidel et al. (1996); cited in Boileau et al. (1998)	Random	0.5–20	<1.4
Wu et al. (1998)	Random	0.5–20	1.0
Boileau et al. (1998)	Random	0.625–10	1.0
Holmlund et al. (2000)	Sine	2–100	1.4
Mansfield and Griffin (2000)	Random	2–20	1.0
Nawayseh (2001)	Random	0.25–25	1.25
Mansfield et al. (2001)	Random	2–20	1.0
Matsumoto and Griffin (2002a)	Random	2–20	1.0
Mansfield and Griffin (2000)	Random	1–20	1.0
Wang et al. (2004)	Random	0.5–40	1.0 -Hands in lap
Maeda and Mansfield (2005)	Random	1–20	1.0
Mansfield and Maeda (2005b)	Random	1–40	1.0
Kim et al. (2005)	Random	1–50	1.0
Hinz et al. (2006b)	Random		1.0
Huang and Griffin (2006)	Random	0.5–20	2.0
Mansfield et al. (2006)	Random	2.0–20	1.0
Mansfield and Maeda (2007)	Random	1.0–20	0.8
Patra et al. (2008)	Random	0.5–20	1.0
Wang et al. (2008)	Random	0.5–15	1.0 – -Hands in lap
Back support			
Boileau et al. (1998) – vb	Random	0.625–10	1.0–2.0
Mansfield and Griffin (2002)- vb	Random	1.0–20	1.0
Nawayseh and Griffin (2004)- vb	Random	0.25–20	0.625
Wang et al. (2004) – ib 12° and vb	Random	0.5–40	1.0 –Hands in lap
Nawayseh and Griffin (2005a)- vb	Random	0.25–20	0.625
Mansfield and Maeda (2005a)- vb	Random	1.0–20	0.4
Mansfield and Maeda (2007)-vb	Random	1.0–20	0.8
Patra et al. (2008) – ib 12°	Random	0.5–20	1.0
Wang et al. (2008) – vb and ib	Random	0.5–15	1.0 – -Hands in lap

vb – vertical back support; ib –inclined back support.

2.2. *Studies reporting seat-to-head vibration transmissibility of seated body under vertical vibration*

Compared to the driving-point biodynamic responses, the seat-to-head vibration transmissibility data have been reported in a fewer studies. Paddan and Griffin (1998) identified a total of 46 studies reporting the seat-to-head transmissibility responses of seated body exposed to vertical vibration. The study did not consider the phase data and included those attained for body seated on soft cushions with harness, while the back support conditions were not defined. It has been well-established that the upper body support conditions affect the seat-to-head vibration transmissibility most significantly (Wang et al., 2006; Paddan and Griffin, 1988). The requirement of feet support was further relaxed, since the contributions are known to be very small. The current standard (ISO-5982, 2001) is based upon 4 and 3 datasets in seat-to-head transmissibility magnitude and phase responses,

Table 3
Summary of experimental conditions employed in studies reporting seat-to-head transmissibility (STHT) of seated human body to vertical vibration.

Author(s)	*n* (gender)	Mass -kg (mean)	Excitation			Function Reported
			Type	Frequency (Hz)	Magnitude (m/s^2)	
Coermann (1962)	1 (M)	84	sine	1–20	< 0.5 g peak	Magnitude
Mertens (1978)	6 (M) 3 (F)	57–90	sine	2–20	4.85 m/s^2 rms	Mean magnitude and phase
Griffin et al. (1978)	18(M) 18(F)	NR	sine	1–100	NR	Mean magnitude
Griffin et al. (1978)	1 (M)	80	sine	1–100	NR	Magnitude and phase
Hinz and Seidel (1987)	4(M)	56–83 (71)	sine	2–12	1.5 m/s^2 rms	Mean magnitude and phase
Paddan and Griffin (1988)	12(M)	58–81 (70.8)	random	Up to 25 Hz	1.75 m/s^2 rms	Individual magnitude; phase (n=1; 80 kg)
Zimmermann and Cook (1997)	30 (M)	(77.6)	sine	4.5–16	1.0 m/s^2 rms	Mean magnitude
Kitazaki and Griffin (1997)	8 (M)	(74.6)	Random	0.5–35	1.7 m/s^2 rms	Mean magnitude
Wu et al. (1998)	6 (M)	58–73 (64.2)	Random	0.625–20	1.0 m/s^2 rms	
Hinz et al. (2001)	39(M)	NR	Random; (1–4 Hz)	1–20	0.7, 1.0 and 1.4 m/s^2 rms – weighted	Mean magnitude and phase (Hands on steering wheel)
Kim et al. (2005)	5 (M)	65.7–98.7	Random	1–50	1.0 m/s^2 rms	Mean magnitude
Wang et al. (2008)	12 (M)	66.4–99.6 (77.3)	Random	0.5–15	0.25, 0.5, 1.0 m/s^2 rms	Median AM magnitude

respectively, of the body seated without a back support. The considered studies were reported prior to 1988. Only a few additional data sets could be found in the literature, particularly for the back supported postures, which would satisfy the selection criteria. The synthesis of the reported seat-to-head vibration transmissibility data is thus limited to upright sitting postures without a back support.

A total of 12 studies were initially identified, which are summarized in Table 3. Three of these had to be excluded from the synthesis, since the studies involved either only one subject or did not report the excitation magnitude (Coermann, 1962; Griffin et al., 1978). The selected datasets include a total of 125 adult subjects with body mass up to nearly 100 kg, exposed to either sinusoidal (up to 4.85 m/s^2 rms) or random vertical vibration (up to 3.0 m/s^2 rms within 2–12 Hz range), while sitting with an upright erect or relaxed posture with no back support. Although the individual or mean body masses were not reported in a few of the selected studies (Mertens, 1978; Hinz et al., 2001), these were retained since the body mass effect on the seat-to-head transmissibility is not as pronounced as it is seen in the apparent mass. Attempts were made to include the datasets reported under excitations in the vicinity of 1 m/s^2 rms, when available.

2.3. *Studies reporting biodynamic responses of standing body under vertical vibration*

Table 4 summarizes the studies reporting the biodynamic responses of standing subjects exposed to vertical vibration. A review of the experimental conditions employed in these studies clearly shows wide variations. A few studies have characterized the biodynamic responses under a wide range of postures, such as upright erect or relaxed, bent knees, standing on one leg or on heels or on toes (Coermann, 1962; Miwa, 1975; Matsumoto and Griffin, 1998a). All the relevant studies, however, have included erect or relaxed upright standing posture, which is considered to be representative of the working posture that may be anticipated in WBV environments, such as high speed crafts and ships. The majority of the reported studies have characterized mechanical impedance or apparent mass or the floor-to-head vibration transmissibility under exposure to vertical vibration, either sinusoidal or random. The majority have reported phase and magnitude of impedance responses, but only magnitude of the floor-to-head transmissibility with only one exception (Paddan and Griffin, 1993). The synthesis of the datasets reported for standing subjects was thus limited to apparent mass only.

A total of six datasets could be identified for the possible synthesis; three of these reporting the mechanical impedance under sinusoidal vibration with acceleration amplitude ranging from 0.1 to 0.5 g peak (Coermann, 1962; Edwards and Lange, 1964; Miwa, 1975) and the remaining three describe the apparent mass under random vibration of rms acceleration ranging from 0.125 to 2 m/s^2 (Matsumoto and Griffin, 1998a, 2000; Subashi et al., 2006). The majority of the studies have reported the biodynamic responses under vibration from a low frequency of 0.5 or 1 Hz up to 20 Hz, with the exception by Miwa (1975), which reports the responses in the 3–100 Hz range.

All of the six datasets are considered to satisfy the selection criteria, although some of the experimental conditions were defined only vaguely in some of the studies. Coermann (1962) conducted experiments with 8 adult male subjects with body mass in the 70–99.5 kg range (mean mass = 86.2 kg) under sinusoidal vibration of peak magnitude in the 0.1 to 0.5 g peak range. The impedance magnitude and phase responses of a single subject with body mass of 84 kg, however, were reported, while the

Table 4
Summary of experimental conditions employed in studies reporting biodynamic responses of standing human body to vertical vibration.

Author(s)	*n*	Mass range, kg (mean)	Posture	Excitation			Function Reported
				Type	Frequency (Hz)	Magnitude	
Coermann (1962)	1	84	Upright- Erect	sine	1–20	≤0.5 g peak	MI magnitude and phase
Edwards and Lange (1964)	2	77.7, 84 (81)	Upright -Relaxed	Sine	1–20	0.2, 0.35, 0.5 g peak	MI magnitude and phase (individual)
Miwa (1975)	20	50–76[a] (59)	Upright -Erect	sine	3 –200	0.1 g peak	MI – Mean magnitude and phase
Matsumoto and Griffin (1998a)	12	Median 73.5	Normal upright,	Random	0.5–30	0.125, 0.25, 0.5, 1.0, 2 m/s^2 rms	AM - Median normalized magnitude and phase
Matsumoto and Griffin (2000)	8	63–83[b] (72)	Normal standing	Random	0.5–20	1.0 m/s^2 rms	AM – Median normalized magnitude and phase
Subashi et al. (2006)	12	65.6–102 (77.5)	Normal standing	Random	0.5–20	0.125, 0.25, 0.5 m/s^2 rms	Median AM magnitude and phase

[a] Body mass range of 5 subjects.
[b] Body mass range estimated from individuals' data.

vibration magnitude is vaguely specified as ‘up to 0.5 g’. Edwards and Lang (1964) presented the impedance magnitude and phase responses of two individual subjects under sinusoidal vibration of acceleration amplitudes of 0.2, 0.35 and 0.5 g peak. The mean of the two individual data corresponding to 0.2 g peak are obtained for the synthesis. Miwa (1975) reported the mean impedance magnitude and phase responses of 20 adult male subjects under 0.1 g peak sinusoidal vibration in the 3–100 Hz range, while the body mass is reported for only 5 subjects (50–76 kg; mean = 58.8 kg). This mass range is assumed to be representative of the entire population. Matsumoto and Griffin (1998a) and Subashi et al. (2006) reported the median apparent mass properties of 12 subjects under random vibration. The median responses and body mass are considered to be close to the mean values, assuming symmetric distribution. Another study by the same authors (Matsumoto and Griffin, 2000) reports median apparent mass of 8 subjects exposed to 1 m/s^2 random vibration, while the body mass data is not defined, which was estimated from the data presented for individual subjects.

2.4. *Studies reporting biodynamic responses of seated body under horizontal vibration*

The biodynamic responses of the seated body to horizontal vibration have been reported in relatively fewer studies than those under vertical vibration. This is most likely due to relatively higher magnitudes of vertical vibration encountered in vehicles, which cause more detrimental effects in view of operators’ health and safety. The relatively low stiffness of tires employed in off-road vehicles together with high location of the operator, and presence of localized slopes and cross-slopes in the terrains can lead to considerable horizontal vibration at the operator location. Many studies have shown that magnitudes of fore-aft (x) and lateral (y) vibration at the driver’s seat of off-road tractors, forklift trucks, and port cranes could be either comparable or exceed the magnitudes of vertical vibration (Kumar et al., 2001; Marsili et al., 2002; Bovenzi et al., 2002).

Despite the high magnitudes of horizontal vibration, the biodynamic responses of the seated body to fore-aft and lateral vibration have been addressed in a few studies. The experimental conditions associated with reported studies on driving-point responses to fore-aft and lateral vibration are summarized in Tables 5 and 6, respectively. The studies reporting responses for sitting posture with feet supported on either a stationary or vibrating foot support are included in the synthesis.

A total of 12 studies characterizing the driving-point biodynamic responses of seated body to fore-aft vibration were initially identified, which are summarized in Table 5. Owing to the strong influence of the back support condition on the measured apparent mass, the datasets reported for postures involving no back support and a back support were synthesized separately. A total of 11 and 6 studies could be identified for the no back and back supported postures, respectively, which satisfied the selection criteria. Furthermore, the datasets reported for male subjects alone were considered due to the limited data available for the female subjects.

The majority of the studies have reported responses under sinusoidal or random vibration of different magnitudes, while the lower and upper limits of the frequency span vary from 0.25 to 2 and 10 to 100 Hz, respectively. The data up to only 10 Hz are considered for the synthesis, since the magnitudes are generally very small at frequencies above 10 Hz. Attempts were made to select data reported under excitation magnitudes equal or closest to 1 m/s^2 rms over a frequency range up to 20 Hz, which is most commonly used in the reported studies. Assuming constant power spectral density of the acceleration due to excitation, this will

Table 5
Summary of experimental conditions employed in studies reporting biodynamic responses of seated human body to fore-aft vibration.

Author(s)	n (gender)	Mass -kg (mean)	Feet support	Sitting conditions		Excitation			Function Reported
				Posture	Back support	Type	Frequency (Hz)	Magnitude (m/s^2)	
Fairley and Griffin (1990)	8 (M)	57-85 (65.7)	Vibrated	Upright	None Vertical	Random	0.25–20	0.5, 1.0, 2 rms	Mean AM magnitude and individual AM phase
Holmlund and Lundström, (1998)	15(M) 15(F)	55–93 (75) 54–76 (63)	Stationary	Upright - erect/ relaxed	None	Discrete sine	1.13–80	0.25, 1.0, 1.4 rms	Mean MI magnitude and phase
Mansfield and Lundström (1999)	15(M) 15(F)	NR (75.8) NR (62.0)	Stationary	Upright Arms folded	None	Random	1.5–20	.25, .5, 1.0 rms	Median AM normalized magnitude
Holmlund and Lundström, (2001)	15(M) 15(F)	55–93 (75) 54–76 (63)	Stationary	Upright - erect/ relaxed	None	Discrete sine	2–100	0.25, 1.0, 1.4 rms	Mean MI magnitude and phase
Holmlund (1999)	3 (M)	74[1]	In-vehicle	Upright - erect/ relaxed	None	In-vehicle	–	NR	Mean MI magnitude only
Mandapuram et al. (2005)	8 (M)	59–92 (71.2)	Vibrated	Upright -relaxed	None, Vertical Inclined	Random	0.5–10	0.25, 0.5, 1.0 rms	Mean AM magnitude and phase
Nawayseh and Griffin (2005b)	12 (M)	56–87 (77.5)	Vibrated	Upright – Different thigh contact	None	Random	0.25–20	0.125, 0.25, 0.5, 1.0 1.25 rms	Median AM magnitude and phase
Nawayseh and Griffin (2005c)	12 (M)	63–103 (76.1)	Vibrated	Upright – Different thigh contact	Vertical;	Random	0.25–10	0.125, 0.25, 0.625, 1.25 rms	Median AM magnitude and phase
Hinz et al. (2006b)	13 (M)	61.3–103.6 (79.3)	Vibrated	Upright Hands on a bar	None	Random	0.25–30	0.25, 1.0, 2.0 rms	Mean AM magnitude
Mansfield and Maeda (2006)	15 (M)	NR (64.3)	Vibrated	Upright	None Vertical	Random	1–20	0.4 rms	Median AM magnitude Median AM magnitude & phase (back support only)
Stein et al. (2007b)	1 (M)	77.1	Vibrated	Upright – relaxed Hands on a bar	Lumbar region contact	Random	0.3–30	2.03 rms	AM magnitude and phase
Mansfield and Maeda (2007)	15 (M)	NR (64.3)	Vibrated	Upright –relaxed	None Vertical	Random	1–20	0.4, 0.8 rms	Median AM magnitude

Table 6
Summary of experimental conditions employed in studies reporting biodynamic responses of seated human body to lateral vibration.

Author(s)	*n* (gender)	Mass -kg (mean)	Feet support	Sitting conditions		Excitation			Function Reported
				Posture	Back support	Type	Frequency (Hz)	Magnitude Range (m/s^2)	
Fairley and Griffin (1990)	8 (M)	57–85 (65.7)	Vibrated	Upright	None Vertical	Random	0.25–20	0.5, 1.0, 2 rms	Mean AM magnitude and individual AM phase
Holmlund and Lundström, (1998)	15(M) 15(F)	55–93 (75) 54–76 (63)	Stationary	Upright – erect/ relaxed	None	Discrete sine	1.13–80	0.25, 0.5, 1.0, 1.4 rms	Mean MI magnitude and phase
Mansfield and Lundström (1999)	15(M) 15(F)	NR (75.8) NR (62.0)	Stationary	Upright Arms folded	None	Random	1.5–20	.25, .5, 1.0 rms	Median AM normalized magnitude
Holmlund and Lundström (2001)	15(M) 15(F)	55–93 (75) 54–76 (63)	Stationary	Upright – erect/ relaxed	None	Discrete sine	2–100	0.25, 0.5, 1.0, 1.4 rms	Mean MI magnitude and phase
Holmlund (1999)	3 (M)	74[a]	In–vehicle	Upright – erect/ relaxed	None	In-vehicle	–	NR	Mean MI magnitude only
Mandapuram et al. (2005)	8 (M)	59–92 (71.2)	Vibrated	Upright –relaxed	None, Vertical Inclined	Random	0.5–10	0.25, 0.5, 1.0 rms	Mean AM magnitude and phase
Hinz et al. (2006b)	13 (M)	61.3–103.6 (79.3)	Vibrated	Upright Hands on a bar	None	Random	0.25–30	0.25, 1.0, 2.0 rms	Mean AM magnitude
Mansfield and Maeda (2006)	15 (M)	NR (64.3)	Vibrated	Upright	None Vertical	Random	1–20	0.4 rms	Median AM magnitude Median AM magnitude & phase (back support only)
Mansfield and Maeda (2007)	15 (M)	NR (64.3)	Vibrated	Upright –relaxed	None Vertical	Random	1–20	0.4, 0.8 rms	Median AM magnitude

[a] Similar mass of the subjects.

translate to an equivalent magnitude of 0.71 m/s^2 rms over the 10 Hz range. The datasets corresponding to equivalent magnitude of 0.71 m/s^2 rms or less over the 10 Hz frequency range could be obtained from most of the studies, with the exception of one study. Stein et al. (2007b) reported the apparent mass response of a single subject exposed to 2.03 m/s^2 excitation in the 0.3–30 Hz range, which is equivalent to nearly 1.17 m/s^2, when the 10 Hz frequency range is considered. The two datasets corresponding to 0.5 and 1.0 m/s^2 excitation over the 0.5–10 Hz range, reported by Mandapuram et al. (2005) were considered for the synthesis. The majority of the selected datasets were acquired for postures with hands on the knees or arms folded with the exception of one reported for hands on a bar (Stein et al., 2007b). The data reported by Mansfield and Maeda (2007) under 0.4 m/s^2 excitation was excluded since this data was included in their other study (Mansfield and Maeda, 2006). This resulted in a total of 10 and 6 datasets in magnitude and phase, respectively, reporting the fore-aft AM of subjects seated without a back support. The AM magnitude reported by Nawayseh and Griffin (2005c) for the vertical back support was significantly lower than those in the other studies in the entire frequency range. This data was thus excluded. The remaining 4 studies reporting fore-aft AM with back support provided a total of 4 and 3 datasets for vertical and inclined backrest, respectively. These included: two datasets reported by Mandapuram et al. (2005) for each of the back support (vertical and inclined); Stein et al. (2007b) for an inclined back support; Mansfield et al. (2006) and Fairley and Griffin (1990) for a vertical back support. The magnitudes of vibration corresponding to the selected datasets are italicized and underscored in Table 5.

For the lateral (y-axis) vibration, a total of 9 studies were initially identified, which are summarized in Table 6. Only three datasets could be retained for the synthesis of driving-point responses of human subjects seated with back support and exposed to lateral vibration (Fairley and Griffin, 1990; Mandapuram et al., 2005; Mansfield and Maeda, 2006). The selected datasets were acquired for postures with hands on the knees or arms folded. Furthermore, the datasets reported for male subjects alone were considered due the availability of limited data for the female subjects. The data synthesis was performed in the frequency range up to 10 Hz due to very small magnitude of the apparent mass above 10 Hz, as in the case of x-axis apparent mass, while the data reported for magnitudes below or equal to 1 m/s^2 excitation were considered. The excitation conditions associated with the selected datasets are italicized and underscored in Table 6. The selected studies provided a total of: 9 and 5 datasets in magnitude and phase, respectively, for sitting without a back support; 4 and 3 datasets in magnitude and phase for the vertical back support; and 2 datasets in both magnitude and phase for the inclined back support.

3. Synthesis of selected datasets

The selected datasets could be synthesized to derive the ranges of most probable biodynamic responses that would be considered applicable under the selected ranges of test conditions and body masses. The resulting ranges could also serve as the target data range for identification of biodynamic models of the body subjected to whole-body vibration. A synthesis of datasets acquired in different laboratory under different, although comparable, conditions with varying body masses, however, is expected to exhibit considerable variability among the data. This may lead to wide ranges of the probable biodynamic response and thereby limit its applicability. The datasets selected for each of the biodynamic response as per the defined set of criterion are thus initially compared to examine the extent of variability.

Figs. 1 to 3 illustrate comparisons of selected data sets in apparent mass magnitude and phase of the seated body without a back support and exposed to whole-body vibration along the x-, y- and z-axes, respectively. The figures show comparisons of 10, 9 and 33 datasets in magnitude and 6, 5 and 26 in phase, respectively, which are summarized in Tables 5, 6 and 2. The selected 9 datasets describing head vertical vibration transmissibility of the seated body exposed to vertical vibration while sitting without a back support are compared in Fig. 4. Fig. 5 illustrates comparisons of 6 datasets describing the apparent mass magnitude and phase of the standing human body exposed to vertical vibration. The selected datasets, in most cases, generally show comparable

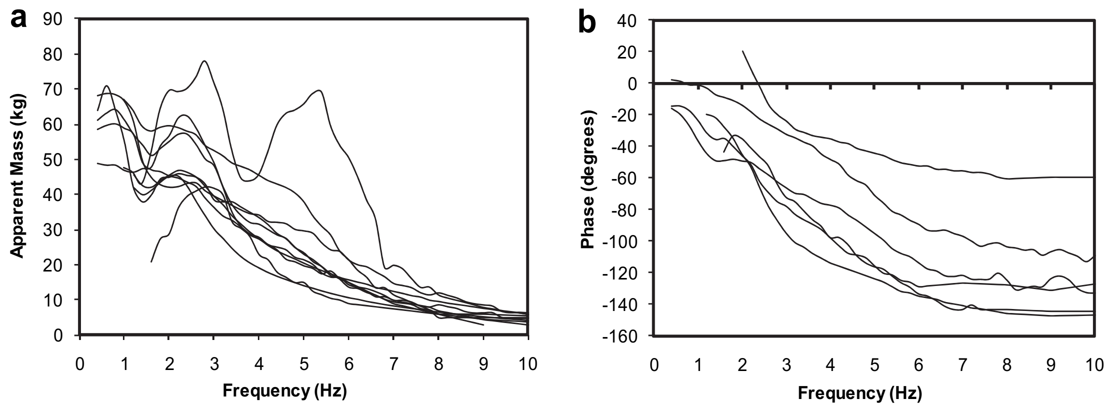

Fig. 1. Comparison of the fore-aft apparent mass responses reported for seated body with no backrest. (a) Magnitude; (b) Phase.

trends, particularly with regards to the frequencies corresponding to the magnitude peaks. Some isolated datasets, however, present anomalies with respect to the trends observed from the majority of the datasets.

In order to identify the most probable outliers that may be excluded from the synthesis, the standard deviations of the means are computed as a function of the vibration frequency for different combinations of datasets within each measure. The combination which yields an acceptable variation over the entire frequency range is subsequently retained for the synthesis and for defining the most probable ranges of idealized values applicable to the seated and standing human body under the specified conditions.

3.1. Fore-aft apparent mass of the seated body without and with a back support

The majority of the datasets describing the apparent mass response of the seated body exposed to fore-aft vibration exhibit a primary peak in the 0.5–1 Hz frequency range and a secondary peak in the 2–3 Hz frequency range (Fig. 1). The absolute magnitudes of different datasets, however, differ substantially, although most show comparable trends with magnitudes within close bounds with a few exceptions. The dataset reported by Holmlund (1999) on the basis of field measurements is considered as an obvious outlier, where the magnitude is considerably higher than the rest of the datasets in the 2 to 7 Hz frequency range. Other anomalies are evident in the datasets by Mansfield and Lundström (1999) and Hinz et al. (2006b), where the magnitudes are considerably lower up to 2.5 Hz. The datasets in fore-aft apparent mass phase, with the exception of one (Holmlund and Lundström, 1998) show a comparable trend. The phase angle is observed to be quite small at low frequencies and gradually approaches -100 to $-150°$ with increasing frequency. The phase datasets by Holmlund and Lundström (1998) is thus considered as an outlier.

Considering relatively fewer datasets, the magnitude and phase responses are treated as independent from each other. A dataset considered as a possible outlier in magnitude is not instinctively assumed to be outlier in phase. Furthermore, the lack of phase data did not imply the exclusion of the corresponding magnitude data. The mean and standard deviations of the magnitude and phase datasets with sequential exclusions of the observed possible outliers are computed and compared in an effort to identify most probable outliers. Fig. 6 presents the distribution of standard deviations of the mean for different combinations of the datasets. The exclusion of the datasets reported by Holmlund (1999), and Mansfield and Lundström (1999) yields considerable reduction in the variability of the results. Whereas, the further exclusion of the data set reported in Hinz et al. (2006b) does not yield a significant decrease in the variability at frequencies above 1 Hz. This dataset was thus retained for the data synthesis. Consequently, a total of 8 and 5 datasets in magnitude and phase, respectively, were considered suitable for defining the probable range of the apparent mass magnitude response of the body seated without a back support and exposed to fore-aft vibration.

The selected data sets identified to represent the fore-aft apparent mass responses of seated body with back support were initially divided into two back support conditions involving vertical and inclined back supports with 4 and 3 datasets, respectively, in magnitude and phase. The reported magnitude and phase responses with the two back supports are compared in Fig. 7(a) and

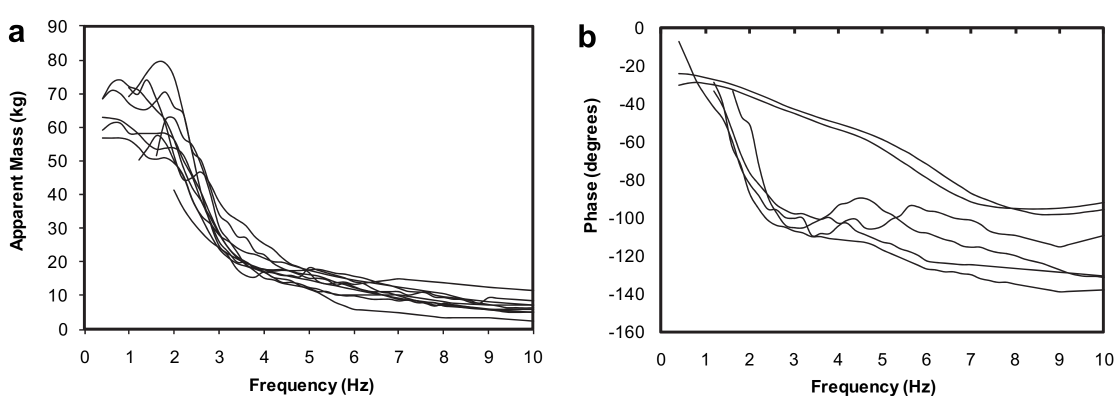

Fig. 2. Comparison of the lateral apparent mass responses reported for seated body with no backrest. (a) Magnitude; (b) Phase.

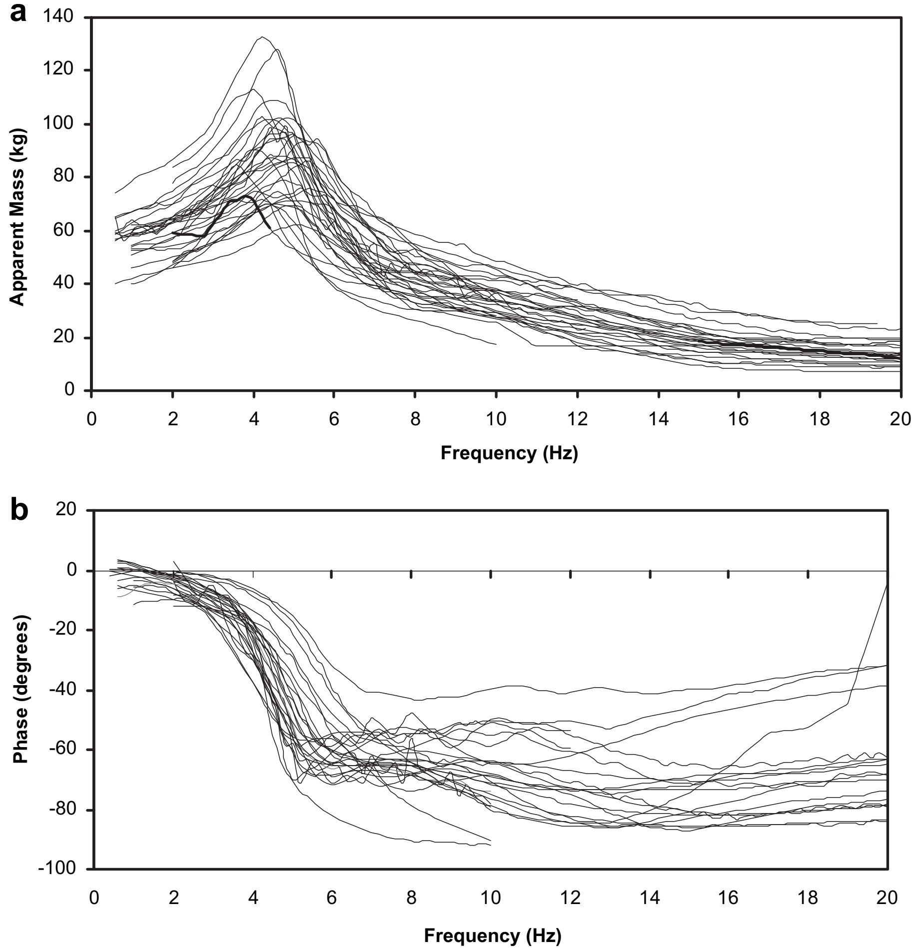

Fig. 3. Comparison of the vertical apparent mass responses reported for seated body with no backrest. (a) Magnitude; (b) Phase.

7(b), respectively. Most of the datasets exhibit a dominant peak in the 3–5 Hz frequency range, irrespective of the backrest angle. The data reported by Mansfield and Maeda (2006) for a vertical backrest and by Stein et al. (2007b) for the inclined back support, however, show considerably lower magnitude in the entire frequency range. These are thus considered clear outliers. The datasets in the phase response show comparable trends, irrespective of the back rest angle, with exception of those by Mansfield and Maeda (2006). Consequently, 3 and 2 datasets could be retained to characterize the fore-aft apparent mass magnitude and phase responses, for the vertical and inclined back support, respectively.

The results further show comparable trends in magnitude and phase for both the back supports. The means and ranges of the selected magnitude and phase datasets for both vertical (vb) and inclined (ib) backrests were also observed to be quite comparable

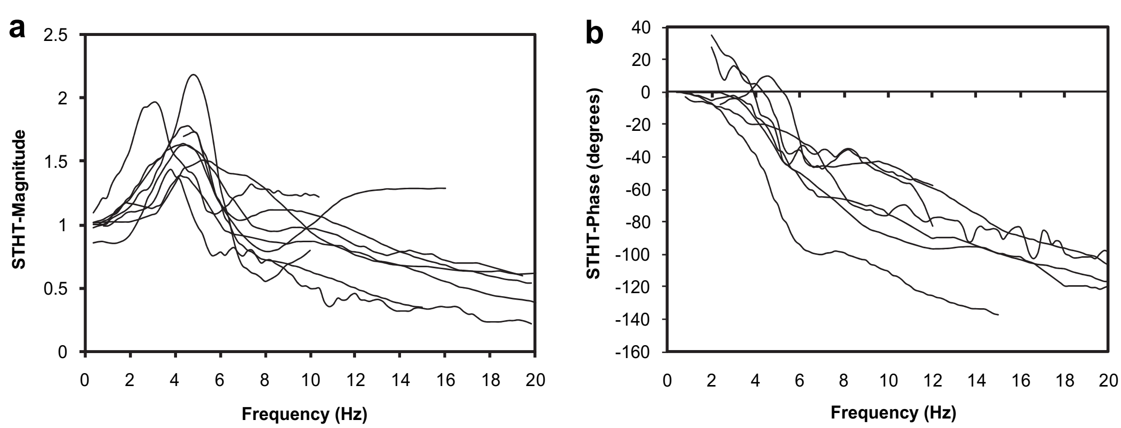

Fig. 4. Comparison of the vertical seat-to-head transmissibility (STHT) responses reported for seated body with no backrest. (a) Magnitude; (b) Phase.

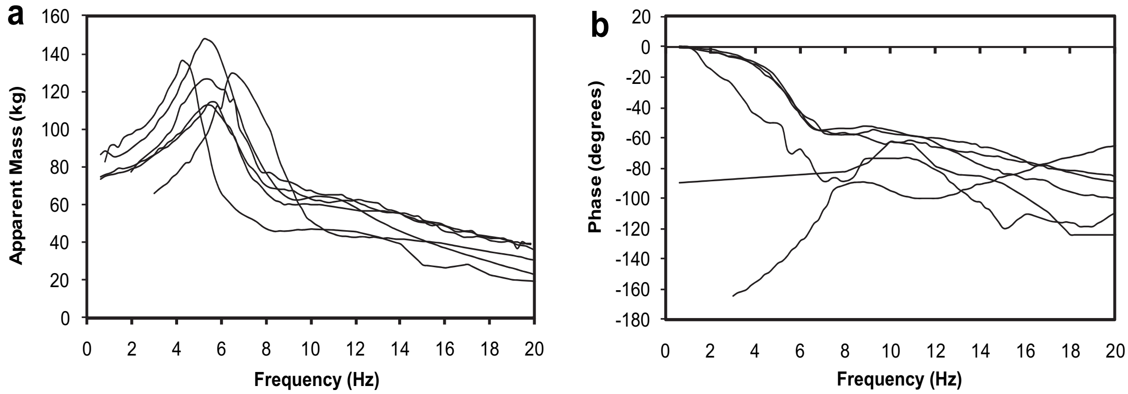

Fig. 5. Comparison of the vertical apparent mass responses reported for standing body (a) Magnitude; (b) Phase.

in both the peak magnitudes and the corresponding frequencies, suggesting relatively small effects of backrest angles considered in the studies. Consequently, the selected datasets for the two backrests are combined to yield a total of 5 datasets for both magnitude and phase for the synthesis, which represent the AM responses of the body seated with a back support with angle ranging from 90° to 102° and subject to fore-aft vibration, as illustrated in Fig. 8.

The datasets selected for the synthesis included a total of 105 and 32 adult male subjects with body mass up to nearly 100 kg, exposed to either sinusoidal or random for-aft vibration with magnitude in the vicinity of 1 m/s^2 over the frequency range of 0.25–20 Hz while sitting with an upright erect or relaxed posture with no back support and with back support, respectively.

3.2. Lateral apparent mass of the seated body without and with a back support

The datasets describing the apparent mass response of the body seated without a back support and exposed to lateral vibration generally exhibit a primary peak in the 1–2 Hz frequency range (Fig. 2). The dataset reported by Mansfield and Maeda (2007) reveals relatively higher peak magnitude and may thus be an outlier. The datasets reported by Holmlund and Lundström (1998), Holmlund (1999), Mansfield and Lundström (1999), and Holmlund and Lundström (2001) also present some anomalies since these generally describe the magnitude response at frequencies above the primary resonant frequency. The datasets in AM phase show general trends, where the phase approaches −80 to −140° near 10 Hz. Two of the datasets reported by Mandapuram et al. (2005) for 0.5 and 1.0 m/s^2 excitations, however, show relatively lower phase value at frequencies above 1.5 Hz. The datasets, however, tend to cluster within a band at frequencies above 6 Hz. All of the 5 phase datasets were thus retained for the synthesis. The mean and standard deviations of the magnitude datasets were subsequently computed by excluding the possible outliers in a sequential manner, which are compared in Fig. 9. The results suggest that exclusion of the datasets reported in Mansfield and Lundström (1999), Holmlund and Lundström (2001), and Mansfield and Maeda (2006) could yield considerable reduction in the variability of the results, while the exclusions of the datasets reported by Holmlund and Lundström (1998) and Holmlund (1999) do not yield a significant further decrease in the variability. The remaining 6 datasets were retained for the data synthesis for defining ranges of lateral apparent mass magnitude response of the body seated without a back support.

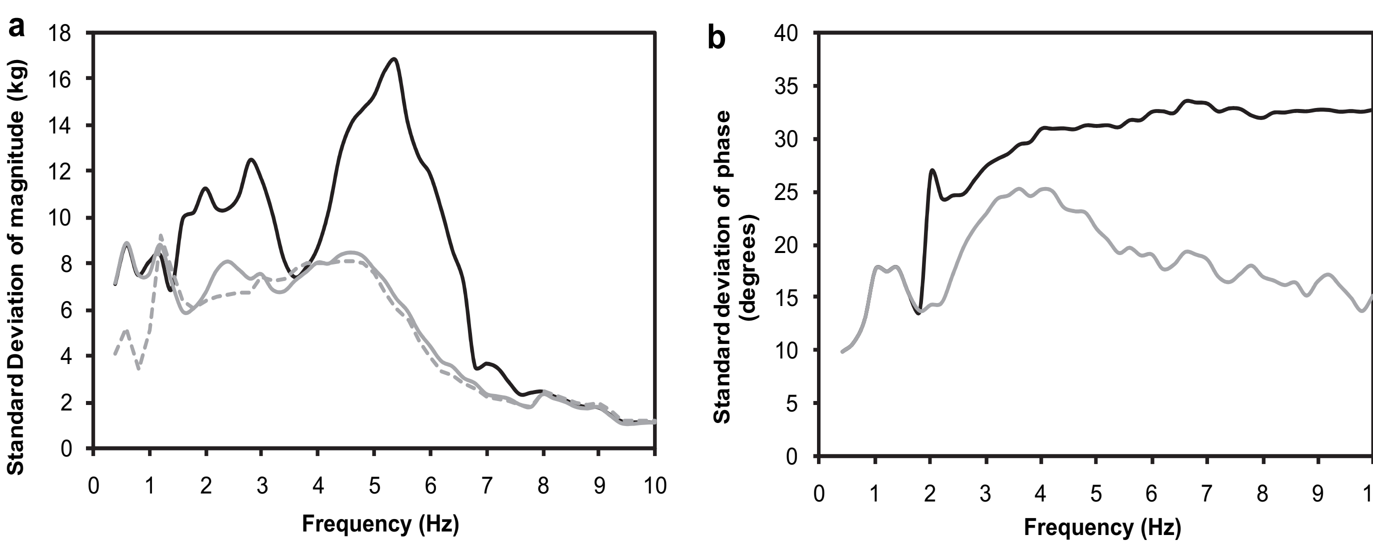

Fig. 6. Standard deviation of the mean magnitude and phase of the fore-aft apparent mass of seated body without any back support computed for various combinations of datasets: (a) Magnitude (— All datasets; — excluding Holmlund, 1999, and Mansfield and Lundström, 1999; -- excluding Holmlund, 1999; Mansfield and Lundström, 1999, and Hinz et al., 2006b) (b) Phase (— All datasets; — excluding Holmlund and Lundström, 1998).

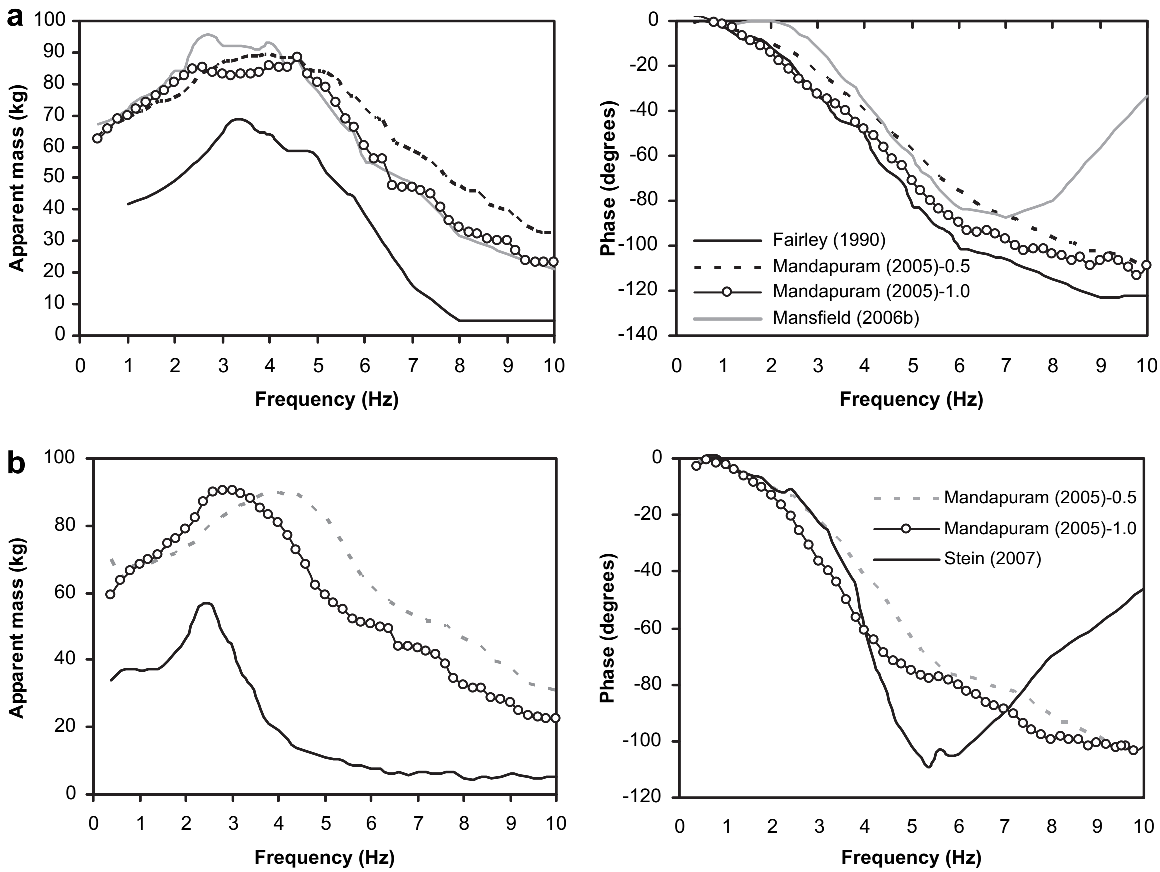

Fig. 7. Comparisons of fore-aft apparent mass magnitude and phase responses of the seated body with: (a) vertical backrest; and (b) inclined backrest.

A total of 6 and 5 datasets were obtained for the lateral AM magnitude and phase responses, respectively, of the body seated against a vertical or an inclined back support. The responses for the two back supports were quite comparable, as it was observed for the fore-aft AM response. The reported magnitude and phase datasets are compared in Fig. 10, which include two datasets by Mandapuram et al. (2005) corresponding to 0.5 and 1.0 m/s^2 excitations for both back supports. The magnitude datasets mostly exhibit consistent trends with primary peak occurring in the 1–2 Hz range. The phase dataset reported by Mansfield and Maeda (2006) is considerably different from the other datasets, and is thus considered an outlier, resulting in a total of 6 and 4 datasets in magnitude and phase, respectively, for synthesis of lateral AM response of the body seated with a back support and exposed to lateral whole-body vibration.

The datasets selected for the synthesis include a total of 92 and 31 adult subjects with body mass up to nearly 100 kg, exposed to either sinusoidal or random lateral vibration with magnitude of 1 m/s^2 or less over the 0.25–20 Hz range, while sitting with an upright erect or relaxed posture with no back and back support, respectively.

3.3. Vertical apparent mass of the seated body without and with a backrest

The datasets describing the AM magnitude and phase responses of the body seated without a back support and exposed to vertical

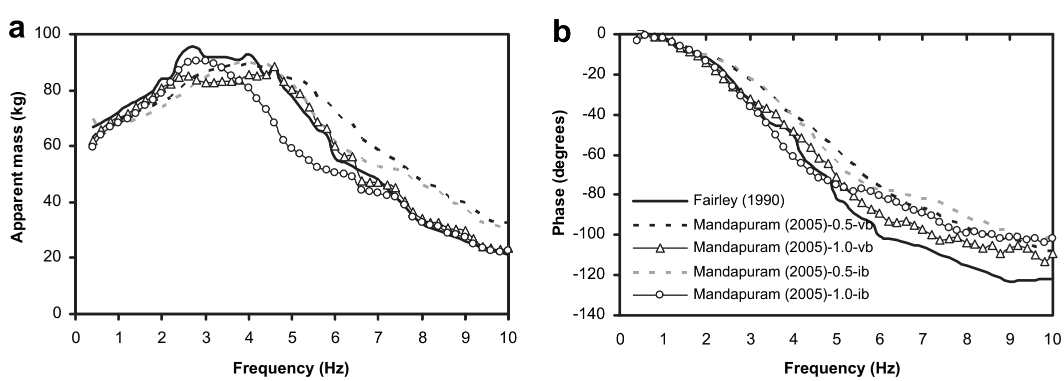

Fig. 8. Comparisons of fore-aft apparent mass responses of the body seated with either a vertical (vb) or an inclined (ib) back support: (a) Magnitude; and (b) Phase.

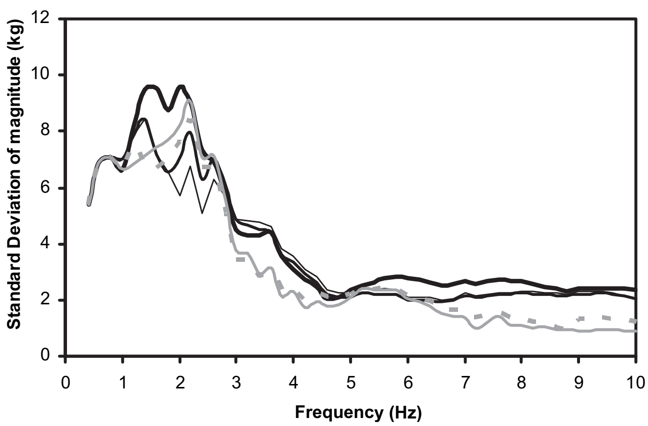

Fig. 9. Standard deviations of mean lateral apparent mass magnitude of the seated body without a back support computed for various combinations of datasets (— All datasets; — excluding Mansfield and Maeda (2007), and Mansfield and Lundström (1999); ——— excluding Mansfield and Maeda (2007); Mansfield and Lundström (1999), and Holmlund and Lundström, 1998; -- excluding Mansfield and Maeda (2007); Mansfield and Lundström (1999) and Holmlund, 1999; — excluding Mansfield and Maeda, 2007; Mansfield and Lundström (1999); Holmlund, 1999; Holmlund and Lundström, 2001).

vibration generally show common important trends (Fig. 3). The majority of the magnitude datasets exhibit a dominant peak in the 4–6 Hz frequency range, widely referred to as the primary resonance frequency. The magnitude values observed in various studies, however, differ substantially, which are attributable to variations in anthropometry of subjects and experimental conditions considered in individual studies. It has been shown that the body mass is the primary factor that strongly influences the AM magnitude, particularly at lower frequencies (Patra et al., 2008; Fairley and Griffin, 1989). The dataset reported by Suggs et al. (1969) shows considerably lower magnitude than the other datasets at frequencies above 6 Hz, and is potentially an outlier. The dataset by Holmlund et al. (2000) corresponding to a relaxed sitting posture also shows considerably lower magnitude in the 5–14 Hz frequency range. The dataset reported by Hinz and Seidel (1987) corresponding to 1.5 m/s^2 sinusoidal excitation exhibits considerable higher resonant peak and relatively higher magnitude up to 12 Hz, while the data under 3.0 m/s^2 random excitation shows peak at a lower frequency near 4 Hz. Furthermore, the datasets reported by Patra et al. (2008) for body masses of 55 kg and 98 kg form possible outliers, due to their very low and very high magnitudes at frequencies up to 5 Hz. This is obviously attributed to extreme differences in the body mass considered in this study in relation to the mean masses in other studies. In a similar manner, the dataset by Kim et al. (2005) exhibits higher resonant peak, while that by Wang et al. (2004) for mean body mass of 70 kg exhibits higher magnitudes at higher frequencies.

The above-stated datasets are thus considered to be possible outliers in the AM magnitude. The phase response datasets generally suggest a consistent trend, where the apparent mass phase is very small at very low frequencies and asymptotically approaches −90° at higher frequencies. While most of the datasets exhibit a generally good agreement in the phase response up to approximately 5 Hz, important differences are observed to arise at higher frequencies. Of the 26 datasets considered, 8 datasets are found to present important differences with respect to the majority of the datasets. These include the datasets by: Suggs et al. (1969) indicating considerably lower phase above 4 Hz; Donati and Bonthoux (1983) with lower phase above 6 Hz corresponding to random vertical excitations; Mansfield and Maeda (2005b), Mansfield and Griffin (2002) and Kim et al. (2005) with considerably higher phase in the most of the frequency range; and Huang and Griffin (2006) with sharply increasing phase above 14 Hz.

The mean and standard deviations of the vertical apparent mass magnitude and phase datasets, shown in Table 2 for the no back support condition, were subsequently computed by excluding the possible outliers, identified above, in a sequential manner, which are compared in Fig. 11(a) and 11(b), respectively. The results suggest that the exclusions of datasets reported by Suggs et al. (1969), Hinz and Seidel (1987)-Sine and -Random, Patra et al. (2008)-55 and −98 would help reduce the variability in magnitude in most of the frequency range. The exclusions of other datasets such as Holmlund et al. (2000)-R, Kim et al. (2005), Wang et al. (2004)-70 did not yield further reductions in the standard deviation of the mean. These datasets were thus retained resulting in a total of 28 datasets for synthesis of the vertical AM magnitude data of the body seated without a back support. The results presented in Fig. 11(b) suggest that the exclusion of the AM phase datasets reported by Suggs et al. (1969), Donati and Bonthoux (1983)-Random, Mansfield and Maeda (2005b), Mansfield Neil and Griffin (2002), Kim et al. (2005) and Huang and Griffin (2006) could considerably reduce the standard deviation of the mean phase, particularly at frequencies above 6 Hz. Consequently, 20 of the 26 datasets were selected to characterize the vertical apparent mass phase response of the seated body without a back support.

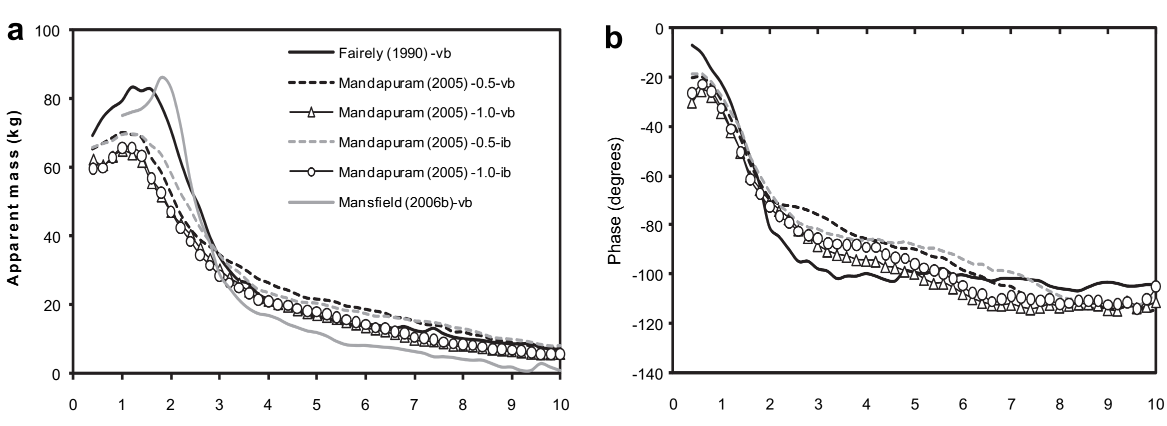

Fig. 10. Comparisons of lateral apparent mass responses of the body seated with either a vertical (vb) or an inclined (ib) back support: (a) Magnitude; and (b) Phase.

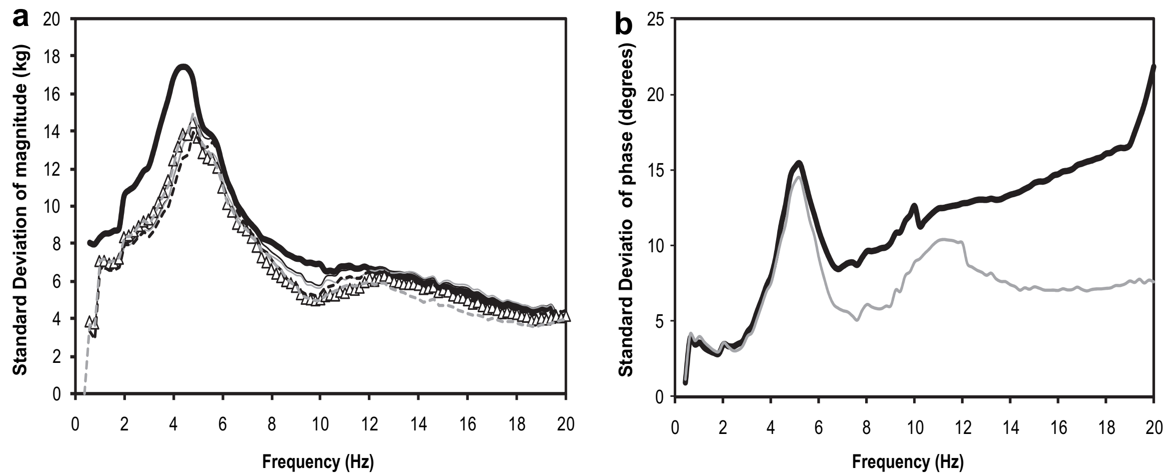

Fig. 11. Standard deviations of the mean vertical apparent mass response of body seated without a back support computed for various combinations of datasets: (a) Magnitude (— All datasets; — excluding *subset I* (Suggs et al., 1969; Hinz and Seidel, 1987-Sine, Hinz and Seidel, 1987-Random, Patra et al., 2008-55, Patra et al., 2008-98); — excluding *subset I* and Holmlund et al., 2000-R; -△- excluding *subset I* and Mansfield and Griffin (2002); ––– excluding *subset I* and Kim et al., 2005; -- excluding subset I and Wang et al., 2004-70; (b) Phase (— All datasets; — excluding Suggs et al., 1969; Donati and Bonthoux, 1983-Random, Mansfield and Griffin, 2002; Mansfield and Maeda, 2005b; Kim et al., 2005; Huang and Griffin (2006)).

The selected data sets identified to represent the vertical apparent mass responses of seated body with back support were initially divided into two back support conditions involving vertical and inclined back supports with 9 and 6 datasets in magnitude, and 4 and 6 in phase, respectively. These include two datasets by Wang et al. (2004) corresponding to mean body masses of 70 and 75.1 kg, three datasets by Patra et al. (2008) corresponding to 55, 75 and 98 kg body masses. The reported magnitude and phase responses with the two back supports are compared in Fig. 12(a) and 12(b), respectively. Most of the datasets exhibit a dominant peak in the 4–6 Hz frequency range, irrespective of the backrest angle. The data reported by Mansfield and Maeda (2005a) for a vertical backrest show considerably lower magnitude up to 6 Hz, whereas those reported by Patra et al. (2008) for the inclined back support,

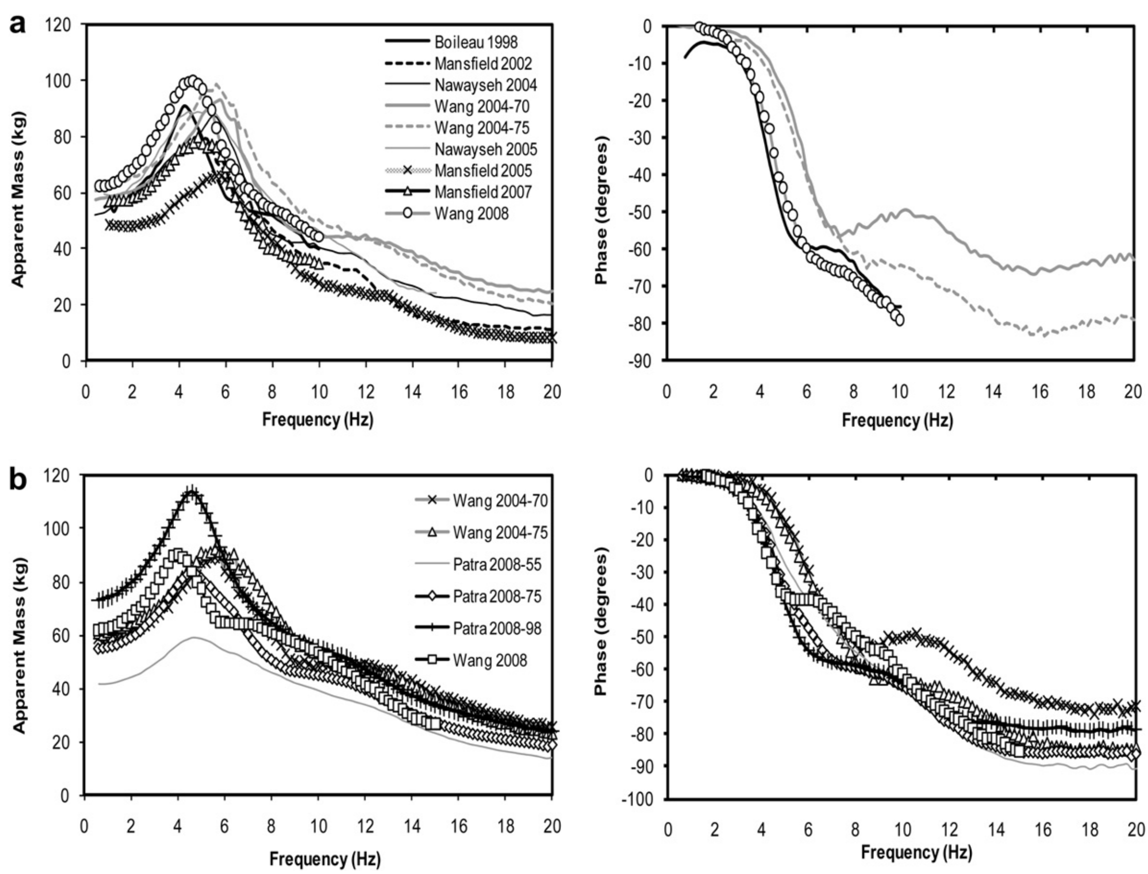

Fig. 12. Comparison of magnitude and phase responses of the vertical apparent mass reported for body seated with a: (a) Vertical backrest; and (b) Inclined backrest.

corresponding to 55 and 98 kg body masses, show considerably lower and higher magnitudes, respectively. These are thus considered outliers. The datasets in the phase response show comparable trends, irrespective of the back rest angle. Consequently, 8 and 4 datasets are identified to characterize the vertical apparent mass magnitude and phase responses, respectively, for the vertical back support, while for the inclined back support 4 and 6 datasets in magnitude and phase are retained.

The results further show comparable trends in magnitude and phase for both the back supports, as observed for the fore-aft and lateral AM responses. Consequently, the selected datasets for the two backrests are combined to yield a total of 12 and 10 datasets in magnitude and phase, respectively, for the synthesis, which would represent the AM responses of the body seated with a back support with angle ranging from 90° to 102° and subject to vertical vibration, as illustrated in Fig. 13.

The selected datasets include a total of 316 adult male subjects with body mass up to nearly 110 kg, exposed to either sinusoidal (up to 4.85 m/s^2) or random vertical vibration (up to 2.0 m/s^2 rms within 0.5–20 Hz range), while sitting with an upright erect or relaxed posture with no back support. The datasets involving a back support included a total 121 adult male subjects.

3.4. Vertical apparent mass of the standing body

The datasets describing the AM magnitude and phase responses of the standing body exposed to vertical vibration generally show common important trends (Fig. 5). The majority of the datasets exhibit a dominant peak around 6 Hz, while extreme scatter is evident in the phase responses. A closer observation of the magnitude curves indicates that 2 of the 6 datasets are possible outlier. These include the data by Miwa (1975) and Edwards and Lange (1964), which shows considerably higher and lower resonance frequencies, respectively, compared to the other datasets. Similarly 2 of the 6 datasets in phase exhibit very different trends (Miwa, 1975; and Coermann, 1962). The results presented in Fig. 14 suggest that the exclusion of these datasets could minimize the variability in the magnitude as well as phase responses over the entire frequency range. Consequently, a total of 4 datasets each in magnitude and phase responses are identified to characterize the apparent mass response of the standing body exposed to vertical whole-body vibration.

The datasets selected for the synthesis include a total of 55 adult male subjects with mean body mass up to nearly 100 kg, exposed to either sinusoidal or random vertical vibration with magnitude below 0.5 g, while standing assuming an upright erect or relaxed posture. The test conditions corresponding to datasets selected for the synthesis are italicized and underscored in Table 4, whenever multiple datasets are reported in a single study.

3.5. Vertical seat-to-head vibration transmissibility of the seated body

The vast majority of the reported datasets in STHT indicate a dominant peak occurring within the 4–6 Hz frequency range (Fig. 4), while considerable scatter in both magnitude and phase data are evident. Some of the magnitude datasets also suggest the presence of a secondary peak at frequencies above 8 Hz. The variations in the frequency corresponding to the primary peak magnitude amongst the datasets, however, are significantly larger than those observed in the vertical apparent mass. The two datasets reported by Hinz and Seidel (1987) corresponding to 1.5 m/s^2 sinusoidal and 3.0 m/s^2 random excitation show primary peaks occurring at very low frequencies near 2.3 and 3.3 Hz. The dataset by Zimmermann and Cook (1997) shows relatively higher magnitude at frequencies above 11 Hz, while that by Hinz et al. (2001) indicates relatively lower magnitude in most of the frequency range. The selected phase datasets also show considerable variability among them. The two datasets by Hinz and Seidel (1987) consistently show leading phase response up to nearly 4 Hz, while that by Wang et al. (2008) show considerably lower phase in the entire frequency range.

The mean and standard deviations of the magnitude and phase datasets were subsequently computed by excluding the possible outliers in a sequential manner, which are compared in Fig. 15. The results suggest that exclusions of the identified datasets by Hinz and Seidel (1987) and Hinz et al. (2001) yields lower standard deviation in the magnitude. Further exclusion of the data by Kitazaki and Griffin (1997) resulted in reduction in variability only in a narrow frequency range around 5 Hz. This dataset was thus retained for the synthesis resulting in a total of 6 datasets describing the STHT magnitude responses of the body seated without a back support and exposed to vertical vibration. Similarly, the variability in the phase response could be considerably reduced by excluding the identified datasets by Hinz and Seidel (1987) and Wang et al. (2008), as seen in Fig. 15(b), which resulted in 4 datasets in STHT phase for further synthesis.

4. Probable ranges of biodynamic responses

The mean and the ranges of the selected datasets are computed to identify ranges of idealized or most probable values

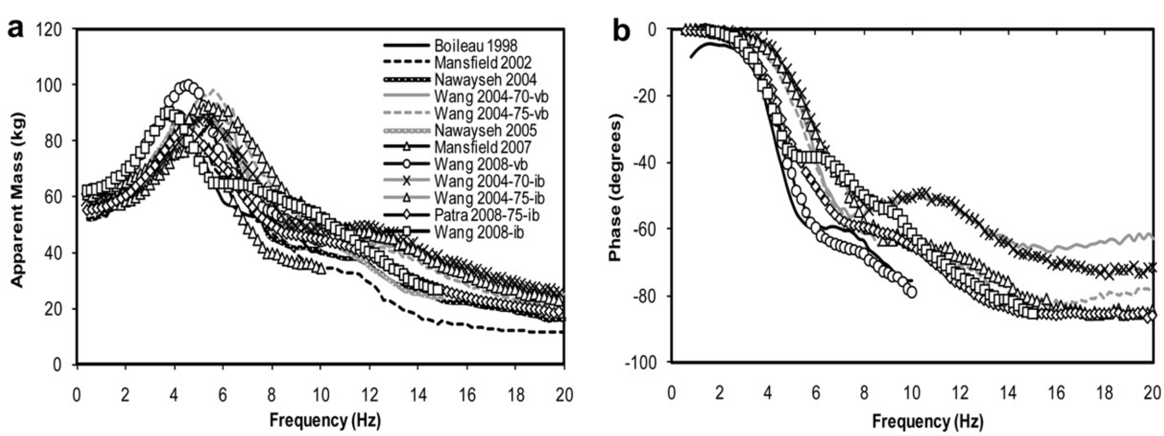

Fig. 13. Vertical apparent mass responses of body seated with either a vertical or inclined back support: (a) Magnitude; and (b) Phase.

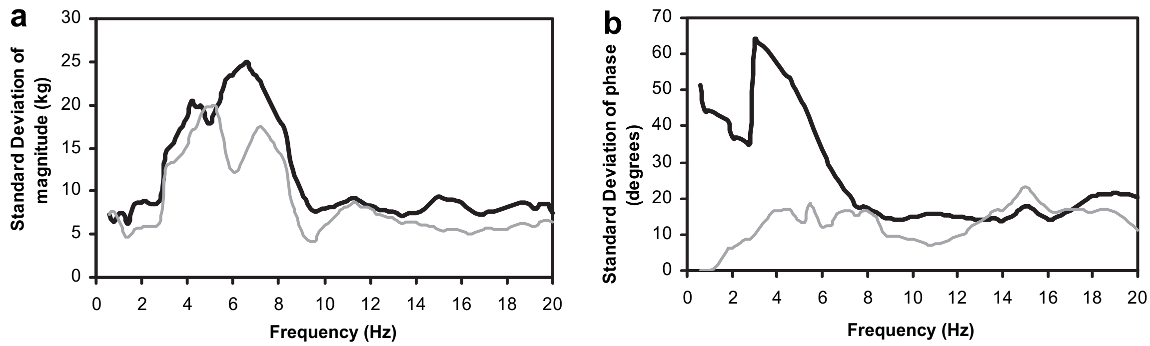

Fig. 14. Standard deviations of mean vertical apparent mass of standing body computed for different combinations of selected datasets: (a) Magnitude (— All datasets; — excluding Edwards and Lange, 1964; Miwa, 1975); (b) Phase (— All datasets; — excluding Coermann, 1962; Miwa, 1975).

characterizing the biodynamic response of the seated and standing body under particular conditions considered. The ranges of biodynamic responses to vertical vibration are computed in the 0.5–20 Hz frequency range, while those to fore-aft and lateral vibration are identified in the 0.5–10 Hz range. The computed upper and lower bound curves are subsequently smoothened using moving average technique.

Figs. 16 and 17 illustrate the ranges of apparent mass magnitude and phase responses of the body seated without and with a back support, respectively, and exposed to vibration along the *x*-, *y*- and *z*-axis. The figures show the mean values of the selected datasets together with the standard deviations of the means. The ranges are defined by the upper and lower bounds of the selected datasets as a function of the vibration frequency. The limits of AM responses, defined in Fig. 16(a), are considered applicable under sinusoidal and random fore-aft vibration with magnitude ranging from 0.4 to 1.0 m/s^2 in the 0.5–10 Hz range for 55 to 103.6 kg body masses, while sitting without a back support. The ranges of AM responses of the body seated with a back support to fore-aft vibration, shown in Fig. 17(a), are considered applicable for body mass varying from 57 to 92 kg, while exposed to random fore-aft vibration of magnitude from 0.4 to 1.0 m/s^2. The results of the synthesis clearly show wide ranges of fore-aft AM magnitude and phase, which are attributable to differences in the body mass and vibration magnitude considered in different studies. The peak values of the coefficient of variation (COV) of the magnitude data approached nearly 35% at 5 Hz for the unsupported back and 20% at frequencies above 8 Hz for the back supported posture. The peak COV values of the magnitude, however, were observed to relatively small in the vicinity of the resonance frequencies for both the postures (15% for no back and only 5% for the back supported postures). The peak COV of the phase data approached nearly 80% and 23% for without and with back support, respectively. The peak COV in the phase data occurred around 2 Hz.

The ranges of apparent mass responses to lateral vibration, illustrated in Fig. 16(b) and 17(b), are considered applicable for 0.4–1.0 m/s^2 sinusoidal or random vibration with body mass varying from 55 to 103 kg for the back not supported condition, and under 0.4–1.0 m/s^2 random vibration with 57–92 kg body for the back supported posture, respectively. The ranges show relatively less variations in both magnitude and phase compared to those derived under fore-aft vibration. The peak COV in the magnitude data approached 13% and 24%, respectively, for the back unsupported and supported postures, in the vicinity of the primary resonance. The peak COV in the phase data approached 39% and 10% for the back unsupported and supported postures, respectively, which occurred near the primary resonance frequency. The relatively lower values of COV of both the fore-aft and lateral AM data for the back supported posture are attributable to limited datasets that were reported by only three laboratories.

Fig. 16(c) and 17(c) show the ranges of AM responses of the body seated without and with a back support, respectively, while

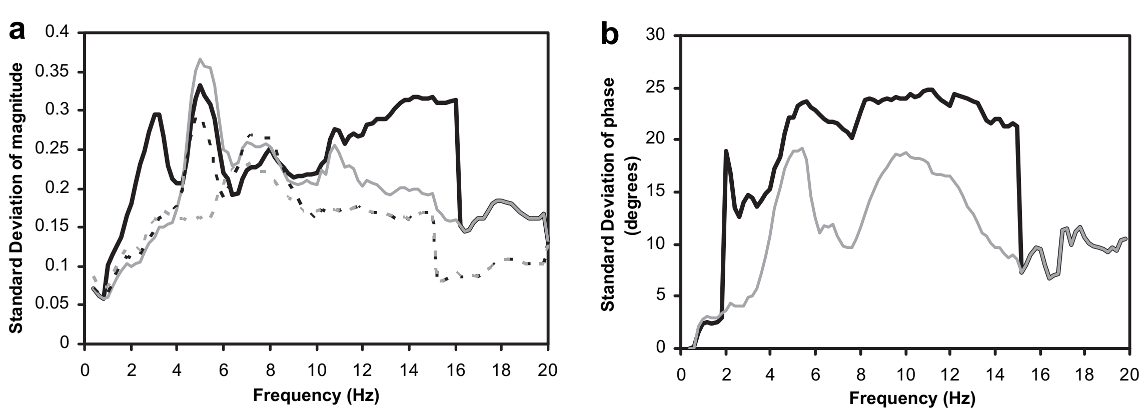

Fig. 15. Standard deviations of mean vertical STHT response of body seated without a back support computed for different combinations of selected datasets: (a) Magnitude (— All datasets; — excluding Hinz and Seidel, 1987–1.5 and −3.0, and Zimmermann and Cook, 1997; — excluding Hinz and Seidel, 1987–1.5 and −3.0, Zimmermann and Cook, 1997 and Hinz et al., 2001; — excluding Hinz and Seidel, 1987–1.5 and −3.0, Zimmermann and Cook, 1997; Hinz et al., 2001 and Kitazaki and Griffin, 1997); (b) Phase (— All datasets; — excluding Hinz, 1987–1.5 and −3.0, and Wang, 2008).

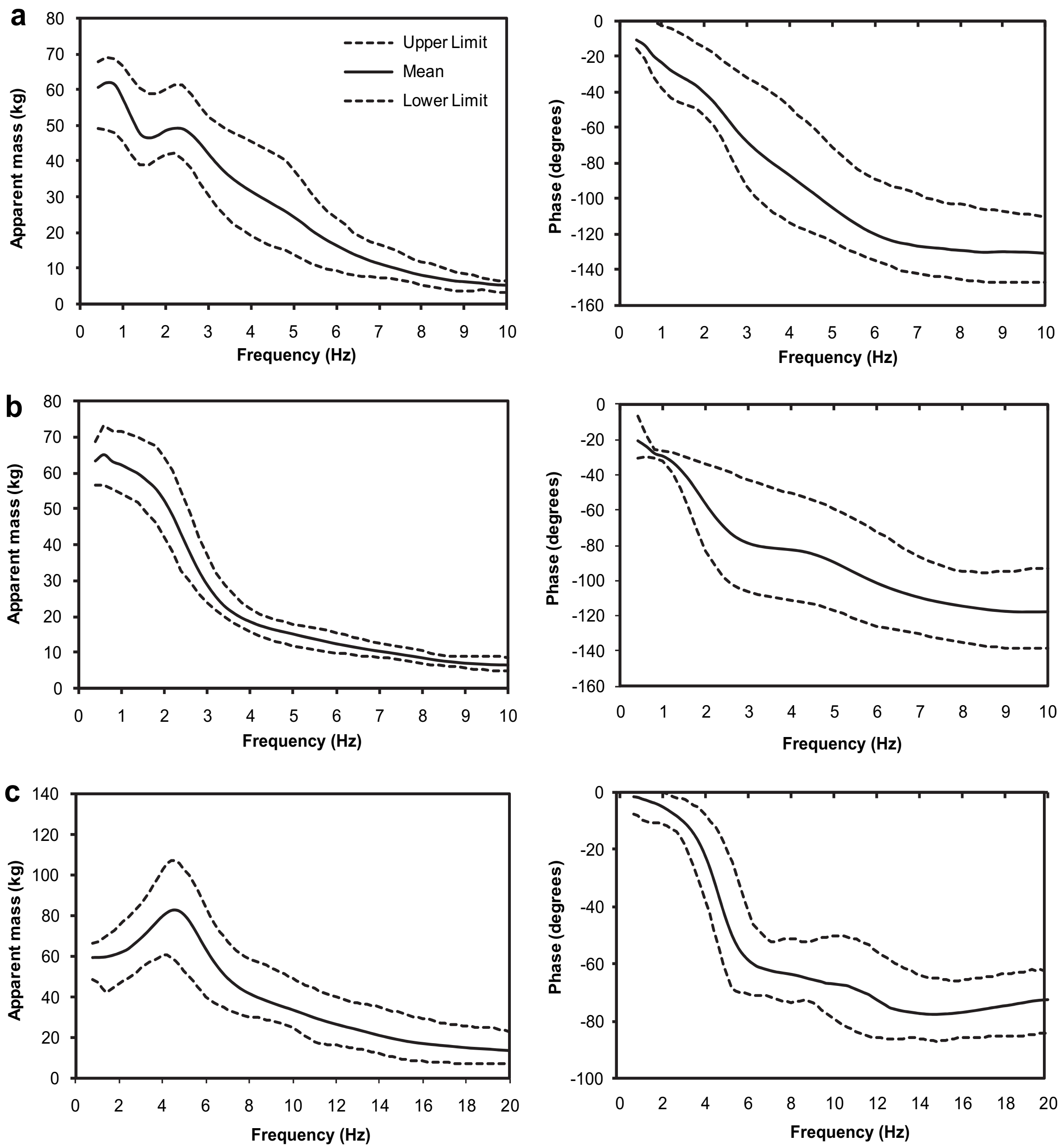

Fig. 16. Idealized ranges of apparent mass magnitude and phase responses of body seated without a back support under vibration along: (a) Fore-aft direction; (b) Lateral direction; and (c) Vertical direction.

exposed to vertical vibration in the 0.5–20 Hz frequency span. For sitting without a back support, the limits would be applicable for body mass ranging from 49 to 107 kg under exposure to sinusoidal or random vertical vibration of 0.8–2.0 m/s^2 magnitude. The limits are considered valid for 0.625 to 1 m/s^2 random vertical vibration and body mass in the 62–106 kg range for the back supported posture. The ranges exhibit wide variations in both magnitude and phase. The peak values of COV of the magnitude data approached 18% and 15% near the primary resonance for the back unsupported and supported postures. The COV values, however, were above 30% at higher frequencies due to relatively small magnitudes. The peak COV of the phase data approached 33% and 60% near the primary resonance frequency, respectively, for the two back support conditions. The COV of the vertical AM magnitude data are relatively lower compared to those observed under x- and y-axis vibration, particularly for the back supported condition. This is most likely attributed to relatively smaller range of vertical vibration magnitudes associated with the selected datasets.

The limits of AM response of the standing body (body mass: 63–102 kg) under exposure to sinusoidal or random vertical vibration of magnitude of 0.5–1.0 m/s^2 are presented in Fig. 18. The results show considerably wider ranges in magnitude and phase compared to those identified for the seated body, which may partly attributed to fewer datasets ($n = 4$) reported by three different laboratories. The peak values of COV in the magnitude and phase data approached nearly 20% and 90%, respectively, at frequencies below 5 Hz.

The ranges of STHT magnitude and phase responses of the human body seated without a back support and exposed to vertical vibration along the z-axis are defined in a similar manner in Fig. 19.

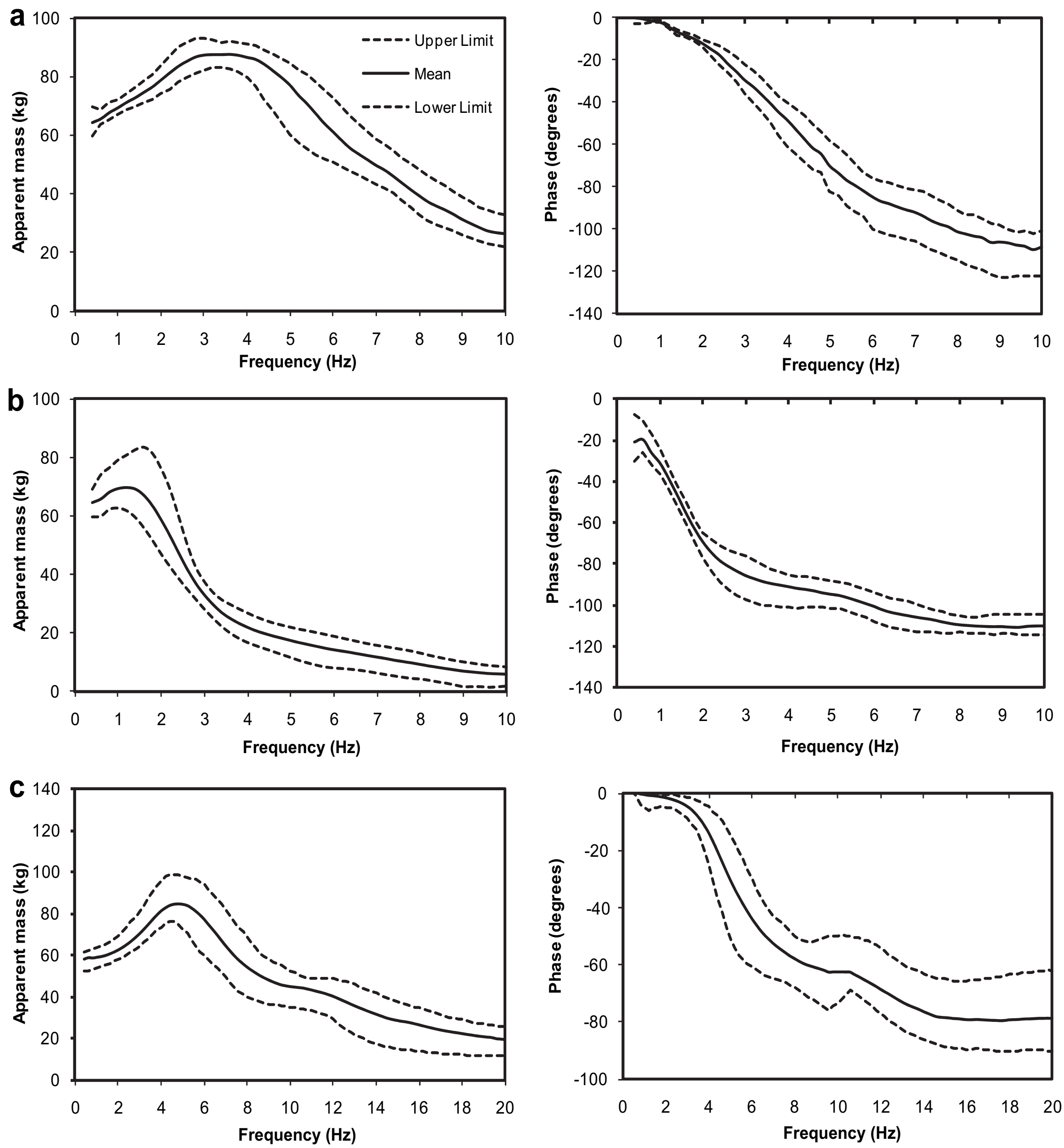

Fig. 17. Idealized ranges of apparent mass magnitude and phase responses of body seated with a back support under vibration along: (a) Fore-aft direction; (b) Lateral direction; and (c) Vertical direction.

These limits in vertical STHT would be considered valid for sitting without a back support under exposure to random or sinusoidal vibration of magnitude ranging from 1 to 2.75 m/s^2. The defined limits are derived from selected datasets involving body mass variations in the 58–99 kg span, although the effect of body mass on the STHT responses has been reported to be negligible. Both the magnitude and phase limits are considerably wide, particularly in the vicinity of the primary resonance frequency. The peak COV in the magnitude and phase data approached nearly 29% and 113% near 7 Hz and 5 Hz, respectively.

5. Discussions

The international standard, ISO-5982 (2001), defines the idealized ranges of AM and STHT magnitude and phase responses of the human body seated without a back support and exposed to vertical vibration of magnitude up to 5 m/s^2. The standard does not provide such limits for the back supported posture and for responses to fore-aft and lateral vibration. The comparisons of the most probable ranges of vertical AM and STHT, identified from the synthesis of selected datasets in this study, with the standardized limits (Fig. 20) show considerable differences in the primary resonance frequencies observed from both the AM and STHT magnitude data, and in the magnitude responses, particularly at frequencies above 9 Hz. The mean and upper limits of vertical AM and STHT responses derived from the synthesis show relatively higher primary resonance frequencies (4.6–4.8 Hz) compared to that observed from the standardized ranges (near 4 Hz), and relatively higher peak magnitude of the mean curves in both the STHT and the AM responses. The considerable lower primary frequency of the

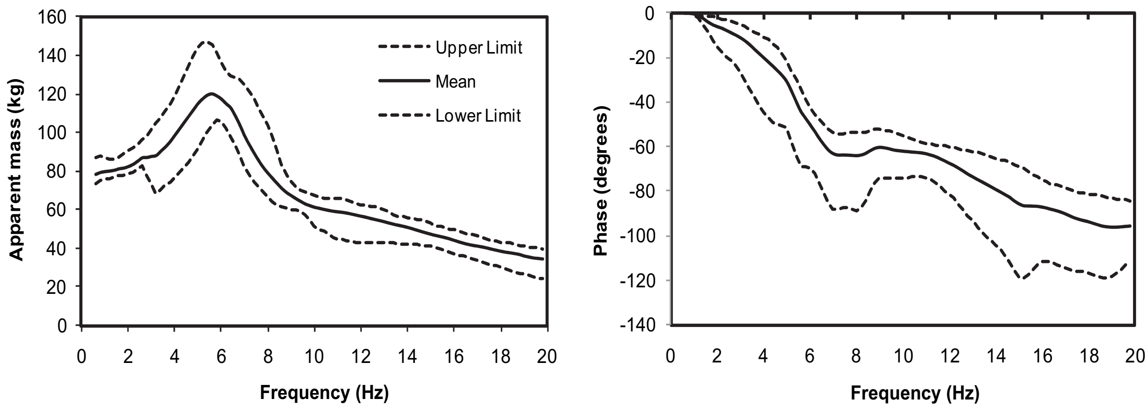

Fig. 18. Idealized ranges of apparent mass magnitude and phase responses of standing human body exposed to sinusoidal or random vertical vibration of magnitude of 0.5–1.0 m/s2 (body mass: 63–102 kg).

standardized ranges is attributable to the considerations of datasets obtained under relatively higher magnitudes of vibration (up to 5 m/s^2). The mean and limits of the AM data corresponding to no back support also exhibit some differences with respect to the standardized values, although the trends are quite comparable. The identified limits in STHT data show relatively larger deviations in both the magnitude and phase. This may be attributed to the differences in the datasets considered in the present synthesis and the study leading to the standardized ranges, which were based on 8 and 7 datasets in AM magnitude and phase, and 4 and 3 datasets in STHT magnitude and phase, respectively (Boileau et al., 1998). The present synthesis is based on selected 28 and 20 datasets in AM magnitude and phase, and 6 and 4 in STHT magnitude and phase, respectively.

Considering that the biodynamic responses of the seated or standing body exposed to whole-body vibration is dependent on many confounding factors in a highly complex manner, the identification of ranges of most probable responses require careful consideration of the major influencing factors. The reported datasets showed large variability among them, although the data were limited to comparable experimental conditions involving specific sitting posture, feet support and ranges of vibration excitation levels. The variability among the selected datasets, however, is greatly limited due to controlled conditions. Significantly larger variations could be observed when the limits on the experimental conditions are relaxed, as it could be seen from the synthesis of vertical STHT data reported by Paddan and Griffin (1998).

Among the factors influencing the AM responses, the body mass is known to be most significant one followed by the back support and the excitation magnitude. Only a few studies, however, have reported data for particular body masses limited to vertical vibration alone (Patra et al., 2008; Wang et al., 2004), which clearly show the most pronounced effect of the body mass on the AM responses, while the effect is small on the STHT responses. The influence of body mass on the AM responses of standing subjects exposed to vertical vibration has not yet been attempted. Other studies have shown significant effects of the back support on both the AM and STHT responses (Fairley and Griffin, 1989; Wang et al., 2004); the effect of back support on fore-aft AM was observed to be even more pronounced (Mandapuram et al., 2005; Fairley and Griffin, 1990). The effect of vibration magnitude is relatively small compared to those of the body mass and the back support, particularly when the excitation magnitudes lie in a narrow range. These suggest that the most probable ranges of the biodynamic responses be defined for specific ranges of body masses around the 5th, 50th and 95th percentile population with back unsupported and supported sitting postures. The mean and limits of biodynamic responses derived from the synthesis of reported mean datasets, irrespective of the direction of excitation, represent the grand average and overall variation among the selected datasets, respectively, corresponding

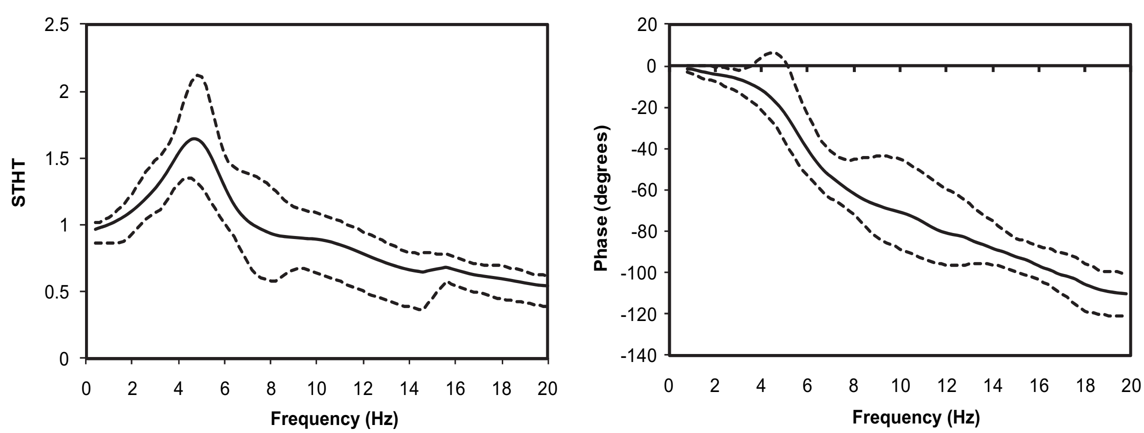

Fig. 19. Idealized ranges of magnitude and phase responses of vertical seat-to-head acceleration transmissibility for human body seated without a backrest.

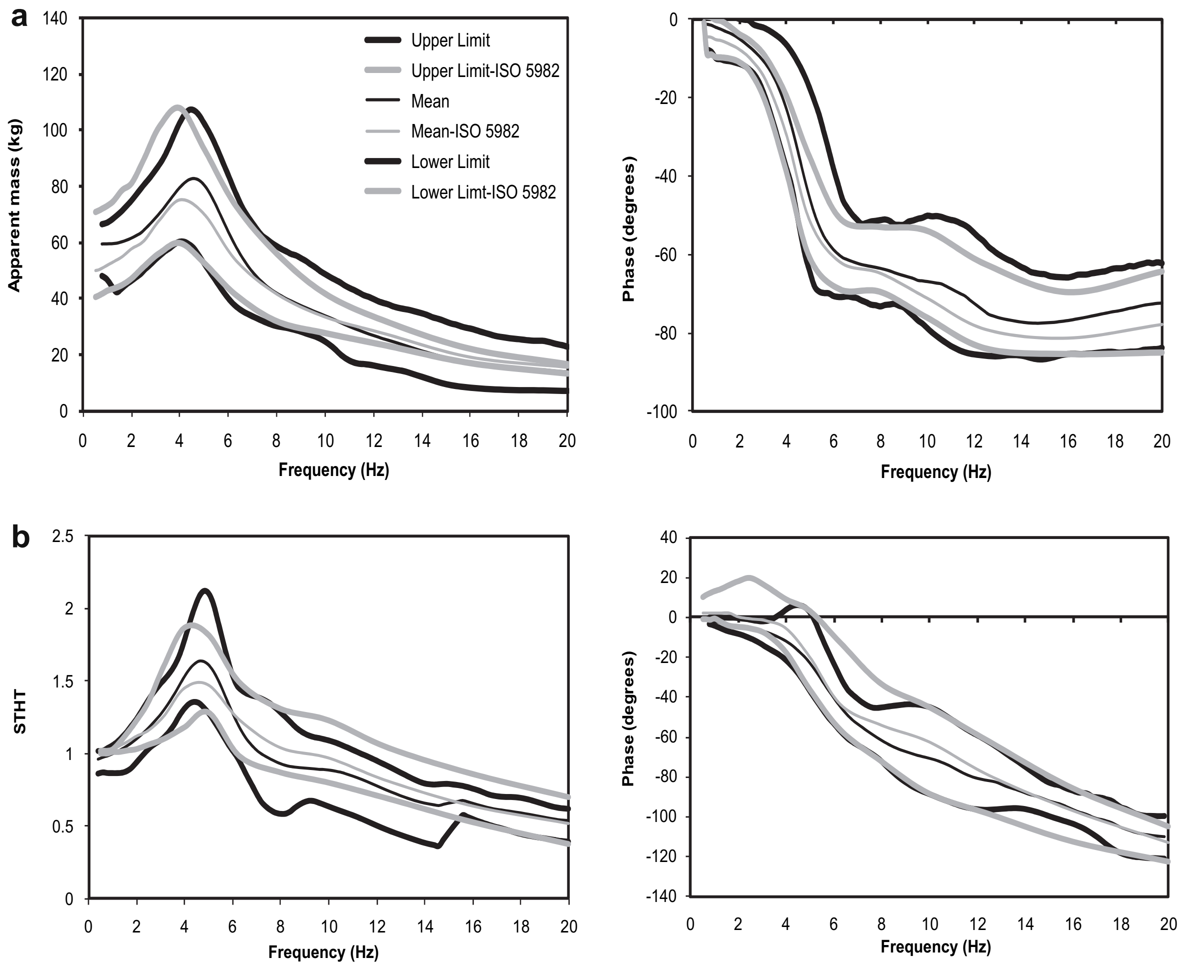

Fig. 20. Comparisons of ranges of biodynamic responses with those defined in ISO-5982 (2001): (a) Vertical apparent mass magnitude and phase; (b) Vertical STHT magnitude and phase.

to the chosen postural and vibration condition. The present study defines the ranges corresponding to two different back support conditions, while these cannot be associated with specific body mass ranges. Fig. 21 illustrates comparisons of the AM magnitude limits with the data reported for three mass groups with mean body masses of 55, 75 and 98 kg for both back unsupported and supported sitting conditions (Patra et al., 2008). The results clearly show strong influence of the body mass suggesting the need for establishing the biodynamic response limits for specific ranges of body masses.

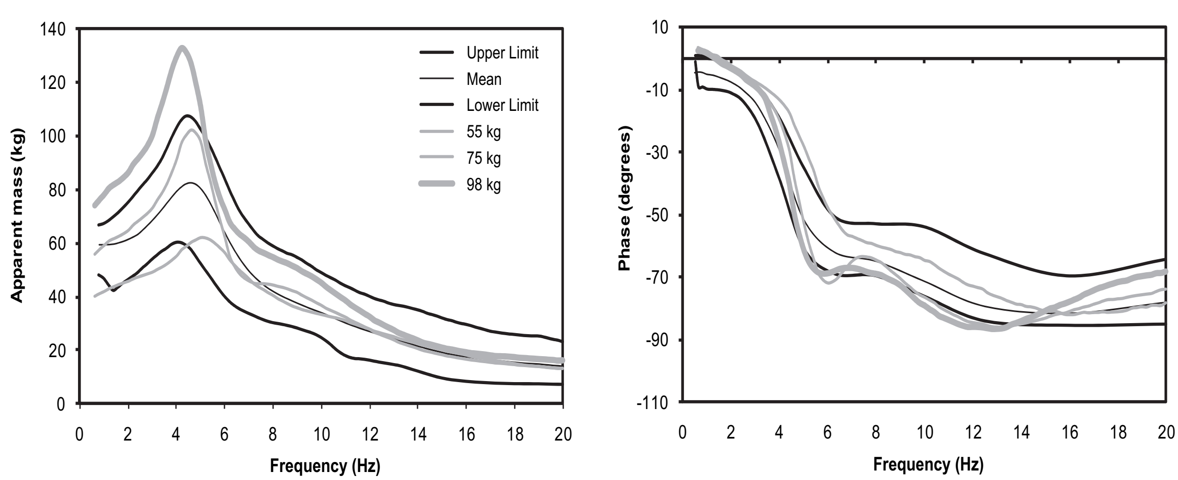

Fig. 21. Comparisons of ranges of vertical apparent mass magnitude and phase responses with data reported for three different body masses (55, 75 and 98 kg).

6. Conclusions

A synthesis of the selected data was performed and limits encompassing the mean values of the selected data were constructed to define the ranges of fore-aft, lateral and vertical apparent mass, and vertical seat-to-head transmissibility responses of the body seated with feet supported and exposed to vibration excitation levels from 0.5 to 1.0 m/s^2 and from 1.0 to 1.75 m/s^2, respectively. The limits of apparent mass responses of standing body exposed to vertical vibration are also proposed on the basis of the synthesis of the available data. The proposed AM ranges are considered applicable for body seated with and without a back support, and exposed to vibration up to 1 m/s^2. Owing to considerable effects of the back support on the biodynamic responses, particularly under fore-aft and vertical vibration, different ranges of AM responses are defined for both back unsupported and back supported conditions. The identified ranges for the vertical AM and STHT responses differ considerably from the standardized ranges in both the primary resonance frequency and the magnitudes in most of the frequency range. The considerably lower primary frequency of the standardized ranges is most likely caused by consideration of data attained under high excitation magnitudes, up to 5 m/s^2. The differences may also be partly caused by inclusion of greater number of datasets in the present synthesis.

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