Whole-body vibration biodynamics – a critical review: II. Biodynamic modelling

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Abstract: Biodynamic models of seated body exposed to whole-body vibration are considered important for design of vibration control devices and anthropodynamic surrogates for efficient performance assessments of vibration isolators. In this second part, the reported biodynamic models of the seated body are briefly reviewed together with the different modelling approaches. The models are identified from target functions derived from the measured biodynamic responses, reviewed in the first part of this paper. Relationships between different target functions are discussed together with the merits and limitations of different modelling approaches. Further efforts are needed for developing representative target functions for deriving reliable models for designing engineering interventions and for predicting potential health and comfort effects.

Keywords: biodynamic models; biodynamic response functions; whole-body vibration; model parameters identification.

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1 Introduction

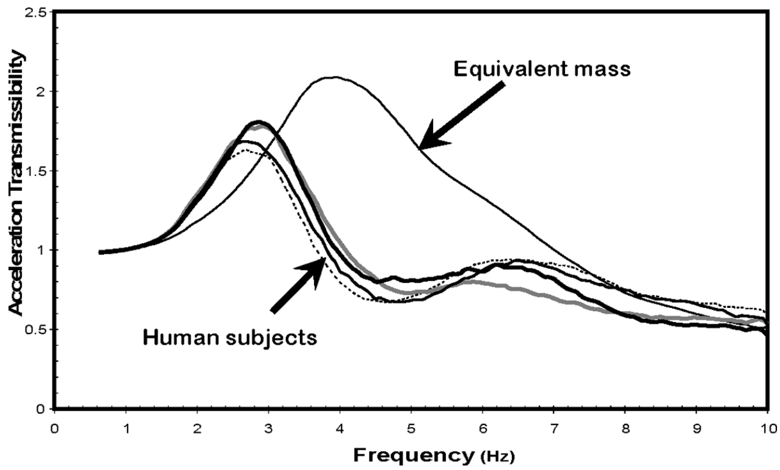
Developments in biodynamic models of the seated human body with representative postural and vibration conditions have been widely emphasised for effectively predicting vibration responses of the biological system and thus the potential injury mechanisms leading to a viable dose-response relationship (Weis et al., 1964; Griffin et al., 1978; Griffin, 2001; Hinz et al., 2001; Seidel, 2005; Kumbhar et al., 2012). Biodynamic modelling continues to be of considerable interest for developing designs of effective interventions, vibration control devices and improved assessment methods. The formulation of biomechanical models, however, necessitates thorough understanding and characterisation of biodynamic responses of the body to whole-body vibration (WBV), and highly complex and coupled effects of various contributing factors.

A range of lumped-parameter, multi-body dynamic and finite element biodynamic models of the standing and seated human body have been formulated on the basis of measured biodynamic responses (Von Gierke and Coermann, 1963; Suggs et al., 1969; Mertens, 1978; Fairley and Griffin, 1989; Boileau and Rakheja, 1998; Pankoke et al., 2001; Fritz, 2005; Rakheja et al., 2006; Kumbhar et al., 2012). Some of these are capable of predicting vibration-induced relative deflections, and compressive and shear stresses of various body substructures (Liu et al., 1998; Fritz, 2000, 2005; Pankoke et al., 2001; Hinz et al., 2002), which could not be measured in-vitro. The human driver is known to contribute considerably to the overall vibration isolation performance of a seat (Fairley and Griffin, 1983; Rakheja et al., 1994; Birlik and Sezgin, 2002; Politis et al., 2003), as is evident from comparisons of acceleration transmissibility of a seat loaded with 4 different human subjects vs an equivalent rigid mass (Figure 1). The biodynamic models have thus been applied to models of seats and vehicles to account for the contribution of the human body in the design and analysis process (Boileau et al., 1998; Wei and Griffin, 1998a; Tchernychouk et al., 2000; Stein and Múča, 2003; Kruczek and Stribrsky, 2004; Pang et al., 2005; Paplukopoulos and Natsivas, 2007). The vertical biodynamic models of a seated body have also served as the basis for developing anthropodynamic manikins for assessing vibration isolation performance of suspension seats. Such manikins have evolved with the intent to eliminate the use of human subjects as required in the standardised seat assessment method (ISO-7096, 2000), and, thereby, the associated ethical concerns.

Some studies have demonstrated good agreement between the responses of the seat model coupled with biodynamic models and those attained with the seat-human system under particular vibration conditions and body mass (Mansfield and Griffin, 1996; Huston et al., 1998; Gu, 1999; Cullmann and Wölfel, 2001; Lewis, 2005), while others have identified substantial disagreements (Wei and Griffin, 1998a; Tchernychouk et al., 2000; Politis et al., 2003; Nelisse et al., 2008). Applications of biodynamic models and anthropodynamic manikins have met limited success thus far, which can be mostly attributed to strongly nonlinear dependence of biodynamic responses on various individual-, posture- and vibration-related factors (Miwa, 1975; Griffin and Whitham, 1978; Kitazaki and Griffin, 1998; Mansfield and Griffin, 2002; Wang et al., 2004; Dewangan et al., 2018), and lack of coupling effects with an elastic seat (Hinz et al., 2006a; Dewangan et al., 2013a, 2015). Furthermore, the reported models generally do not account for contribution of various intrinsic and extrinsic variables.

In this second part of the paper, the reported biodynamic models of the human body together with modelling approaches are reviewed. The relationships among the different target functions used for model parameters identification are discussed to highlight the need for further research in deriving reliable target biodynamic functions and thus the models.

Figure 1 Comparison of the acceleration transmissibility of a seat loaded with human subjects and that of the seat loaded with an equivalent inert mass



Source: Politis et al. (2003)

2 Biodynamic modelling

Human body is a complex dynamic system, whose mechanical properties vary in a highly nonlinear manner under varying stimuli. The mechanical properties also vary considerably with individuals' anthropometric dimensions, sitting posture and seating supports, as it is evidenced from the measured 'to-the-body' and 'through-the-body' responses to vibration (Rakheja et al., 2009). Moreover, the mechanical properties exhibit certain temporal dependencies. The complexity of human body, and non-linear and coupled dependency of its responses to vibration on various intrinsic and extrinsic factors make biodynamic modelling task highly challenging. The vast majority of the models have thus been primarily employed to complement experimental vibration research and for gaining a deeper analytical understanding of biodynamic responses. A number of biodynamic models of the seated body have been developed over the past few decades on the basis of one or more experimentally-established response functions. Based on the type of analytical approach employed, bio-modelling activity may be classified under three categories: lumped-parameter, multi-body dynamic and finite element models. Furthermore, the reported models have mostly focused on vertical biodynamics alone, although some have attempted to model sagittal plane dynamic responses. The reported models within each category are discussed below.

Table 1 Summary of selected lumped-parameter models

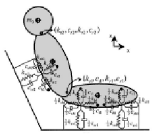
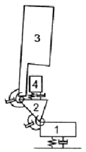
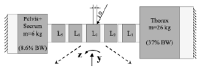
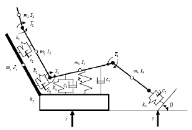
Model	*Author(s)*	*No. of inertial segments*	*Interface S: Seat, B: Back*	*Posture*	*Anthropometric data source* (mass, kg)	*Reference data*	*Joint parameters source*	*Responses*	*Resonance frequencies* (Hz)
	Cho and Yoon (2001)	3	S, B	S, B (Inclined)	Chosen to match reference data (≈56.8)	Responses: Head, hip, back	Chosen to match reference data	Head, back motions – *z*	≈4
	Matsumoto and Griffin (2001)	4	S	Erect	Databases and reported studies (83.6)	AM, segment transmissibility (Matsumoto, 1998)	Chosen to match reference data	AM- z, segments motions- x, z	5.66
	Keller et al. (2002)	7	–NA–	–NA–	Reported studies (70 kg)	Impact and PA* lumbar data	Reported studies.	Relative motions, transmissibility (PA, FE, Axial)	4.2
	Kim et al. (2003)	4	S, B	Normal inclined	Seat mannequin (63.9)	Hip response of seat mannequin	Mannequin components	Hip motion -z	5.5, 7.5

Table 1 Summary of selected lumped-parameter models (continued)

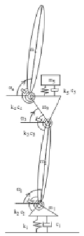
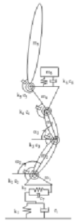
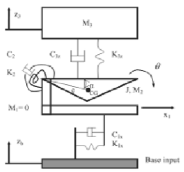
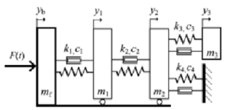
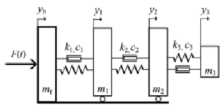
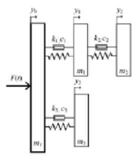
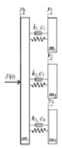
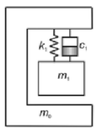
Model	*Author(s)*	*No. of inertial segments*	*Interface S: Seat, B: Back*	*Posture*	*Anthropometric data source* (mass, kg)	*Reference data*	*Joint parameters source*	*Responses*	*Resonance frequencies* (Hz)
	Subashi et al. (2008)	5	NA	Upright standing; lordotic; anterior lean	Reported studies (60)	AM (Subashi et al., 2006)	Chosen to match reference data	AM – z, x (cross axis)	6.13 (Upright); 6.09 (lordotic); 6.42 (anterior lean)
	Subashi et al. (2008)	6	NA	knee bent; knee more bent	Reported studies (60)	AM (Subashi et al., 2006)	Chosen to match reference data	AM – z, x (cross axis)	3.03 (knee bent); 2.92 (knee more bent)
	Nawayseh and Griffin (2009)	3	S	Erect	Reported databases (74.6)	AM (Nawayseh and Griffin, 2003)	Chosen to match reference data	AM – z, x (cross axis)	≈4

Table 1 Summary of selected lumped-parameter models (continued)

Model	*Author(s)*	*No. of inertial segments*	*Interface S: Seat, B: Back*	*Posture*	*Anthropometric data source* (mass, kg)	*Reference data*	*Joint parameters source*	*Responses*	*Resonance frequencies* (Hz)
	Stein et al. (2009)	4	S, B	Upright in cushioned seat	(80.5)	AM – *y*	Chosen to match reference data	AM – *y*	≈4
	Stein et al. (2009)	4	S, B	Upright in cushioned seat	(80.5)	AM – *y*	Chosen to match reference data	AM – *y*	3.5–4.7
	Stein et al. (2009)	4	S, B	Upright in cushioned seat	(80.5)	AM – *y*	Chosen to match reference data	AM – *y*	≈4
	Stein et al. (2009)	4	S, B	Upright in cushioned seat	(80.5)	AM – *y*	Chosen to match reference data	AM – *y*	≈4
	Toward and Griffin (2010)	2	S, B (vertical, inclined)	Relaxed upright; Hands on lap, SW	Reported databases (64.5)	AM (Toward and Griffin, 2009, 2010)	Chosen to match reference data	AM – *z*	3.5–7.0

*PA: Posterior anterior; FE: Flexion-extension (pitch); SW: hands on a steering wheel; *x*: fore-aft motion; *y*: lateral motion; *z*: vertical motion.

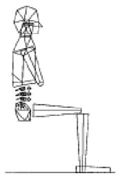
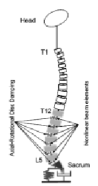
2.1 Lumped parameter models

Simplistic lumped parameter models have been formulated to reproduce biodynamic responses through mechanical analogy rather than geometry or anatomy of the human body (Fairley and Griffin, 1989; ISO-5982, 2001). Such phenomenological models are generally composed of point-inertias connected by mass-less spring and damping elements. Table 1 summarises selected lumped-parameters biodynamic models. The reported models are mostly derived for specific body mass, vibration level and sitting support condition. The table also presents the reference data used for model parameters identification together with the anthropometric data sources, posture, body-seat interface conditions and model mass. The response measures and resonant frequencies are also presented, when reported.

A comparison of the performance of several lumped parameter models could be found in Boileau et al. (1997). In this study, the mechanical impedance (MI) and seat-to-head vibration transmissibility (STHT) were extracted from selected reported models, and statistically compared with biodynamic response data synthesised in the international standard (ISO-5982, 2001). It was shown that only half of the reported models yield a sufficiently acceptable response match with the standardised responses. Liang and Chiang (2006) further showed that only a couple of reported models with multiple degrees-of-freedom (DOF) in the vertical axis (Muksian and Nash, 1974; Wan and Schimmels, 1995) could reproduce the measured biodynamic functions synthesised from the literature. This may be partly due to the fact that most of these models have been developed to satisfy means of one or more biodynamic response functions, which are established experimentally under specific experimental conditions or taken from synthesis of responses reported in many studies (ISO-5982, 2001).

The reported lumped-parameter models range from single-DOF to several-DOF. Toward and Griffin (2010) concluded that through appropriate variations in model parameters, a single-DOF model could provide a useful fit to the vertical apparent mass (AM) of the human body over a wide range of postures and vibration magnitudes. A number of model structures were attempted by Matsumoto and Griffin (2001) before arriving at two configurations with multiple DOF for representing the pitch-plane movement of the seated human body at the resonance frequency under exposure to vertical vibration (Matsumoto and Griffin, 1998). Although displaying a good match with the AM, the models overestimated vibration transmitted to the body segments and showed poor phase response. Adopting a similar approach a coupled seat-human model was developed by Cho and Yoon (2001) to represent the pitch-plane motion of the human body seated on a cushioned seat. The inclusion of the back support elements in the model significantly improved the performance, although an analysis of the cross-axis biodynamic response was not attempted. Subashi et al. (2008) developed two models for determination of vertical and cross-axis fore-aft AM of standing body in five different postures, namely, upright, lordotic, anterior lean, knees bent, and knees more bent. Nawayseh and Griffin (2009) also developed model for estimation of vertical and cross-axis fore-aft AM of seated body and found that the optimum model parameters found by fitting the median AM were similar to the medians of the same parameters found by fitting to the individual AM of the same 12 subjects. Stein et al. (2009) presented four models for reproducing AM responses to side-to-side (lateral) vibration.

Table 2 Summary of selected finite-element models

Model	*Author(s)*	*No. of inertial segments*	*Interface S: Seat, B: Back*	*Posture*	*Anthropometric data source* (mass, kg)	*Reference data*	*Joint parameters*	*Responses*	*Resonance frequencies* (Hz)
	Kitazaki and Griffin (1997)	33	S	Erect, normal, slouched	Reported studies (60)	AM and segment transmissibility	Reported studies	AM, STHT – z, L3 – x, z modes (<10 Hz)	5.25 (Erect posture)
	Pankoke et al. (1998), Seidel et al. (2001)	14	S	Normal, bent forward, relaxed	Reported databases (75)	MI	*In vitro* studies and fitting MI, STHT	MI, L4, dynamic force at L5-S1 joint	≈5
	Wang et al. (2010)	18	S, B (vertical, inclined)	Upright relaxed; hands on lap; SW	Reported databases (77)	AM – z, STHT (Wang et al., 2006b, 2008	Reported studies	AM – z, STHT, vertebral disc compression, shear	4–5.5

x: fore-aft motion; y: lateral motion; z: vertical motion.

Majority of the lumped-parameter models developed for predicting WBV biodynamics are primarily phenomenological in nature; the effects of certain independent parameters such as posture and seating conditions, and the movements of body segments are difficult to capture using such models (Wei and Griffin, 1998b). There are some discrepancies between the response-based average AM and the property-based average AM of a set of human subjects (Dong et al., 2010). It must be noted that even while these models are not structurally comparable to the human anatomy, the use of such low order formulations may help in understanding the nature of biodynamic responses from a whole-body perspective with relative ease. These models also offer considerable ease in realising quick solutions in order to extract significant resonance characteristics.

2.2 Finite element models

It is probably interesting to note that at present, finite element (FE) modelling is the only analytical approach available for observing localised deformations in the biological structures. The scatter in the published data on measured tissue properties such as stiffness and damping values of vertebral discs (Markolf, 1970; Panjabi et al., 1976; Berkson, 1977), widely used in the FE formulations of the human body, poses a considerable impediment to making reliable judgements based on the results from these models. Some of the reported FE models are summarised in Table 2, together with the reference data, anthropometric data sources, body-seat interface condition, and the responses and resonant frequencies, when reported.

The models reported by Buck and Wölfel (1996) and Buck (1997) with detailed (discrete) vertebral elements provide the possibility of extending their capabilities to different anthropometric domains. Modifications to these models, proposed by Pankoke et al. (1998) with a lumped thoracic segment and individual vertebral, and visceral inertia in the lumbar region, have been utilised to extract biodynamic response functions. While the model showed acceptable MI responses below 7 Hz, there were considerable deviations in the predicted STHT and high frequency AM responses. These could be due to the oversimplifications in the form of modal damping values and linearisation of the muscle forces. This reduced model, however, has been employed for a wide range of applications including extracting vibration responses at different body segments and estimating spinal forces (Pankoke et al., 2001). Further, the versatility of the model has been exploited to systematically study the effects of posture and anthropometry on vibration responses, and the prediction of possible health risks. Wang et al. (2010) observed that the incorporation of muscle forces led to more realistic physical responses, yielding estimations of biodynamic responses in terms of STHT and the AM in close agreement with the measured data. Groups of models of five different body sizes were developed by Seidel et al. (2001), which concluded that the shape of the STHT response was primarily determined by the postural condition. A whole-body FE model developed by Belytschko and Privitzer (1978) with lumped nodal properties was modified by Kitazaki and Griffin (1997) to identify deflection modes of the seated body under vertical seat vibration. The visco-elastic parameters of the sagittal-plane model were adjusted to match the measured AM responses and experimentally computed modal parameters (Kitazaki and Griffin, 1998). Two principal resonances at 5.06 and 8.96 Hz were observed in the simulations with coupled visceral movements in the higher frequency mode.

Table 3 Summary of selected multi-body dynamic models (see online version for colours)

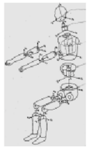
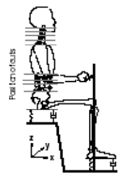
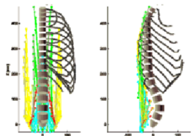
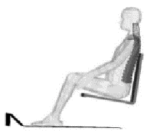
Model	*Author(s)*	*No. of inertial segments*	*Interface S: Seat, B: Back*	*Posture*	*Anthropometric data source* (mass, kg)	*Reference data*	*Joint parameters*	*Responses*	*Resonance frequencies* (Hz)
	Amirouche and Ider (1988)	13	S	Erect	Hybrid III crash test dummy (74)	Lumbar response (Panjabi et al., 1986)	Chosen to match reference data	Head – *z*, lumbar – *z*, pitch	2.18, 4.86
	Fritz (1998)	16	S, SW	Erect	Cadaver data (74)	Lumbar response (Panjabi et al., 1986)	*In vitro* spine properties (modified)	AM, vertebrae force – *z*	4–5
	de Craecker (2003)	18 (no head)	S	Erect	Cadaver data (50th percentile male)	STHT-Z	*In vitro* spine properties	Head – *z*	≈6
	Verver et al. (2003)	Spine-RAMSIS Model	S, B	Normal	MADYMO human model (75.7)	Vertical response: head, T1, Pelvis	In-built in RAMSIS	Vertebral disc compression, shear	6, 8 (head with backrest)

Table 3 Summary of selected multi-body dynamic models (see online version for colours) (continued)

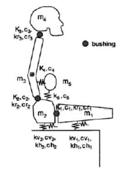
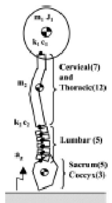
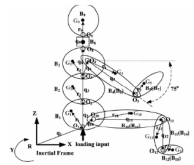
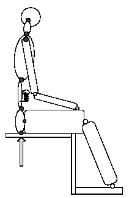
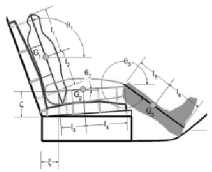
Model	*Author(s)*	*No. of inertial segments*	*Interface S: Seat, B: Back*	*Posture*	*Anthropometric data source* (mass, kg)	*Reference data*	*Joint parameters*	*Responses*	*Resonance frequencies* (Hz)
	Kim et al. (2005)	6	S	Normal	Other models (71.32)	AM, STHT-Z,	Chosen to match reference data	Head – *z*, pitch), AM – *z*	4.8, 5.35, 8.34
	Yoshimura et al. (2005)	8	S	Erect	Other models (–NR–)	Lumbar response	Chosen to match reference data	L1, L5, relative motion – *z*	4.3, 6.8, 13.9
	Teng et al. (2006)	15	S	Erect	Hybrid III (75.92)	Lumbar response (Panjabi, 1986)	–NR–	STHT – *z*, lumbar – *z*, *x*, pitch	≈4

Table 3 Summary of selected multi-body dynamic models (see online version for colours) (continued)

Model	*Author(s)*	*No. of inertial segments*	*Interface S: Seat, B: Back*	*Posture*	*Anthropometric data source* (mass, kg)	*Reference data*	*Joint parameters*	*Responses*	*Resonance frequencies* (Hz)
	Pranesh et al. (2008)	14	S	Erect	50th Percentile male (75.6)	AM, STHT (X, Z)	Chosen to match reference data	AM, STHT – x, z; segment motions – z, VPA	3.14, 5.07, 8.12
	Joshi et al. (2010)	9	S, B	Erect	NA	STHT	Chosen to match reference data	STHT	2.8–3.5

x: fore-aft motion; y: lateral motion; z: vertical motion; SW: hands on a steering wheel; NR: not reported.

With our present level of understanding on the reasons for low back-pain due to the interplay of vibration exposure and postural conditions (Lings and Leboeuf-Yde, 2000), the FE models may have limited applicability, not to mention their excessive computational demand, for the study of WBV biodynamics. Furthermore, most of the FE models are yet to be validated in a comprehensive manner due to the lack of reliable experimental data on localised vibration responses.

2.3 Multi-body dynamic models

Multi-body models are composed of discrete inertia segments connected by appropriate kinematic joints and/or force elements. The reported models have used widely different structures of the body and are mostly limited to erect sitting posture without a back support. Table 3 summarises some of the reported multi-body biodynamic models together with the reference data, anthropometric data sources, body-seat interface condition, and response measures and resonant frequencies, when reported. Using anthropometric data from a crash test dummy (Wisman, 1983), a 13-segment pitch-plane sitting human model was constructed by Amirouche and Ider (1988) with linear stiffness and damping properties of the joints. The visco-elastic properties chosen to match acceleration transmissibility measurements at the lumbar level (Panjabi et al., 1986) revealed a whole-body vertical mode at 4.8 Hz and upper-body pitch around 2 Hz. A similar approach has been adopted for the analysis of postural effects on biodynamic responses by Teng et al. (2006). Fritz (1998, 2000) developed a biodynamic model to obtain estimates of vibration transmission to different segments under sitting and standing conditions, frequency-dependent muscle activity and for the definition of a force-based health risk weighting (Fritz, 2000, 2005). Joshi et al. (2010) developed a biodynamic model for prediction of STHT. It must, however, be noted that other than the comparison with STHT reported in the international standard (ISO-5982, 2001), thorough validation of the models' responses and muscle behaviour is lacking.

Attempts made to develop the multi-body model of the entire spine with detailed representations of muscle forces have met with limited success (de Craecker, 2003). A hybrid approach with a finite element representation of the body surface and multi-body spine model was employed by Verver et al. (2003). The resonant frequency of the model compared well with the measurements, while acceleration transmissibility magnitudes seemed to be overestimated. A more simplified approach has been adopted in other studies by formulating model segment inertias and joint definitions based on body-segment vibration data. The 10-DOF model by Yoshimura et al. (2005) was employed to study relative displacements between the lumbar vertebrae. While relative movement magnitudes in the sagittal plane were high for the lumbar vertebrae around 6 Hz (primary resonance), the L5-sacrum joint showed greater magnitude at a higher frequency, suggestive of dissociated vibration modes in the lower torso. Kim et al. (2005) showed that a model structure including the head, torso with a lumped element representing the abdominal viscera, along with pelvic and thigh segments, could efficiently represent multiple biodynamic functions. It was further shown by Pranesh et al. (2008) that an appropriately constructed multi-body model with sufficient DOF and validated with multiple biodynamic response functions, including the transmission of vibration through the body, may be applied to extract vibration power absorption (VPA) of different segments. It has been suggested that a sufficient level of complexity is essential for the representation of bi-dimensional pitch-plane movements of the upper body exposed to vertical seat vibration (Hinz et al., 1988). However, the dearth of appropriate joint stiffness and damping values together with the lack of sufficient datasets for the localised segments of the human body for model validations demand a more pragmatic approach with a gradual increase in complexity of these models.

Table 4 Modal characteristics extracted from selected reported vertical biodynamic models

Frequency range (Hz)	*Mode* (*frequency,* Hz)	*Source*
0.1–1	Spinal Bending (0.59)	Pankoke et al. (1998)
	Torso fore-aft (0.35)	Kim et al. (2005)
	Torso vertical (0.51)	Kim et al. (2005)
	Torso pitch (0.96)	Kim et al. (2005)
	Body pitch about pelvis (0.28)	Kitazaki and Griffin (1997)
1–2	Pelvis and upper body pitch (1.1)	Matsumoto and Griffin (2001)
	Horizontal head and pelvis – in phase (1.49)	Kitazaki and Griffin (1997)
	Buttock shear, torso pitch – out of phase (1.8)	Pranesh et al. (2008)
2–3	Torso pitch (2.18)	Amirouche and Ider (1988)
	Spine, head and viscera horizontal (2.71)	Kim et al. (2005)
	Spinal bending (2.75)	Pankoke et al. (1998)
	Horizontal head/ neck and pelvis – out of phase (2.81)	Kitazaki and Griffin (1997)
3–4	Buttock shear, torso pitch – in phase (3.14)	Pranesh et al. (2008)
	Thigh and pelvis horizontal (3.41)	Kim et al. (2005)
4–5	Thigh and pelvis pitch (4.12)	Kim et al. (2005)
	Whole body vertical (4.68)	Pankoke et al. (1998
	Head and torso pitch (4.8)	Kim et al. (2005)
	Whole body vertical (4.86)	Amirouche and Ider (1988)
5–6	Whole body vertical, buttock shear with viscera vertical – in phase (5.06)	Kitazaki and Griffin (1997)
	Whole body mode: buttock vertical and shear, visceral vertical, lumbar stretch (5.07)	Pranesh et al. (2008)
	WB and viscera vertical (5.35)	Kim et al. (2005)
	WB mode: Pelvis pitch, viscera and thighs vertical (5.66)	Matsumoto and Griffin (2001)
	Spine bending, horizontal pelvis and buttock shear (5.77)	Kitazaki and Griffin (1997)
6–8	Thigh and pelvis horizontal (6.39)	Kim et al. (2005)
	Visceral vertical, slight pelvis pitch (7.51)	Kitazaki and Griffin (1997)
	Spinal Bending (7.78)	Pankoke et al. (1998)

Table 4 Modal characteristics extracted from selected reported vertical biodynamic models (continued)

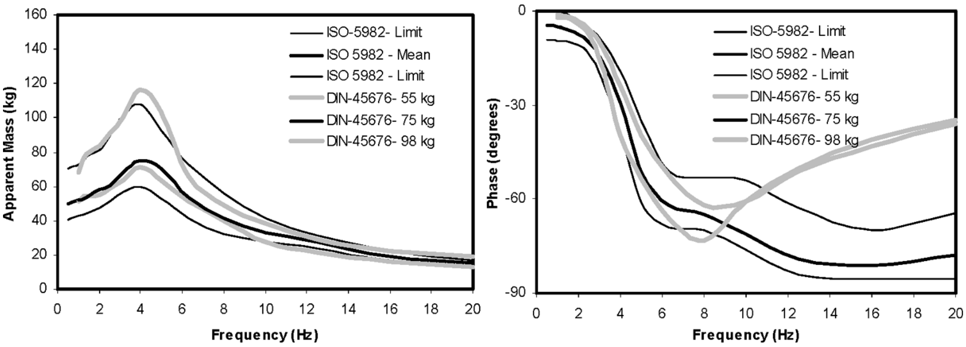
Frequency range (Hz)	*Mode* (*frequency,* Hz)	*Source*
8–10	Thigh pitch (8.04)	Kim et al. (2005)
	Spine and head pitch (8.34)	Kim et al. (2005)
	Viscera vertical, pelvis and upper body pitch (8.34)	Matsumoto and Griffin (2001)
	Pelvic pitch, slight visceral vertical (8.96)	Kitazaki and Griffin (1997)
	Visceral, head-neck vertical (8.12)	Pranesh et al. (2008)
	Head pitch about neck (9.6)	Pranesh et al. (2008)
10–15	Shoulder movement (11.42)	Pankoke et al. (1998)
	Pelvis and upper body pitch, legs vertical (12.3)	Matsumoto and Griffin (2001)
	Shoulder vertical (13.46)	Pranesh et al. (2008)
	Viscera vertical (14.34)	Pankoke et al. (1998)
	Shoulder vertical (14.94)	Pranesh et al. (2008)
>15	Local abdominal viscera horizontal (15.39)	Pankoke et al. (1998)
	Head pitch (16.67)	Amirouche and Ider (1988)
	WB Vertical (18.38)	Pankoke et al. (1998)

The multi-body dynamic and FE models have also reported modal properties of the biodynamic models in terms of resonant frequencies and dominant deflection modes. The modal characteristics extracted from selected vertical WBV biodynamic models are summarised in Table 4. Only minimal agreement could be observed in the deflection modes reported in different studies. The resonance frequencies identified in different studies are grouped within narrow frequency bands in order to illustrate similarities and contradictions among the reported frequencies and mode shapes (Pranesh, 2011).

3 Model parameters and target response functions

The parameters of the reported biodynamic models have been identified through minimisation of errors between the model predicted response and a target function established from the measured responses. Majority of the studies have employed either AM or STHT magnitude and phase responses as the target function, although some have attempted a combination of AM and segment vibration transmissibility as the target functions. The prediction ability of the model strongly relies on the chosen target function. Experimental biodynamic studies have provided substantial knowledge on movement and mechanical properties of the body, the influences of posture and vibration-related variables, resonance frequencies and probable modes of vibration, potential injury mechanisms and frequency-weighting for exposure assessments (Coermann, 1962; Suggs et al, 1969; Mertens, 1978; Fairley and Griffin, 1989, 1990; Hinz et al., 2002; Wang et al, 2004; Mansfield and Maeda, 2005b; Nawayseh and Griffin, 2005a; Rakheja et al., 2006; Toward and Griffin, 2009; Shibata and Maeda, 2010). ISO-5982 (2001) has defined the range of driving-point mechanical impedance (MI) and seat-to-head transmissibility (STHT) characteristics of the seated body exposed to vertical vibration in the 0.5–20 Hz range on the basis of a synthesis of reported data performed by Boileau et al. (1998). The defined ranges have been widely used as target functions for identifying model parameters, although these are applicable under particular conditions, namely, human subjects sitting erect without a back support but with feet supported and exposed to vertical vibration with magnitudes equal to or less than 5 m/s^2, and a body mass in the 49-93 kg range. The German Institute for Standardization (DIN 45676, 1992) has also defined the ranges of biodynamic responses in terms of vertical driving point MI magnitude and phase for three different body masses (55, 75 and 98 kg). The two standardised values, however, show considerable differences, as seen in Figure 2.

Figure 2 Comparisons of standardised ranges of AM magnitude and phase of seated body under vertical vibration, as defined in ISO-5982 (2001) and DIN 45676 (1992)



The reported studies on biodynamics have placed a far greater emphasis on the responses to vertical vibration, while far fewer efforts have been made under horizontal vibration, whose magnitudes may be comparable to those of the vertical in many off-road vehicles (Rakheja et al., 2008). This may be partly due to lack of sufficient data on biodynamic responses to horizontal vibration. The draft standard (ISO-DIS-5982, 2018) presents the ranges of biodynamic responses to horizontal vibration, which may serve as target functions for deriving biodynamic models for predicting responses to vertical as well horizontal WBV.

3.1 Relationships among target biodynamic response functions

It is recognised that knowledge of the relationships among different forms of biodynamic functions can facilitate an understanding of vibration response of the human body and help build reliable models (Wu et al., 1999). Dong et al. (2013) recently formulated a theorem relating 'to the body' and 'through-the-body' functions. With the conceptual model shown in Figure 3, the relationship theorem can be generally expressed as follows:

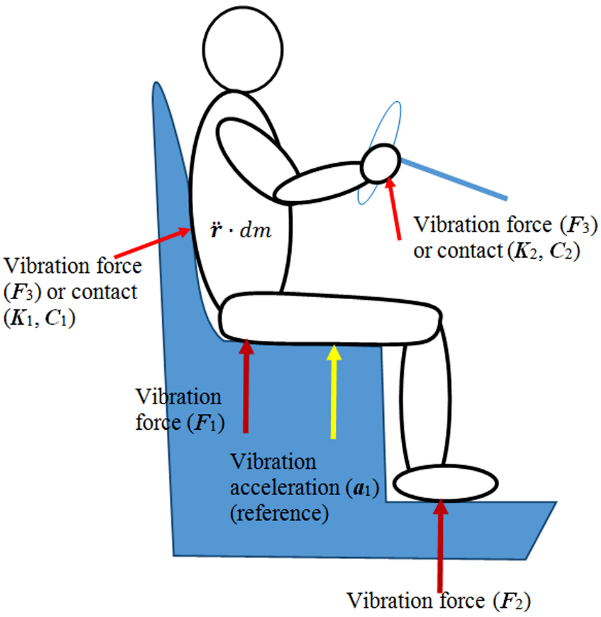
$$\int d(\mathbf{M}_d) = \int \mathbf{T} \cdot \mathrm{d}m = \int \mathbf{T} \cdot \rho \cdot \mathrm{d}V, \tag{1}$$

where $\mathbf{M}_d$ is the direct or cross-point apparent mass distributed on the boundary of the system in a given direction, $\mathbf{T}$ is the vibration transfer function at a point in the body in the same direction, and dm is the local mass at the point, which can be calculated using the local mass density (ρ) and the volume (V) of the mass. If the distributed apparent masses can be lumped at limited points, the vibration input to the body at the back support, the hands, and arms can be ignored, and the support contact stiffness ($\boldsymbol{K}_c$) and damping ($\boldsymbol{C}_c$) at each contact point have linear behaviours; the relationship at a given frequency (ω) can be expressed as follows:

$$\sum \mathbf{M}_d = \int \mathbf{T}_i \cdot dm + \sum \mathbf{T}_c \cdot (\mathbf{C}_c / j\omega - \mathbf{K}_c / \omega^2) \quad (2)$$

This theorem enhances the classic vibration theory. Although it was created with the conceptual whole-body vibration model shown in Figure 3, it can be generally applicable to any vibration system with linear or nonlinear behaviours in any vibration direction. Based on this theorem and other vibration theory, a set of validation criteria for models have been further proposed (Dong et al., 2015). It can be used to explain some phenomena observed in the reported studies and it is a useful tool for further biodynamic studies.

Figure 3 A conceptual model of whole-body response to input vibration (see online version for colours)

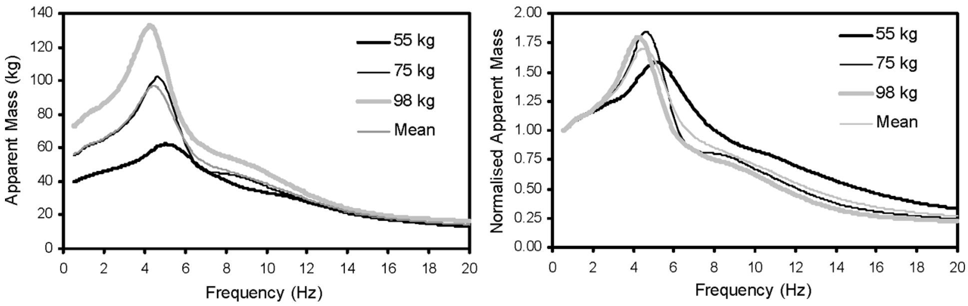


Prior to the above relationship theorem, the 'to the body' and 'through-the-body' response functions were mostly acquired either by different investigators or during different test sessions. Mertens (1978) suggested that the two functions needed to be measured simultaneously in order to develop reliable models. Although a few studies report both the functions, whether measured simultaneously or sequentially (Coermann, 1962; Hinz and Seidel, 1987; Matsumoto and Griffin, 1998, 2000, 2002a; Wu et al., 1999; Mansfield and Griffin, 2000; Kim et al., 2005; Wang et al., 2008), only two explored relationship between the two measures. Wu et al. (1999) explored the relationship using simple vertical biodynamic models. Wang et al. (2008) measured normalised AM and STHT responses simultaneously, which showed good agreements in view of the primary resonances, irrespective of the back support condition, while considerable differences were shown between the normalised AM and STHT magnitudes. The normalisation of the AM response, however, tends to alter the response behaviour considerably, especially the body mass effect, as seen in Figure 4 (Patra et al., 2008). The study concluded that the 'through-the-body' response would emphasise biodynamic responses corresponding to higher vibration modes compared to the 'to-the-body' measure. While such observations and conclusions touched some superficial phenomena, it is actually very difficult to use an experimental method to understand the basic mechanism behind the phenomena or to identify their true relationship without using the theorem expressed in equation (1). This is primarily for the following reasons:

- it is difficult to accurately measure the vibration transmitted to the human body primarily due to limitations of the available measurement technologies; the STHT responses in general have far greater inter-subject variability than those observed in the 'to-the-body' responses, which may be partly attributable to involuntary head movement, misalignment of the sensors and skin artefacts
- as expressed in the relationship theorem in equation (1), the total apparent mass is equal to the sum of the distributed transmissibility multiplied by its corresponding mass; even if a single STHT at a specific location (e.g., on a head) can be accurately measured, it only represents a part of the distributed responses. It is not sufficiently representative of the vibration motion of the entire body, especially at high frequencies.

As a result, the local vibration responses may not match with the summed response.

Figure 4 Effect of normalisation on the vertical apparent mass magnitude of subjects seated without a back support under 1 m/s^2 rms random vibration



Source: Patra et al. (2008)

Coermann (1962) suggested that the frequency at peak MI magnitude does not correspond to the natural frequency of the well-damped human body. The frequency corresponding to peak MI magnitude converges to natural frequency, as the damping vanishes. Wu et al. (1999) investigated relationships between the AM, MI and STHT functions on the basis of the available vertical AM data and analyses of four different vertical biodynamic models. It was shown that the peak MI magnitude occurs at a frequency higher than that of the peak AM. This trend was also confirmed through results attained for 4 different single- and two-DOF biodynamic models, reported by Coermann (1962), Suggs et al. (1969), Allen (1978) and Fairley and Griffin (1989). Moreover, the frequency corresponding to peak MI magnitude revealed greater variability than that corresponding to the peak AM magnitude. It was further shown that normalised AM and STHT responses are identical only for the single-DOF models, while the frequencies of higher modes of the higher-order models differed (Wu et al., 1999). Boileau et al. (1997) reported the same finding on the basis of results obtained from 11 different one-dimensional (vertical) models of the seated body ranging from single- to seven-DOF, although the majority did not include a head sub-structure. The two functions revealed primary magnitude peaks at the identical frequencies, irrespective of the model order. Data reported in many other studies, however, show differences in the mean primary frequencies deduced from AM and STHT responses (Boileau et al., 1998; Matsumoto and Griffin, 1998, 2000; ISO-5982, 2001; Kim et al., 2005; Rakheja et al., 2010). Dong et al. (2015) have explained some of these phenomena based on the relationships among the AM, MI, and STHT. Since the MI magnitude equals the AM multiplied by frequency (ω), the transformation from AM to MI magnitude may alter the frequency corresponding to the peak magnitude. For this reason, the relative weightings of different frequency components may differ in model calibration. As a result, the model parameters determined on the basis of AM response may differ from those identified using the MI response. Dong et al. (2015) suggested using MI, when frequency components across the entire frequency range are equally important, because the AM emphasises components in the relatively lower frequency range. According to the relationship theorem, expressed in equation (1), if the measured STHT is representative of the overall vibration behaviour of the system, the STHT peaks should correlate with those of the AM. Near the first fundamental resonance of vertical vibration, the entire body is likely to move in phase; as a result, the first peak in AM should match with that of the STHT, if the two measures are reliably measured. Wu et al. (1999) also illustrated this tendency. The higher frequency peaks observed in vibration transmissibility responses may not be observed in the AM since the transfer functions representing the local motions or motions of low inertia segments may not play a significant role in the overall system response.

3.2 Model parameters identification

The majority of the lumped parameter models are formulated to reproduce biodynamic response in terms of AM or STHT through a mechanical analogy rather than the geometry or anatomy of the human body. Some of the lumped-parameter models and majority of the FE and multi-body dynamic models employ representative inertial and geometric parameters of the body segments from the reported anthropometric or cadaver data. The visco-elastic properties of various joints, however, are identified through minimisation of errors between the model responses and a target response function derived from the measured responses. The challenging task of identifying appropriate visco-elastic parameters of the biodynamic models is a widely reported issue in many analytical WBV studies (Kim et al., 2005). Due to the large number of assumptions made in order to simplify the structure of the biodynamic human models, it is not possible to directly utilise the mechanical properties measured from the human cadaver spines. Most studies thus employ some form of a parameter-search approach to identify the unknown values in the formulation. It is common to employ an optimisation-based technique that minimises the error between the chosen biodynamic response(s) of the model and the corresponding target measurements so as to identify the model's unknown parameter values. This is an acceptable methodology given the limited availability of reliable visco-elastic properties. The parameter identification task, however, becomes more complex for higher order models involving a large number of unknown parameters. The solutions of the error minimisation problems in this case are not likely to yield a set of unique visco-elastic parameters. A few studies have identified bounds of some of the stiffness and damping parameters from biomechanical properties of the spine reported in (Keller et al., 2002; Panjabi et al., 1976).

The complexity of parameters identifications via error minimisation depends on the number and types of target biodynamic functions used. The vast majority of the reported studies consider the measured vertical AM (magnitude and phase) as the target function, while a few have taken STHT as the target function (Cho and Yoon, 2001). The majority of the lumped-parameter models cannot yield the motion responses such as STHT due to lack of the anatomical structure. Only a few studies have reported models for predicting motion responses of selected body segments (Cho and Yoon, 2001; Matsumoto and Griffin, 2001; Keller et al., 2002; Kim et al., 2003). The parameters identifications based on AM response functions is considered to be most convenient due to rapid convergence of the AM error minimisation problem, while the AM alone may not describe the contributions of low inertia upper body segments to the total response (Wang et al., 2006a). The model identified on the basis of an AM response function alone yields acceptable prediction of APMS response, while considerable errors could be found in other biodynamic responses of the model such as STHT.

Pranesh (2011) identified parameters of a sagittal plane seated body model through minimisation of errors in a series of biodynamic response functions for predicting vertical AM, fore-aft and vertical STHT, and vertical vibration transmissibility of L3, L5, T5 and C7. The error minimisation functions included vertical AM; vertical STHT; fore-aft and vertical STHT; Combined vertical AM and STHT; a weighted sum of vertical AM, and fore-aft and vertical STHT; weighted sum of vertical and fore-aft motion of C7; and weighted sum of vertical AM, fore-aft motion of C7, and fore-aft and vertical STHT. The error minimisation of vertical AM response alone showed very good agreement in AM and acceptable degree of agreement in vertical STHT and L5 response magnitudes only up to 6 Hz. Large errors were evident in most of the body segment vibration responses. Parameters obtained through minimisation of vertical STHT error function alone showed very good agreement in vertical STHT response in the entire frequency range but large errors in fore-aft STHT and AM magnitude and phase responses. The results also showed better agreements in the C7, T5, T12 and L3 vertical transmissibility responses with the mean measured data but very poor predictions of the fore-aft acceleration transmissibility responses. It was further shown that the use of weighted sum of vertical AM and STHT could provide good agreement in both the target response functions but large error in the fore-aft vibration response. It was thus concluded that a model based on either vertical AM or vertical STHT or a combination of the two target functions may not be sufficient for identifying model parameters relating to the sagittal-plane motion of the seated human body.

Owing to the complex pitch motion of the head and neck, model parameters were identified through minimisation of a weighted error sum of fore-aft and vertical STHT and fore-aft C7 vibration transmissibility target functions. This approach provided better agreements in APMS and segmental transmissibility responses. The phase response of the vertical transmissibility of most of the body locations also seemed to be better reflected in this model suggestive of better estimations for damping parameters. However, the formulation seems to over-estimate the peak vertical magnitude at the body segments, while also slightly reducing the fore-aft response magnitude at the neck.

4 Discussion

ISO-5982 (2001) and DIN 45676 (1992) have defined the ranges of vertical biodynamic responses of the seated body to aid the developments in models, and the design and assessment of seats. The standards define the ranges for vertical vibration under a limited range of experimental conditions, considered representative of vehicle driving. The ranges defined in ISO-5982 (Figure 2), were based upon synthesis of datasets reported in different studies under selected vibration and sitting conditions (Boileau et al., 1998), namely: datasets reported for mean body mass ranging from 49 to 93 kg; sitting erect without a back support with feet supported and vibrated; and exposure to vertical vibration with magnitude equal to less than 5 m/s^2. The defined ranges of MI, AM and STHT magnitude and phase have served as the basis for developing mechanical-equivalent biodynamic models of the seated body and anthropodynamic manikins for assessing vibration isolation effectiveness of vehicle seats (Boileau et al., 2002; Fritz, 2005; Yoshimura et al., 2005; Lemerle and Boulanger, 2006; Nelisse et al., 2008). The ranges of biodynamic responses in terms of MI magnitude and phase have also been defined by the German Institute for Standardization (Figure 2), which are considered applicable for sitting without a back support and vertical vibration exposure (DIN 45676, 1992). Owing to the strong effects of body mass on the 'to-the-body' responses, the standard defines the MI values for three body masses (55, 75 and 98 kg), where the values corresponding to the 75 kg body were taken as the mean values defined in ISO-5982 (2001).

The data synthesis associated with ISO-5982 involved data with subject population ranging from 1 to 30 and mean body mass in the 49–93 kg range. While the mean of mean body masses was 75 kg, the grand mean of the synthesis cannot be interpreted to represent the response of 75 kg seated body. Moreover, the synthesis was performed by considering the magnitude and phase data independently, as was done by Paddan and Griffin (1998) for the STHT responses. Despite the comparable ranges of conditions, the two standardised ranges of magnitudes exhibit substantial differences, particularly in the limits and at frequencies below 8 Hz, and phase response at frequencies above 8 Hz (Figure 2). It has been suggested that both the reference values defined in DIN-45676 are most likely inadequate to serve as the basis for design of manikins or models (Nelisse et al., 2008). The ISO-5982 also provides reference values of vertical MI and AM for three body masses (55, 75 and 90 kg) derived from a linear one-dimensional lumped-parameter model, reported in one of its annexes. The validity of these reference values has not been established. Moreover, these were attained by varying the mass parameters alone of the baseline model that satisfied the 'grand mean' of the synthesised data. Although the baseline model defined in ISO-5982 satisfies the defined mean AM and STHT responses, further validity of the models is essential, particularly for lower and upper limits of the body masses, in order to realise reliable reference values.

Furthermore, the standardised AM values have been defined for vertical WBV and seated without a back support, while the range of vertical STHT magnitudes was defined from only a few reported datasets. More comprehensive syntheses of biodynamic response data has been presented by Rakheja et al. (2010), which includes the AM and STHT responses along the three axis for back unsupported and supported sitting conditions, apart from the standing subjects' vertical biodynamics. The measured biodynamic responses of the seated body exhibit the strongest effects of the body mass, sitting posture (including supports) and vibration magnitude, which are also coupled.

A few studies have defined one-dimensional lumped parameter models on the basis of AM data of individual subjects (Wei and Griffin, 1998a; Matsumoto and Griffin, 2001), which exhibit extreme differences in the identified parameters. Defining the target responses for population groups of body mass within a narrow range is perhaps most desirable considering its strongest effect (Figure 4) on the ‘to-the-body’ response, as also reported in DIN-45676 (Figure 2) and by Seidel (1996), cited in Boileau et al. (1998), Hinz et al. (2004) and Patra et al. (2008). Moreover, the responses of human subjects of particular body mass would allow better interpretations of the other contributory factors, decoupled from the body mass (Wang et al., 2004; Dewangan et al., 2013b, 2013c, 2018), such as posture and gender effects. This approach will also facilitate the identification of the gender effect, if any.

The seat geometry, sitting supports and postures considered in the reported studies are widely different and not entirely representative of the vehicular environment. Considering the effect of these parameters on biodynamic responses, the identification of appropriate and representative seat geometry and sitting posture for particular classes of vehicles (commercial vehicles and automobiles) is of primary importance. These should include the seat height, legs orientation, inclinations of the pan and backrest, seat to steering distances, hands position, etc. The implementation of these conditions in experimental biodynamics studies would help formulate reliable data and thereby the models, although it may be applicable for a class of vehicles. The vast majority have performed measurements with body seated upright without a back support, while some report the data with full back support. Both the conditions do not represent a typical driving posture, which may involve support in the lumbar region alone for wide ranges of off-road vehicles. Further characterisations are thus vital under representative back support conditions.

The reported studies have generated a considerable amount of experimental data related to different sitting postures, such as erect, relaxed, tense buttocks, tense arms and legs, and slouched. These have shown important effects on the measured biodynamic responses (Coermann, 1962; Hinz et al., 2002; Matsumoto and Griffin, 2002a, 2002b; Boileau and Rakheja, 1998; El-Khatib et al., 1998; Kitazaki and Griffin, 1998; Holmlund et al., 2000; Mansfield et al., 2006). Tense postures are most likely not representative for both standing and sitting work situations, and are expected to yield greater variability in responses due to time-varying properties of phasic muscles (Pope et al., 1998; Bluthner et al., 2001). The target biodynamic responses should thus be formulated for representative postures that can be comfortably maintained for reasonably long periods in work situations. Although the effects of twisted postures is shown to be relatively small on the AM response to vertical vibration (Mansfield and Maeda, 2005a), the effects under horizontal vibration may be more significant and need to be explored. The twisted posture may also alter the modes of vibration of the spine and thus the nature of vibration transmitted to the spine.

The reported data have consistently shown the nonlinear dependence of the biodynamic response on the magnitude of WBV. The body softening effect under increasing vibration magnitude has been most widely reported, while the reported effects on the response magnitudes are mostly conflicting (Griffin et al., 1978; Hinz and Seidel, 1987; Holmlund et al., 2000; Mansfield et al., 2001, 2006; Matsumoto and Griffin, 2002b; Wang et al., 2004, 2006b; Nawayseh and Griffin, 2005a, 2005b). The extent of this nonlinearity appears to depend on the body supports, gender, posture and relative magnitude of vibration in a complex manner. It would thus be appropriate to define target biodynamic responses applicable within a range of vibration magnitude that is considered representative of a class of vehicles or work situations.

The standardisation efforts have thus far defined the ranges of vertical AM and STHT responses of the seated body. The WBV environment of most off-road vehicles generally encompasses comprehensive magnitudes of horizontal vibration. Exposure to large magnitudes of horizontal vibration could cause greater shear forces in the lumbar spine (Fritz, 2005). Characterisation of biodynamic responses to horizontal vibration and the developments in biodynamic models are perhaps more central for the design of horizontal suspension seats. The primary resonance frequency of the seated body to vertical vibration (5–7 Hz) is well above the resonance frequency of the vertical suspension seats (generally below 2 Hz). The human responses to horizontal vibration exhibit primary resonance at a very low frequency near 0.7 Hz, when seated without a back support (Fairley and Griffin, 1990; Mandapuram et al., 2005). Far greater coupling effects of the seated body would thus be expected when designing horizontal seat isolators (Stein et al., 2008). The draft standard (ISO-DIS-5982, 2018) has progressed substantially in defining ranges of vertical as well as horizontal AM and STHT responses of subjects seated with and without a back support. These may facilitate the formulations of horizontal vibration biodynamic models.

The WBV environment constitutes vibration in multiple axes. Although, a few studies have shown only small differences between the AM responses to single and multiple-axes vibration (Hinz et al., 2006b; Mansfield and Maeda, 2006, 2007), additional efforts are highly desirable to identify coupling effects, especially under correlated multi-axis vibration, which are encountered in vehicle driving. The total biodynamic force developed along a particular axis at the driving-point would be the sum of forces caused by the direct and cross-axis AM components (Rakheja et al., 2007). The systematic measurements of cross-axis components of ‘to-the-body’ and ‘through-the-body’ responses under single, dual and multiple axes vibration could provide significant insight into the coupling between the various vibration modes of the body.

Additional target functions, apart from AM/MI and STHT, are also extremely desirable for identifying reliable parameters for the continuum and discrete distributed-parameter models based upon multi-body dynamic and finite element techniques (Mertens, 1978; Fairley and Griffin, 1989; Pankoke et al., 2001; Fritz, 2005; Dong et al., 2015). The vast majority of the models are based on AM data acquired under selected experimental conditions, although a few have also considered STHT responses (Boileau et al., 2002; Kim et al., 2005; Yoshimura et al., 2005). The use of a single target function may lead to multiple solutions for model parameters, which are evident from the wide ranges of model parameters (Boileau et al., 1997; Wei and Griffin, 1998a; Liang and Chiang, 2006). Considering the relationship between the ‘to-the-body’ and ‘through-the-body’ response functions (Dong et al., 2013), the uniqueness of identified parameters could be considerably enhanced through minimisation of a composite error function of multiple biodynamic target responses, such as direct-, across-point, and cross-axis AM/MI, STHT and vibration transfer functions on different body substructures (Dong et al., 2015). Although a few studies have reported the transfer functions of vibration transmitted to lumbar and thoracic spine and other locations, very little agreement can be seen among them (Starck et al., 1991; Zimmermann and Cook, 1997; Kitazaki and Griffin, 1998; Matsumoto and Griffin, 1998, 2000). The discrepancies are partly attributed to differences in measurement methods and the contributions due to skin movement, which is compensated for in only a few studies. This suggests that further efforts are required to increase the accuracy and reliability of the measurements by improving and/or developing new measurement techniques. Additional efforts in characterising the direct, cross-point, and cross-axis vibration transfer functions of the body substructures are highly desirable to define the 'through-the-body' response target functions and model development. It is also important to note that the directly measured transfer function at a point on a substructure may not be sufficiently representative of the overall vibration of the substructure simulated as a lumped mass in a model (Dong et al., 2015). While a formula for deriving the representative transfer function for the model calibration has been proposed (Dong et al., 2013, 2015), its effective implementation remains an issue for further studies.

The biodynamic responses have been mostly derived for the body seated or standing on a rigid platform in order to deduce the uncoupled body responses. The applications of resulting models to seating dynamics have met limited success in simulating coupled occupant-seat system dynamic responses to vibration (Wei and Griffin, 1998a; Tchernychouk et al., 2000; Politis et al., 2003). Furthermore, the manikins designed on the basis of standardised biodynamic responses have shown limited effectiveness in assessing the vibration isolation performance of ranges of suspension seats exposed to vibration spectra of different vehicles (Nelisse et al., 2008). The performance limitations of the models and the manikins may be attributed to many factors. The designs are mostly based upon target biodynamic responses derived either from broad ranges of experimental conditions (ISO-5982, 2001) or the target function is valid in the vicinity of the chosen experimental conditions (e.g., body mass, sitting posture, magnitude of vibration). Furthermore, the contributions of the body coupling with elastic seats may also yield considerable differences, since the target functions are based on sitting on rigid platforms (Dewangan et al., 2013a, 2015).

Hinz et al. (2006a) investigated the 'to-the-body' response of subjects seated on a cushioned seat through measurement and integration of distributed contact pressure at the interface of the buttock and elastic seat. The study revealed mean static AM (near 1 Hz) in the order of 58% of the mean body weight, which is considerably lower than the generally reported proportion of the body mass supported on the seat (≈70–75%). Stein et al. (2007) applied the conventional method to measure the AM of body seated on a cushion seat under horizontal vibration. The data showed considerably higher static AM for the cushioned seat compared to the rigid seat, although the method does not account for the contributions of the visco-elastic effects of the cushion. The use of thin-film flexible pressure sensors is perhaps most appropriate to characterise the 'to-the-body' biodynamic response of the body to vibration, the excessive deformation of the pressure sensing mat caused by cushion contouring together with limited frequency bandwidth of the sensors could lead to considerable errors (Dewangan et al., 2013a). Furthermore, the elastic properties of the cushion would also be expected to influence the resultant biodynamic force (Dewangan et al., 2015). More efforts are thus vital to quantify the effects of elastic body-seat interface on both the 'to-the-body' and 'through-the-body' biodynamic responses, and the role of the viscous and elastic properties of the cushion.

The target biodynamic responses of the seated body have been generally measured with feet supported on the vibrating platform, resulting in zero to minimal relative motions across the legs. The legs and thighs of the body seated in a vehicle seat undergo compression and extension. The AM responses of seated body with a stationary footrest influenced the low frequency AM magnitude, while the effect was negligible with a moving footrest (Fairley and Griffin, 1989). Lemerle and Boulanger (2006) showed considerable differences in AM of the body seated on a freely-moving and locked suspension without a cushion, and attributed the differences to pelvic rotations caused by relative movements across the legs. A vertical suspension seat would cause considerable phase between motions of the thighs and the legs over most of the frequency range, which may affect the biodynamic responses. Such effects on the 'to-the-body' and 'through-the-body' biodynamic responses need to be quantified.

Apart from the above, additional efforts are also needed for defining reliable target biodynamic responses of the standing body exposed to WBV under representative conditions, since many work situations involve standing postures, such as ship workers and high speed boat operators.

5 Conclusions

Reported vibration biodynamic models of seated and standing human body are mostly limited to specific body mass, anthropometric dimensions, sitting/support conditions and magnitude and direction of vibration. Such models thus do not fully describe important effects associated with variations in many seating-, anthropometry- and vibration-related factors. Formulations of reliable vibration biodynamic models of seated and standing human body are vital developing human-centred tools for design and analyses of vibration control devices and to gain deeper knowledge of potentials of vibration exposure. The quality and thus the applicability of the biodynamic model strongly relies on the target biodynamic response functions established under conditions representative of the work-related factors. Further systematic efforts are thus needed to derive representative target functions for realising reliable biodynamic models.

References

Allen, G. (1978) 'A critical look at biodynamic modeling in relation to specifications for human tolerance of vibration and shock', *Proceeding AGARD Conference*, pp.A35-5–A25-15.

Amirouche, F.M.L and Ider, S.K. (1988) 'Simulation and analysis of a biodynamic human model subjected to low accelerations – a correlation study', *Journal of Sound and Vibration*, Vol. 123, pp.281–292.

Belytschko, T. and Privitzer, E. (1978) *Refinement and Validation of a Three-dimensional Head-spine Model*. Aerospace Med. Research Lab., Wright-Patterson Air force Base, Report No. AMRL-TR-78-7, Ohio.

Berkson, M. (1977) 'Mechanical properties of the human lumbar spine flexibilities, intradiscal pressures, posterior element influences', *Proceeding Institution of Medicine of Chicago*, Vol. 31, No. 5, pp.138–143.

Birlik, G. and Sezgin, Ö. (2002) 'The coupling effect in biodynamic models', *Proc. 6th Conference on Computational Structures Technology*, 4–6 September, Prague, Czech Republic, pp.89–90.

Bluthner, R., Seidel, H. and Hinz, B. (2001) 'Examination of the myoelectric activity of back muscles during random vibration – methodical approach and first results', *Clinical Biomechanics*, Vol. 16, Suppl. 1, pp.S25–S30.

Boileau, P-É. and Rakheja, S. (1998) 'Whole-body vertical biodynamic response characteristics of the seated vehicle driver: measurement and model development', *International Journal of Industrial Ergonomics*, Vol. 22, No. 6, pp.449–472.

Boileau, P-É., Rakheja, S. and Wu, X. (2002) 'A body mass dependent mechanical impedance model for applications in vibration seat testing', *Journal of Sound and Vibration*, Vol. 253, No. 1, pp.243–264.

Boileau, P-É., Rakheja, S., Yang, X. and Stiharu, I. (1997) 'Comparison of biodynamic response characteristics of various human body models as applied to seated vehicle drivers', *Noise and Vibration Worldwide*, Vol. 28, No. 9, pp.7–15.

Boileau, P-É., Wu, X. and Rakheja, S. (1998) 'Definition of a range of idealized values to characterize seated body biodynamic response under vertical vibration', *Journal of Sound and Vibration*, Vol. 215, No. 4, pp.841–862.

Buck, B. (1997) *Modell für das Schwingungsverhalten des sitzenden Menschen mit detaillierter Abbildung der Wirbelsäule und Muskulatur im Lendenbereich*, Dissertation, TH Darmstadt, Shaker Verlag, Darmstadt.

Buck, B. and Wolfël, H. (1996) 'A dynamic model for human WBV with detailed representation of the lumbar spine', *Proc. of the 10th Conference of the European Society of Biomechanics*, 18–31 August, Leuven, Belgium, p.338.

Cho, Y. and Yoon, Y-S. (2001) 'Biomechanical model of human on seat with backrest for evaluating ride quality', *International Journal of Industrial Ergonomics*, Vol. 27, pp.331–345.

Coermann, R.R. (1962) 'The mechanical impedance of the human body in sitting and standing position at low frequencies', *Human Factors*, Vol. 4, pp.227–253.

Cullmann, A. and Wölfel, H.P. (2001) 'Design of an active vibration dummy of sitting man', *Clinical Biomechanics*, Vol. 16, Suppl. 1, pp.S64–S72.

de Craecker, W. (2003) 'Whole-body vibration comfort analysis based upon spine modeling', *38th UK Conference on Human Responses to Vibration*, Southampton, UK.

Dewangan, K., Rakheja, S., Marcotte, P. and Shahmir, A. (2013a) 'Comparisons of apparent mass responses of human subjects seated on rigid and elastic seats under vertical vibration', *Ergonomics*, Vol. 56, No. 12, pp.1806–1822.

Dewangan, K., Rakheja, S., Marcotte, P. and Shahmir, A. (2013c) 'Seated body apparent mass response to vertical whole body vibration: gender and anthropometric effects', *International Journal of Industrial Ergonomics*, Vol. 43, No. 4, pp.375–391.

Dewangan, K., Shahmir, A., Rakheja, S. and Marcotte, P. (2013b) 'Vertical and fore-aft seat-to-head transmissibility response to vertical whole body vibration: gender and anthropometric effects', *Journal of Low Frequency Noise, Vibration and Active Control*, Vol. 32, Nos. 1–2, pp.11–40.

Dewangan, K.N., Rakheja, S., Pierre, M. and Shahmir, A. (2015) 'Effects of elastic seats on seated body apparent mass responses to vertical whole body vibration', *Ergonomics*, Vol. 58, No. 7, pp.1175–1190.

Dewangan, K.N., Rakheja, S. and Marcotte, P. (2018) 'Gender and anthropometric effects on whole-body vibration power absorption of the seated body', *Journal of Low Frequency Noise, Vibration and Active Control*, Vol. 37, No. 2, pp.167–190.

DIN 45676 (1992) *Mechanical Impedances at the Driving Point and Transfer Functions of the Human Body*, Deutsches Institut für Normung e.V.

Dong, R.G., McDowell, T.W., Welcome, D.E. and Wu, J.Z. (2010) 'An evaluation of the methods for deriving representative frequency response functions of the human whole-body system', *Industrial Health*, Vol. 48, pp.596–605.

Dong, R.G., Welcome, D.E., McDowell, T.W. and Wu, J.Z. (2013) 'Theoretical relationship between vibration transmissibility and driving-point response functions of the human body', *Journal of Sound and Vibration*, Vol. 332, No. 24, pp.6193–6202.

Dong, R.G., Welcome, D.E., McDowell, T.W. and Wu, J.Z. (2015) 'Fundamental theory, methods, and criteria for calibrating the human vibration models using frequency response functions', *Journal of Sound and Vibration*, Vol. 356, pp.95–216.

El-Khatib, A., Guillon, F. and Dômont, A. (1998) 'Vertical vibration transmission through the lumbar spine of the seated subject – first results', *Journal of Sound and Vibration*, Vol. 215, No. 4, pp.763–773.

Fairley, T.E. and Griffin, M.J. (1983) 'Application of mechanical impedance methods to seat transmissibility', *International Conference on Noise Control Engineering*, Edinburgh, UK, pp.533–536.

Fairley, T.E. and Griffin, M.J. (1989) 'The apparent mass of the seated human body: vertical vibration', *Journal of Biomechanics*, Vol. 22, pp.81–94.

Fairley, T.E. and Griffin, M.J. (1990) 'The apparent mass of the seated human body in the fore-and-aft and lateral directions', *Journal of Sound and Vibration*, Vol. 139, pp.299–306.

Fritz, M. (1998) 'Three-dimensional biomechanical model for simulating the response of the human body to vibration stress', *Medical and Biology Engineering*, Vol. 36, No. 6, pp.686–692.

Fritz, M. (2000) 'Simulating the response of a standing operator to vibration stress by means of a biomechanical model', *Journal of Biomechanics*, Vol. 33, pp.795–802.

Fritz, M. (2005) 'Dynamic properties of the biomechanical model of the human body – influence of posture and direction of vibration stress', *Journal of Low Frequency Noise, Vibration and Active Control*, Vol. 24, No. 4, pp.233–249.

Griffin, M.J. (2001) 'The validation of biodynamic models', *Clinical Biomechanics*, Vol. 16, Suppl. 1, pp.S81–S92.

Griffin, M.J., Lewis, C.H., Parsons, K.C. and Whitham, E.M. (1978) 'The biodynamic response of the human body and its application to standards', *Proceedings of the AGARD Conference*, Proceeding No. 253, Paris, France.

Griffin, M.J. and Whitham, E.M. (1978) 'Individual variability and its effect on subjective and biodynamic response to whole-body vibration', *Journal of Sound and Vibration*, Vol. 58, pp.239–250.

Gu, Y. (1999) *A New Dummy for Vibration Transmissibility Measurement in Improving Ride Comfort*, Society of Automotive Engineers (SAE) Technical Paper 01-0629.

Hinz, B., Menzel, G., Blüthner, R. and Seidel, H. (2001) 'Transfer functions as a basis for the verification of models – variability and restraints', *Clinical Biomechanics*, Vol. 16, Suppl. 1, pp.S93–S100.

Hinz, B., Rützel, S., Blüthner, R., Menzel, G., Wölfel Horst, P. and Seidel, H. (2006a) 'Apparent mass of seated men – first determination with a soft seat and dynamic seat pressure distribution', *Journal of Sound and Vibration*, Vol. 298, pp.704–724.

Hinz, B., Blüthner, R., Menzel, G., Rützel, S., Seidel, H. and Wölfel Horst, P. (2006b) 'Apparent mass of seated men – determination with single and multi-axis excitation at different magnitudes', *Journal of Sound and Vibration*, Vol. 298, pp.788–809.

Hinz, B. and Seidel, H. (1987) 'The nonlinearity of human body's dynamic response during sinusoidal whole-body vibration', *Industrial Health*, Vol. 25, pp.169–181.

Hinz, B., Seidel, H., Bräuer, R., Menzel, G., Blüthner, R. and Erdmann, U. (1988) 'Bidimensional accelerations of lumbar vertebrae and estimation of internal spinal load during sinusoidal vertical whole-body vibration: a pilot study', *Clinical Biomechanics*, Vol. 3, pp.241–248.

Hinz, B., Seidel, H., Menzel, G. and Blüthner, R. (2002) 'Effects related to random whole-body vibration and posture on a suspended seat with and without backrest', *Journal of Sound and Vibration*, Vol. 253, No. 1, pp.265–282.

Hinz, B., Seidel, H., Menzel, G., Gericke, L., Blüthner, R. and Keitel, J. (2004) *Seated Occupant Apparent Mass in Automotive Posture–examination with Groups of Subjects Characterized by a Representative Distribution of Body Mass and Body Height*, FIOSH Document 2004/4 Z.ARB.WISS.

Holmlund, P., Lundström, R. and Lindberg, L. (2000) 'Mechanical impedance of the human body in vertical direction', *Applied Ergonomics*, Vol. 31, No. 4, pp.415–422.

Huston, D.R., Johnson, C.C. and Zhao, X.D. (1998) 'A human analog for testing vibration attenuating seating', *Journal of Sound and Vibration*, Vol. 214, No. 1, pp.195–200.

ISO-5982 (2001) *Mechanical Vibration and Shock – Range of Idealized Values to Characterize Seated-body Biodynamic Response under Vertical Vibration*, International Organization for Standardization, Geneva.

ISO-7096 (2000) *Earth-moving Machinery – Laboratory Evaluation of Operator Seat Vibration*, International Organization for Standardization, Geneva.

ISO-DIS-5982 (2018) *Mechanical Vibration and Shock – Range of Idealized Values to Characterize Seated-body Biodynamic Response under Whole-body Vibration*. International Organization for Standardization, Geneva.

Joshi, G., Bajaj, A.K. and Davies, P. (2010) 'Whole-body vibratory response study using a nonlinear multi-body model of seat-occupant system with viscoelastic flexible polyurethane foam', *Industrial Health*, Vol. 48, pp.663–674.

Keller, T.S., Colloca, C.J. and Béliveau, J.G. (2002) 'Force-deformation response of the lumbar spine: a sagittal plane model of posteroanterior manipulation and mobilization', *Clinical Biomechanics*, Vol. 17, No. 3, pp.185–196.

Kim, S., White, S., Bajaj, A. and Davies, P. (2003) 'Simplified models for the vibration of mannequins in car seats', *Journal of Sound and Vibration*, Vol. 264, pp.49–90.

Kim, T-H., Kim, Y-T. and Yoon, Y-S. (2005) 'Development of a biomechanical model of the human body in a sitting posture with vibration transmissibility in the vertical direction', *International Journal of Industrial Ergonomics*, Vol. 35, pp.817–829.

Kitazaki, S. and Griffin, M. (1997) 'A modal analysis of whole-body vertical vibration, using a finite element model of the human body', *Journal of Sound and Vibration*, Vol. 200, pp.83–103.

Kitazaki, S. and Griffin, M.J. (1998) 'Resonance behaviour of the seated human body and effects of posture', *Journal of Biomechanics*, Vol. 31, No. 2, pp.143–149.

Kruczek, A. and Stribrsky, A. (2004) 'A full-car model for active suspension – some practical aspects', *Proceeding of the IEEE Conference on Mechatronics*, Istambul, Turkey, pp.110–115.

Kumbhar, P-B., Xu, P. and Yang, J. (2012) 'A literature survey of biodynamic models for whole body vibration and vehicle ride comfort', *Proceeding ASME International Design Engineering Technical Conference & Computers and Information in Engineering Conference*, Paper No. DETC2012-71061, 17p.

Lemerle, P. and Boulanger, P. (2006) 'Lower limb contribution to the biodynamic response of the seated man', *Journal of Sound and Vibration*, Vol. 294, pp.1004–1015.

Lewis, C.H. (2005) 'Variability in measurements of seat transmissibility with an active anthropodynamic dummy and with human subjects', *40th UK Conference on Human Response to Vibration*, Liverpool, UK, 15p.

Liang, C-C. and Chiang, C-F. (2006) 'A study of biodynamic models of seated human subjects exposed to vertical vibration', *International Journal of Industrial Ergonomics*, Vol. 36, pp.869–890.

Lings, S. and Leboeuf-Yde, C. (2000) 'Whole-body vibration and low back pain: a systematic critical review of the epidemiological literature 1992–1999', *International Archive Occupational Environmental Health*, Vol. 73, pp.290–297.

Liu, X.X., Shi, J. and Li, G.H. (1998) 'Biodynamic response and injury estimation of ship personnel to ship shock motion induced by underwater explosion', *Proceeding of 69th Shock and Vibration Symposium*, St. Paul., MN, Vol. 18, pp.1–18.

Mandapuram, S., Rakheja, S., Ma, S. and Demont, R. (2005) 'Influence of back support conditions on the apparent mass of seated occupants under horizontal vibration', *Industrial Health*, Vol. 43, pp.421–35.

Mansfield, N.J. and Griffin, M.J. (1996) 'Vehicle seat dynamics measured with an anthro-podynamic dummy and human subjects ', *Proceeding of Inter-Noise'96*, Vol. 4, pp.1725–1730.

Mansfield, N.J. and Griffin, M.J. (2000) 'Nonlinearities in apparent mass and transmissibility during exposure to whole-body vertical vibration', *Journal of Biomechanics*, Vol. 33, pp.933–941.

Mansfield, N.J. and Griffin, M.J. (2002) 'Effects of posture and vibration magnitude on apparent mass and pelvis rotation during exposure to whole-body vertical vibration', *Journal of Sound and Vibration*, Vol. 253, No. 1, pp.93–107.

Mansfield, N.J., Holmlund, P. and Lundström, R. (2001) 'Apparent mass and absorbed power during exposure to whole-body vibration and repeated shocks', *Journal of Sound and Vibration*, Vol. 248, No. 3, pp.427–440.

Mansfield, N.J., Holmlund, P., Lundström, R., Lenzuni, P. and Nataletti, P. (2006) 'Effect of vibration magnitude, vibration spectrum and muscle tension on apparent mass and cross-axis transfer functions during whole-body vibration exposure', *Journal of Biomechanics*, Vol. 39, pp.3062–3070.

Mansfield, N.J. and Maeda, S. (2005a) 'Effect of backrest and torso twist on apparent mass of the seated body exposed to vertical vibration', *Industrial Health*, Vol. 43, pp.413–420.

Mansfield, N.J. and Maeda, S. (2005b) 'Comparison of the apparent mass of the seated human measured using random and sinusoidal vibration', *Industrial Health*, Vol. 43, pp.233–240.

Mansfield, N.J. and Maeda, S. (2006) 'Comparisons of the apparent masses and cross-axis apparent masses of seated body exposed to single- and dual-axis whole-body vibration', *Journal of Sound and Vibration*, Vol. 298, pp.841–853.

Mansfield, N.J. and Maeda, S. (2007) 'The apparent mass of the seated human exposed to single-axis and multi-axis whole-body vibration', *Journal of Biomechanics*, Vol. 40, pp.2543–2551.

Markolf, K. (1970) 'Stiffness and damping characteristics of the thoracic lumbar spine', *Proceeding Workshop on Bioengineering Approaches to Problems of the Spine*, National Institute of Health, Bathesda, MA, pp.87–142.

Matsumoto, Y. and Griffin, M.J. (1998) 'Movement of the upper body of seated subjects exposed to vertical whole-body at the principal resonance frequency', *Journal of Sound and Vibration*, Vol. 215, No. 4, pp.734–762.

Matsumoto, Y. and Griffin, M.J. (2000) 'Comparison of biodynamic responses in standing and seated human bodies', *Journal of Sound and Vibration*, Vol. 238, No. 4, pp.691–704.

Matsumoto, Y. and Griffin, M.J. (2001) 'Modeling the dynamic mechanisms associated with principal resonance of the seated subjects human body', *Clinical Biomechanics*, Vol. 16, Suppl. 1, pp.S31–S44.

Matsumoto, Y. and Griffin, M.J. (2002a) 'Effect of muscle tension on non-linearities in the apparent masses of seated subjects exposed to vertical whole-body vibration', *Journal of Sound and Vibration*, Vol. 253, No. 1, pp.77–92.

Matsumoto, Y. and Griffin, M.J. (2002b) 'Nonlinear characteristics in the dynamic responses of seated subjects exposed to vertical whole-body vibration', *Transaction of ASME, Journal of Biomechanical Engineering*, Vol. 24, pp.527–532.

Mertens, H. (1978) 'Nonlinear behaviour of sitting humans under increasing gravity', *Aviation Space and Environmental Medicine*, Vol. 49, pp.287–298.

Miwa, T. (1975) 'Mechanical impedance of human body in various postures', *Industrial Health*, Vol. 13, pp.1–22.

Muksian, R. and Nash, C. (1974) 'A model for the response of seated humans to sinusoidal displacements of the seat', *Journal of Biomechanics*, Vol. 7, pp.209–215.

Nawayseh, N. and Griffin, M.J. (2003) 'Non-linear dual-axis biodynamic response to vertical whole-body vibration', *Journal of Sound and Vibration*, Vol. 268, pp.503–523.

Nawayseh, N. and Griffin, M.J. (2005a) 'Non-linear dual-axis biodynamic response to for-and-aft whole-body vibration', *Journal of Sound and Vibration*, Vol. 282, pp.831–862.

Nawayseh, N. and Griffin MJ (2005b) 'Effect of seat surface angle on forces at the seat surface during whole-body vertical vibration', *Journal of Sound and Vibration*, Vol. 284, pp.613–634.

Nawayseh, N. and Griffin, M.J. (2009) 'A model of the vertical apparent mass and the fore-and-aft cross-axis apparent mass of the human body during vertical whole-body vibration', *Journal of Sound and Vibration*, Vol. 319, pp.719–730.

Nelisse, H., Patra, S., Rakheja, S. and Boileau, P-E. (2008) 'Assessments of two dynamic manikins for laboratory testing of seats under whole-body vibration', *International Journal of Industrial Ergonomics*, Vol. 38, pp.457–470.

Paddan, G.S. and Griffin, M.J. (1998) 'A review of the transmission of translation seat vibration to the head', *Journal of Sound and Vibration*, Vol. 215, No. 4, pp.863–882.

Pang, J., Qatu, M., Dukkipati, R. and Sheng, G. (2005) 'Nonlinear seat cushion and human body model', *International Journal of Vehicle Noise and Vibration*, Vol. 1, Nos. 3–4, pp.194–206.

Panjabi, M.M., Anderson, G.B.J., Jorneus, L., Hulet, E. and Mattsson, L. (1986) 'In vivo measurements of spinal column vibrations', *Journal of Bone and Joint Surgery*, Vol. 68A, pp.693–702.

Panjabi, M.M., Brand, R. and White III, A. (1976) 'Three-dimensional flexibility and stiffness properties of the human thoracic spine', *Journal of Biomechanics*, Vol. 9, pp.185–192.

Pankoke, S., Buck, B. and Wölfel, H. (1998) 'Dynamic FE model of sitting man adjustable to body height, body mass and posture used for calculating internal forces in the lumbar vertebral disks', *Journal of Sound and Vibration*, Vol. 215, pp.827–839.

Pankoke, S., Hofmann, J. and Woelfel, H.P. (2001) 'Determination of vibration-related spinal loads by numerical simulation', *Clinical Biomechanics*, Vol. 16, Suppl. 1, pp.S45–S56.

Paplukopoulos, C. and Natsivas, S. (2007) 'Nonlinear biodynamics of passenger coupled with quarter car models', *Journal of Sound and Vibration*, Vol. 304, pp.50–71.

Patra, S.K., Rakheja, S., Nelisse, H., Boileau, P-É. and Boutin, J. (2008) 'Determination of reference values of apparent mass responses of seated occupants of different body masses under vertical vibration with and without a back support', *International Journal of Industrial Ergonomics*, Vol. 38, pp.483–498.

Politis, H., Rakheja, S., Boileau P-E., Juras, D. and Boutin, J. (2003) 'Limits of application of human body dynamics in assessing vibration comfort of seats', *SAE Transactions, Journal of Passenger Cars–Mechanical Systems*, Vol. 112, pp.973–979.

Pope, M.H., Wilder, D.G. and Magnusson, M. (1998) 'Possible mechanisms of low back pain due to whole-body vibration', *Journal of Sound and Vibration*, Vol. 215, pp.687–697.

Pranesh, A., Rakheja, S. and DeMont, R. (2008) 'Analysis of biodynamic responses of a seated body under vertical vibration', *International Journal on Industrial Risks Engineering*, Vol. 1, pp.102–119.

Pranesh, A.M. (2011) 'Experimental and analytical study of transmission of whole body vibration to segments of the seated human body. Doctoral Thesis, Concordia University, Montreal, Canada.

Rakheja, S., Afework, Y. and Sankar, S. (1994) 'An analytical and experimental investigation of the driver-seat suspension system', *Vehicle System Dynamics*, Vol. 23, pp.501–524.

Rakheja, S., Dong, R.G., Patra, S., Boileau, P-É., Marcotte, P. and Warren, C. (2010) 'Biodynamics of the human body under whole-body vibration: synthesis of the reported data', *International Journal of Industrial Ergonomics*, Vol. 40, pp.710–732.

Rakheja, S., Dong, R.G., Welcome, D. and Ahmed, A.K.W. (2007) 'A preliminary study of cross-axis coupling effects in biodynamic response of the hand-arm system', *Proceeding of the 11th International Hand-Arm Vibration Conference*, Bologna, Italy, May, pp.327–334.

Rakheja, S., Mandapuram, S. and Dong, R. (2008) 'Energy absorption of seated occupants exposed to horizontal vibration and role of back support', *Industrial Health*, Vol. 46, pp.550–566.

Rakheja, S., Stiharu, I., Zhang, H. and Boileau, P-É. (2006) 'Seated occupant interactions with seat backrest and pan, and biodynamic responses under vertical vibration', *Journal of Sound and Vibration*, Vol. 298, pp.651–671.

Rakheja, S., Dewangan, K.N., Dong R.G. and Marcotte, P. (2020) 'Whole-body vibration biodynamics – a critical review: I. Experimental biodynamics', *International Journal of Vehicle Performance*, Vol. 6, No. 1, pp.1–51

Seidel, H. (2005) 'On the relationship between whole-body vibration exposure and spinal health risk', *Industrial Health*, Vol. 43, pp.361–377.

Seidel, H., Bluthner, R. and Hinz, B. (2001) 'Application of finite-element models to predict forces acting on the lumbar spine during whole-body vibration', *Clinical Biomechanics*, Vol. 16, Suppl. 1, pp.S57–63.

Shibata, N. and Maeda, S. (2010) 'Determination of backrest inclination based on biodynamic response study for prevention of low back pain', *Medical Engineering and Physics*, Vol. 32, pp.577–583.

Starck, J., Pekkarinen, J., Pyykkö, I., Aalto, H. and Toppila, E. (1991) 'Transmission of vibration to the heads of standing subjects', *Journal of Low Frequency Noise, Vibration and Active Control*, Vol. 10, pp.1–7.

Stein, G.J. and Múča, P. (2003) 'Theoretical investigation of a linear planar model of a passenger car with seated people', *Proceeding Institution Mechanical Engineers, Journal of Automobile Engineering*, Vol. 217, pp.257–268.

Stein, G.J., Múčka, P., Chmúrny, R., Hinz, B. and Blüthner, R. (2007) 'Measurement and modelling of x-direction apparent mass of the seated human body–cushioned seat system', *Journal of Biomechanics*, Vol. 40, pp.1493–1503.

Stein, G.J., Múčka, P., Hinz, B. and Blüthner, R. (2009) 'Measurement and modelling of the y-direction apparent mass of sitting human body–cushioned seat system', *Journal of Sound and Vibration*, Vol. 322, pp.454–474.

Stein, G.J., Zahoranský, R., Gunston, T.P., Burström, L. and Meyer, L. (2008) 'Modelling and simulation of a fore-and-aft driver's seat suspension system with road excitation', *International Journal of Industrial Ergonomics*, Vol. 38, pp.384–395.

Subashi, G.H.M.J., Matsumoto, Y. and Griffin, M.J. (2006) 'Apparent mass and cross-axis apparent mass of standing subjects during exposure to vertical whole-body vibration', *Journal of Sound and Vibration*, Vol. 293, pp.78–95.

Subashi, G.H.M.J., Matsumoto, Y. and Griffin, M.J. (2008) 'Modelling resonances of the standing body exposed to vertical whole-body vibration: effects of posture', *Journal of Sound and Vibration*, Vol. 317, pp.400–418.

Suggs, C.W., Abrams, C.F. and Stikeleather, L.F. (1969) 'Application of a damped spring-mass human vibration simulating vibration testing of vehicle seats', *Ergonomics*, Vol. 12, pp.79–90.

Tchernychouk, V., Rakheja, S., Stiharu, I. and Boileau, P-É. (2000) 'Study of occupant-seat models for vibration comfort analysis of automotive seats', *Transactions of SAE, Journal of Passenger Vehicles – Mechanical Systems*, Vol. 109, No. 6, pp.2308–2313.

Teng, T-L., Chang, F-A. and Peng, C-P. (2006) 'Analysis of human body response to vibration using multi-body dynamics method', *Proceeding Institution Mechanical Engineers, Part K: Journal Multi-Body Dynamics*, Vol. 220, pp.191–202.

Toward, M.G.R. and Griffin, M.J. (2009) 'Apparent mass of the human body in the vertical direction: effect of seat backrest', *Journal of Sound and Vibration*, Vol. 327, pp.657–669.

Toward, M.G.R. and Griffin, M.J. (2010) 'A variable parameter single degree-of-freedom model for predicting the effects of sitting posture and vibration magnitude on the vertical apparent mass of the human body', *Industrial Health*, Vol. 48, pp.654–662.

Verver, M., van Hoof, J., Oomens, C., van de Wouw, N. and Wismans, J. (2003) 'Estimation of spinal loading in vertical vibrations by numerical simulation', *Clinical Biomechanics*, Vol. 18, pp.800–811.

Von Gierke, H.E. and Coermann, R.R. (1963) 'The biodynamics of human response to vibration and impact', *Industrial Medicine & Surgery*, Vol. 32, pp.30–32.

Wan, Y. and Schimmels, J. (1995) 'A simple model that captures the essential dynamics of a seated human exposed to whole body vibration', *Advances in Bioengineering, ASME*, Vol. 31, pp.333–334.

Wang, W., Bazrgari, B., Shirazi-Adl, A., Rakheja, S. and Boileau, P-É. (2008) 'Relationship between measured apparent mass and seat-to-head transmissibility responses of seated occupants exposed to vertical vibration', *Journal of Sound and Vibration*, Vol. 314, pp.907–922.

Wang, W., Bazrgari, B., Shirazi-Adl, A., Rakheja, S. and Boileau, P-É. (2010) 'Biodynamic response and spinal load estimation of seated body in vibration using finite element modeling', *Industrial Health*, Vol. 48, pp.557–564.

Wang, W., Rakheja, S. and Boileau, P-É. (2004) 'Effects of sitting postures on biodynamic response of seated occupants under vertical vibration', *International Journal of Industrial Ergonomics*, Vol. 34, No. 4, pp.289–306.

Wang, W., Rakheja, S. and Boileau, P-É. (2006a) 'Effect of back support condition on seat to head transmissibilities of seated occupants under vertical vibration', *Journal of Low Frequency Noise, Vibration and Active Control*, Vol. 25, No. 4, pp.239–259.

Wang, W., Rakheja, S. and Boileau, P-É. (2006b) 'The role of seat geometry and posture on the mechanical energy absorption characteristics of seated occupants under vertical vibration', *International Journal of Industrial Ergonomics*, Vol. 36, pp.171–184.

Wei, L. and Griffin, M. (1998b) 'Mathematical models for the apparent mass of the seated human body exposed to vertical vibration', *Journal of Sound and Vibration*, Vol. 212, pp.855–874.

Wei, L. and Griffin, M.J. (1998a) 'The prediction of seat transmissibility from measures of seat impedance', *Journal of Sound and Vibration*, Vol. 214, No. 1, pp.121–137.

Weis Jr., B.B., Clarke, N.P., Brinkley, J.W. and Martin, P.J. (1964) 'Mechanical impedance as a tool in research on human response to acceleration', *Aerospace Medicine*, Vol. 35, pp.945–950.

Wisman, J. (1983) *Comparison of Mass Distribution of the Part 572 Dummy*, Ohio State University, Columbus, Ohio, USA.

Wu, X., Rakheja, S. and Boileau, P-É. (1999) 'Analysis of relationships between biodynamic response functions', *Journal of Sound and Vibration*, Vol. 226, No. 3, pp.595–606.

Yoshimura, T., Nakai, K. and Tamaoki, G. (2005) 'Multi-body dynamics modeling of seated human body under exposure to whole-body vibration', *Industrial Health*, Vol. 43, pp.441–447.

Zimmermann, C.L. and Cook, T.M. (1997) 'Effects of vibration frequency and postural changes on human responses to seated whole-body vibration', *International Archives of Occupational Environmental & Health*, Vol. 69, pp.165–179.