REVIEW OF THE NONLINEAR BIODYNAMIC RESPONSES OF THE SEATED HUMAN BODY DURING VERTICAL WHOLE-BODY VIBRATION: THE SIGNIFICANT VARIABLE FACTORS

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Abstract

The consistent finding of a nonlinearity in the human body apparent mass has gradually received more attention when modelling biodynamic responses of the human body. However, the factors causing the nonlinearity and the extent of the nonlinearity are not yet understood. Investigators have mainly speculated on causality of the nonlinearities rather than designed experiments to test hypothetical explanations for the nonlinearity. This paper aims to identify variables governing the nonlinear responses of the seated human body during vertical whole-body vibration. The apparent mass data and experimental conditions from six of the more relevant studies are compared. Explanations of the mechanisms controlling nonlinear behaviour are also compared. The dominant variables are classified as: posture, muscle tone, dynamics of buttocks tissue, and geometric nonlinearity.

1. Introduction

Nonlinear characteristics in the seated human body dynamic response during vertical whole-body vibration have been observed in several studies (e.g. Fairley and Griffin, 1989; Mansfield and Griffin, 2000; Mansfield and Griffin, 2002; Matsumoto and Griffin, 2002a; Matsumoto and Griffin, 2002b; Nawayseh and Griffin, 2003). A consistent finding has been that the principal resonance frequency in the frequency response functions (i.e., driving-point impedance and transmissibilities) decrease with increasing vibration magnitude – a nonlinear softening effect, and that the size of the change in resonance frequency varies with vibration magnitude (i.e. there is a greater change in the resonance frequency at lower vibration magnitudes than at higher vibration magnitudes). An understanding of the nonlinearities in the biodynamic responses of the human body may advance understanding of the mechanisms controlling body movement and improve anthropodynamic models of responses to vibration at various magnitudes.

A two-dimensional response during single-axis excitation in either the vertical or the fore-and-aft direction has been reported (Matsumoto and Griffin, 2002b; Nawayseh and Griffin, 2003). Nonlinearities have been observed both in the driving-point frequency response functions and in the cross-axis frequency response functions. In this paper, the main interest is in nonlinearities measured during vertical whole-body excitation with responses of the human body measured in the vertical and the fore-and-aft directions.

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During vertical excitation, a primary resonance is consistently found around 5 Hz (e.g. Fairley and Griffin, 1989; Matsumoto and Griffin, 2002a; Mansfield and Griffin, 2002; Nawayseh and Griffin, 2003) with a secondary resonance at about 8 to 13 Hz (Fairley and Griffin, 1989; Mansfield and Griffin, 2002). Mansfield and Griffin (2000) observed that apparent mass nonlinearities were most apparent in the frequency range of 3 to 16 Hz. Most studies have investigated the frequency range from 0.2 to 20 Hz so as to encompass both resonances.

Most researchers have used random vibration because it is less time-consuming to obtain coverage over a frequency range. However, variations in the input power spectra have been reported to have a significant effect on the human body nonlinearity (Sandover, 1978; Fairley, 1986; Toward, 2002). So, to investigate some effects of nonlinearity, it would be more appropriate to use sinusoidal excitation (e.g. Matsumoto and Griffin, 2002b).

The driving-point frequency response functions are used to describe the relations between the driving force and the ensuing movements (acceleration, velocity, or displacement) of the human body over the frequency range. Most data have been reported in one of two forms: apparent mass (a type of driving-point mechanical impedance) or transmissibility.

The 'apparent mass' ('driving-point apparent mass' or 'effective mass'), $M(f)$, is defined as the ratio of the driving force, $F(f)$, to the resulting acceleration, $\ddot{z}(f)$, of the system measured at the same point and in the same direction (*z*-axis for the vertical direction) as the applied force:

$$M(f) = \frac{F(f)}{\ddot{z}(f)}$$

Transmissibilities are ratios of the movements (acceleration, velocity, or displacement) between the driving point and points of interest in, or on, the human body. These points can be the head, pelvis, lumbar vertebrae, thoracic vertebrae. With vertical excitation at the seat, movement is usually measured in the vertical, fore-and-aft and pitch directions. For instance,

$$T(f) = \frac{\ddot{x}_l(f)}{\ddot{z}(f)}$$

where $T(f)$ may be the vertical seat to fore-and-aft lumbar transmissibility; $\ddot{x}_l(f)$ is the measured fore-and-aft acceleration at the lumbar vertebra, and $\ddot{z}(f)$ is the measured vertical acceleration at the seat-subject interface. Transmissibilities have been used to identify the modes involved in the dynamic resonances of the human body and to analyse the relative movements between two measuring points (e.g. Kitazaki, 1994; Kitazaki and Griffin, 1998).

The 'normalised apparent mass' is the apparent mass divided by the static weight of the body when seated on the platform. The introduction of normalised apparent mass serves to reduce the variability among subjects due to their differing static weights (Fairley, 1986).

This paper aims to identify the principal variables governing the nonlinear responses of the seated human body during excitation by vertical whole-body vibration, with responses in the vertical and fore-and-aft directions. The conditions of previous experiments and the reported apparent mass data are compared. The hypothetical explanations of the mechanisms controlling nonlinear behaviour are also compared. The variables that may influence the nonlinearity are classified as: posture, muscle tone, the dynamics of buttocks tissue, and geometric nonlinearity.

2. Review of six studies

The six most relevant studies of nonlinear biodynamic response to whole-body vertical vibration are reviewed in this section. The experiments are compared in terms of the experimental conditions (Table 1), resonance frequencies at various vibration magnitudes (Table 2), and the size of the difference in resonance frequency between two pairs of vibration magnitudes (Figure 1). The review of each paper commences with a summary of the hypothesis, or the hypothetical explanation of the characteristic nonlinearity.

Table 1 Comparison of experimental conditions from six studies.

Authors	Subjects	Excitation	Procedure
TEF-MJG 1989	60 subjects from public, 12 children, 24 women, 24 men	Random vertical 0.2 – 20 Hz	No backrest. Footrest moved with platform. Comfortable upright sitting posture with normal muscle tension.
NJM-MJG 2000	12 subjects	Random vertical 0.2 – 20 Hz	No backrest. Footrest moved with platform. Comfortable upright sitting posture.
YM-MJG 2002a	8 male subjects	Random vertical 0.5 – 20 Hz	No backrest. No footrest. Comfortable upright sitting posture.
YM-MJG 2002b	8 male subjects	Random vertical 2.0 – 20 Hz, and sinusoidal vertical.	No backrest. Stationary footrest. Comfortable upright sitting posture with: 1. Normal muscle tension. 2. Buttocks muscle tensed. 3. Abdominal muscle tensed.
NJM-MJG 2002	12 male subjects	Random vertical 1.0 – 20 Hz.	No backrest. Footrest moved with platform. Nine sitting postures and muscle tension conditions: 1. Comfortable upright 2. Anterior lean bending at pelvis. 3. Posterior lean bending at pelvis. 4. Kyphotic slouched upper spine. 5. Back-on. 6. Pelvis support 7. Inverted SIT-BAR increased pressure under ischial tuberosities. 8. Bead cushion. 9. Belt on.
NN-MJG 2003	12 male subjects	Random vertical 0.25 – 25 Hz.	No backrest. Footrest moved with platform. Four foot heights: 1. Foot hanging 2. Maximum thigh contact 3. Average thigh contact 4. Minimum thigh contact

Notations: TEF-MJG1989 = Fairley, T.E. and Griffin, M.J. (1989); NJM-MJG2000 = Mansfield, N.J. and Griffin, M.J. (2000); YM-MJG2002a = Matsumoto, Y. and Griffin, M.J. (2002a); YM-MJG2002b = Matsumoto, Y. and Griffin, M.J. (2002b); NJM-MJG2002 = Mansfield, N.J. and Griffin, M.J. (2002); NN-MJG2003 = Nawayseh, N. and Griffin, M.J. (2003).

Table 2 Characteristic nonlinearity: resonance frequencies (Hz) at various vibration magnitudes (ms^{-2} r.m.s.)

		Vibration magnitudes (ms^{-2}r.m.s.)												
	Conditions	0.125	0.200	0.250	0.350	0.500	0.625	0.700	1.000	1.250	1.400	1.500	2.000	2.500
TEF-MJG 1989	Upright normal	-	-	6.00	-	n.a	-	-	n.a	-	-	-	4.00	-
NJM-MJG 2000	Upright normal	-	-	5.40	-	5.00	-	-	4.70	-	-	4.60	4.40	4.20
YM-MJG 2002a	Upright normal	6.40	-	6.16*	-	5.61*	-	-	5.36*	-	-	-	4.75	-
YM-MJG 2002b	Upright normal	-	-	-	5.25	5.17*	-	5.03*	4.82*	-	4.25	-	-	-
	Buttocks	-	-	-	5.00	4.89*	-	4.67*	4.48*	-	4.38	-	-	-
	Abdomen	-	-	-	5.13	5.03*	-	4.69*	4.36*	-	4.50	-	-	-
NJM-MJG 2002	Upright normal	-	5.27	-	-	-	-	-	5.08	-	-	-	4.69	-
	Anterior	-	6.06	-	-	-	-	-	5.18	-	-	-	4.79	-
	Posterior	-	5.47	-	-	-	-	-	4.59	-	-	-	4.39	-
	Kyphotic	-	6.25	-	-	-	-	-	5.08	-	-	-	4.49	-
	Back-on	-	5.47	-	-	-	-	-	5.08	-	-	-	4.69	-
	Pelvis support	-	5.86	-	-	-	-	-	5.08	-	-	-	4.69	-
	SIT-BAR	-	5.76	-	-	-	-	-	4.79	-	-	-	4.59	-
	Cushion	-	5.37	-	-	-	-	-	4.49	-	-	-	4.10	-
	Belt	-	6.45	-	-	-	-	-	5.08	-	-	-	4.88	-
NN-MJG 2003	Feet hanging	5.85#	-	5.85#	-	-	5.07#	-	-	4.68#	-	-	-	-
	Max. thigh contact	6.24#	-	5.85#	-	-	5.07#	-	-	4.68#	-	-	-	-
	Average thigh contact	5.85#	-	5.85#	-	-	5.46#	-	-	4.68#	-	-	-	-
	Min. thigh contact	5.85#	-	5.85#	-	-	5.07#	-	-	5.07#	-	-	-	-

Note:
- n.a = not available
- * = peak resonance frequency value estimated from graphic results
- # = apparent mass (otherwise the date are normalised apparent mass)
- Refer to Table 1 for notations.

2.1 Fairley and Griffin (1989)

The authors reported a softening effect with increasing vibration magnitude and suggested that a greater movement with high magnitudes of vibration may reduce the stiffness of the musculo-skeletal structure. A lesser change in the resonance frequency was observed at higher vibration magnitudes and it was suggested that subjects may involuntarily increase muscle tension to reduce the motion, or there may be limited ability to vary body stiffness.

The authors demonstrated the nonlinearity in apparent mass in all individual subjects with the primary resonance frequency decreasing from about 6 to 4 Hz as the vibration magnitude increased from 0.25 to 2.0 ms^{-2} r.m.s. A different change in resonance frequency was observed at different vibration magnitudes. The authors hypothesised that the reasons may be some combination of muscle tone or the dynamic properties of the human skeletal structure. Additionally, the authors noted a similarity to the nonlinear softening effect with thixotropic behaviour (Lakie, *et al.*, 1979).

2.2 Mansfield and Griffin (2000)

Nonlinearity was observed along a transmission path common to the spine and the abdomen and it was suggested that the nonlinearity could be caused by a combination of factors:

- Softening response of the buttocks tissue.
- Bending or buckling response of the spine (physically, an inverted pendulum).
- Softening system in the muscle forces (a doubling of vibration magnitude did not result in a doubling of the muscle activity).

A greater change in the resonance frequency was observed at lower vibration magnitudes than at higher vibration magnitudes.

It was reported that the principal resonance frequency in the apparent mass decreased from 5.4 to 4.2 Hz as the vibration magnitude increased from 0.25 to 2.5 ms^{-2} r.m.s. (Table 2). The apparent mass nonlinearities were observed in the frequency range 3 to 16 Hz. Transmissibilities from the seat to the lower and upper abdomen wall were measured to investigate the cause of the primary apparent mass resonance frequency. It was concluded that the primary resonance of the human body dynamic system consists of several highly coupled modes. The authors attributed the nonlinear behaviour to three factors (dynamics of buttocks tissue, geometric nonlinearity, and muscle tone) giving rise to 'a transmission path common to the spine and the abdomen'. They extended the causes of the characteristic nonlinearity from a previous study (Mansfield, 1998), which had rejected all other factors except geometric nonlinearity.

Individual data on the effect of vibration magnitude on the apparent mass resonance frequency showed a greater change in the resonance frequency at lower vibration magnitudes than at higher vibration magnitudes (in 11 out of 12 subjects). The different change in peak resonance frequency at the lowest and highest vibration magnitudes was also evident in the median normalised apparent mass data (Figure 1).

2.3 Matsumoto and Griffin (2002a)

These authors concluded that the geometry of the body is not the only cause of the nonlinearity in apparent mass and suggested that a softening characteristic in the soft tissues in the body makes a contribution to the nonlinearity (e.g., thixotropic behaviour, visceral tissues, voluntary and involuntary muscle activity).

The resonance frequency decreased from 6.4 to 4.75 Hz as the vibration magnitude increased from 0.125 to 2.0 ms^{-2} r.m.s. (Table 2). The extracted body modes from the transmission of vertical seat vibration to the vertical, fore-and-aft, and pitch axes along the vertebral column, and to the pelvis, suggested that the spine and softening soft tissue along the spine might contribute to the nonlinearity.

The median normalised apparent mass showed a consistently lower change in resonance frequency caused by changes in higher vibration magnitudes than caused by changes in lower vibration magnitudes (Figure 1).

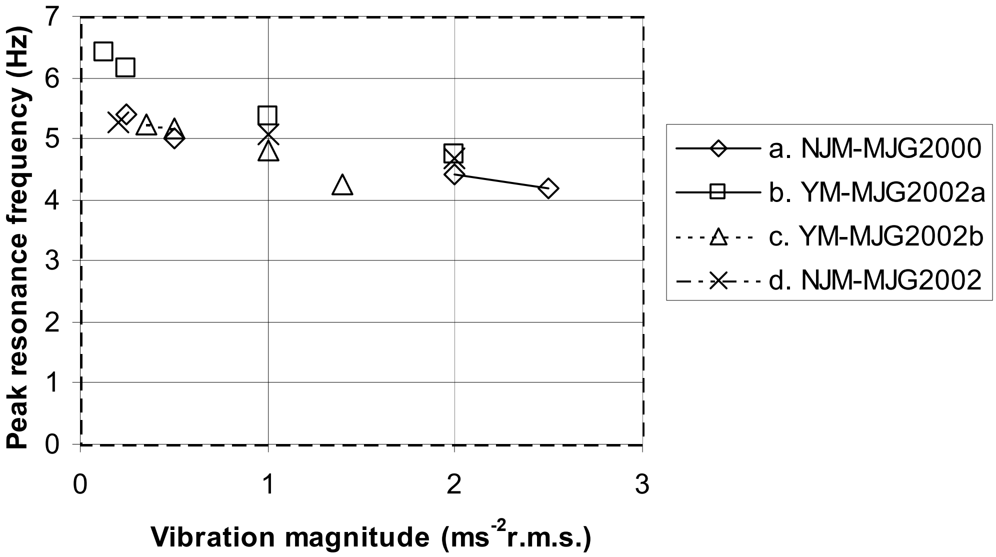

Figure 1. The effect of vibration magnitude on the resonance frequency and the size of the change in resonance frequency with varying vibration magnitude (there is a greater change in the resonance frequency at two consecutive lower vibration magnitudes than at two higher vibration magnitudes).

Note: - The peak resonance frequencies have been estimated from graphic results; all data apply to the median normalised apparent mass.
- Refer to Table 1 Notations a, b, c, and d.

2.4 Matsumoto and Griffin (2002b)

A reduced degree of nonlinearity with controlled muscle tension in the buttocks and abdomen suggested that involuntary changes in muscle tension might partly be responsible for the characteristic nonlinearity. Nonlinearity in cross-axis apparent mass (the ratio of force in the fore-and-aft direction to the acceleration in the vertical direction) was not significantly affected by changes in muscle tension in the buttocks or abdomen.

The authors measured apparent mass in conditions with different muscle tensions and found that involuntary changes in muscle tension in the buttocks and abdomen may be partly responsible for the characteristic nonlinearity: less nonlinearity was observed with the controlled buttocks and abdomen muscle conditions (the subjects were instructed only to tense the buttocks or the abdomen with a comfortable upright sitting posture; Table 2). The researchers found a similar pattern of nonlinearity in the fore-and-aft cross-axis apparent mass. However, there was no evident effect of muscle tension in the buttocks or abdomen on the nonlinearity of the fore-and-aft cross-axis apparent mass.

Sinusoidal excitation was applied in this study. However, the frequency resolution was too coarse to locate precisely the resonance frequency and to allow the quantification of the nonlinear change in apparent mass resonance frequency.

2.5 Mansfield and Griffin (2002)

A consistent nonlinear softening effect was found but there was no significant change in the nonlinearity over nine different sitting conditions.

Nine sitting postures were developed (Table 1) to investigate their effects on the nonlinearity in vertical apparent mass. A similar pattern of nonlinearity was found in the seat-to-pelvis transmissibility. With the vibration magnitude at 0.2 and 1.0 ms^{-2} r.m.s. no significant difference in apparent mass resonance frequency was observed in a condition that controlled the rotation of the pelvis (pelvis support condition). Significantly higher resonance frequencies were reported in a condition with the visceral movement restricted ('belt on' condition) at 0.2 and 2.0 ms^{-2} r.m.s. Except for an 'anterior lean' condition at 0.2 ms^{-2} r.m.s., both whole-body bending conditions - anterior and posterior lean conditions - showed no significant change in apparent mass resonance frequency compared to an upright posture. Increasing the contact area (decreasing the pressure) at the buttocks tissue, by reducing the area of the seat surface, decreased the apparent mass resonance frequencies at 1.0 and 2.0 ms^{-2} r.m.s. Differences in the nonlinearity were found in some of the postures, however they were mainly small and difficult to interpret (Table 2) .

2.6 Nawayseh and Griffin (2003)

A reduced nonlinearity was found when there was increased pressure in buttocks tissue, suggesting that the dynamics of the buttocks tissue is involved in the nonlinearity.

The authors observed less nonlinearity with increased pressure in the tissue beneath the ischial tuberosities. The pressure of the tissue beneath the ischial tuberosities was controlled by varying the thigh contact area (raising or lowering the feet). A similar nonlinearity was found in the cross-axis apparent mass in the fore-and-aft direction. However, changing the pressure on the tissue beneath the ischial tuberosities did not significantly affect the nonlinearity in the cross-axis apparent mass resonance frequency. This was consistent with the findings of Masumoto and Griffin (2002b). There were large dynamic responses in the fore-and-aft direction during vertical excitation, suggesting a two-dimensional (vertical and fore-and-aft) biodynamic model of the human body. The authors concluded that responses of the body in the vertical and fore-and-aft directions might contribute to the characteristic nonlinearity (see Section 3).

3. Identification of four variables

Two characteristics of the nonlinear responses in frequency response functions (apparent mass, and transmissibilities) of the seated body during vertical whole-body vibration will be considered:

- An increase in the apparent mass resonance frequency with decreasing vibration magnitude – a nonlinear softening effect (Table 2)
- The change in the resonance frequency is dependent on vibration magnitude – there is a greater change in the resonance frequency at lower vibration magnitudes than at higher vibration magnitudes (Figure 1).

There are four main variables that have been suggested as factors influencing the characteristic nonlinearity: posture, muscle tone, the dynamics of the buttocks tissue, and the geometry of the body.

3.1 Posture

With excitation at a single vibration magnitude, a more erect sitting posture tends to produce greater resonance frequencies and greater magnitudes of apparent mass, consistent with a stiffening effect (Fairley and Griffin, 1989; Kitazaki and Griffin, 1997).

Mansfield (1998) and Mansfield and Griffin (2002) found limited changes (at particular vibration magnitudes) in the apparent mass resonance frequency with pelvis support, belt on, whole body bending and varying buttocks tissue pressure conditions. The nonlinear change in the resonance frequency with varying vibration magnitude did not differ significantly over a range of postures. This may indicate that the nonlinearity in apparent mass might not be caused by involuntary postural change (e.g., a possible self-protect reaction of the human body when exposed to a sudden change of vibration).

3.2 Muscle tone

Often, muscle changes occur with postural changes. Changes in muscle tone are difficult to define without objective measurement of muscle activity because the extent of muscular activity is not accurately judged via human perception.

Increased muscle tension tends to stiffen the human body. This might counteract the nonlinear softening effect in the apparent mass: when the body experiences high vibration magnitudes the tonic vibration reflex contracts muscles (Griffin, 1990). This may partially explain the smaller change in the resonance frequency at higher vibration magnitudes than at lower vibration magnitudes.

During dynamic excitation, muscle activity can be categorised into tonic responses and phasic responses. The tonic component refers to the resistance to stretch in the skeletal muscle (Lakie, 1986); the phasic component refers to muscle activity fluctuating with the vibration waveform. Robertson and Griffin (1989) investigated the effect of vibration frequency, vibration magnitude, vibration duration and vibration direction on the electromyographic (EMG) activity of back muscle. The study found that increases in vibration magnitude increased the muscle activity while there was no obvious effect on the timing of the phasic component of the muscle. Tonic muscle activity was increased after 90 minutes of exposure and continued to increase.

Controlled muscle activity at the buttocks and abdomen reduced the extent of the characteristic nonlinearity (Matsumoto and Griffin, 2002b). Tensed buttocks and abdomen muscle may lead to different tonic components of the skeletal muscle activity.

3.3 Dynamics of buttocks tissue

Contact of the thighs and the buttocks with a seat surface affects the nonlinearity in the resonance frequency change (Sandover, 1978; Kitazaki, 1994). A posture that produced greater pressure on the tissue beneath the ischial tuberosities and reduced the contact area between the thighs and a seat tended to reduce the nonlinear softening effect (Nawayseh and Griffin, 2003).

3.4 Geometric nonlinearity

Potential sources of geometric nonlinearity include interaction between axial and transverse forces and translational and rotational movement of an element (Izzuddin, 1991). Mansfield (1998) suggested that the nonlinear response of the human body was due to the geometry of the body. He represented the geometric nonlinearity by a single degree-of-freedom inverted pendulum. The representation was based on the apparent mass resonance frequency data with different vibration magnitudes. The vertical axial movement was transmitted into a pitching motion of the pendulum.

The two-dimensional response of the body in the vertical and fore-and-aft directions is a form of geometric nonlinearity. Responses in the vertical and fore-and-aft directions during vertical excitation (Nawayseh and Griffin, 2003; Matsumoto and Griffin, 2002b) indicate that internal forces in the vertical direction can be transmitted to the fore-and-aft direction giving rise to a nonlinear response in both the vertical and the fore-and-aft direction.

4. General discussion

Four variables have been identified. Posture may make a minor contribution to the nonlinearity (Mansfield and Griffin 2002). Muscle tone may make the primary contribution to the nonlinearity as many of the internal forces and movements are transmitted by, and affected by, the responses of the muscle (Robertson and Griffin 1989; Matsumoto and Griffin 2002b). The dynamics of the buttocks tissue (e.g. the nonlinear movement in the vertical axis and the nonlinear deformation of the buttocks tissue in the fore-and-aft direction) has an apparent effect on the nonlinearity (Nawayseh and Griffin 2003). Geometric nonlinearity can be another principal explanation for the nonlinear behaviour of the body (Mansfield 1998) – the human body anatomy results in many interactions between different elements in the body.

Some of the above four variables influencing the nonlinearity of the body are interrelated to each other. Postural changes may cause changes in muscle tone. Changes in posture may result in, or be caused by, changes in the geometry of the body (e.g., the eccentricity of the centre of mass, the spinal curvature). The complex nature of the human body challenges the isolation of the variables affecting the nonlinear properties of the body. The observed overall nonlinearity in the apparent mass resonance frequency may arise from a combination of the effects of all four variables.

External causes (e.g., the nature of the excitation and the frequency resolution possible in the measurements) may also influence the observed nonlinearity. Sinusoidal and random vibration were found to result in different muscle activity (Robertson and Griffin, 1989) and different nonlinearity in apparent mass resonance frequency (Toward, 2002). Sinusoidal excitation has advantages in eliminating the effect of the spectral content of the random vibration on the nonlinearity (Toward, 2002). However, measurements with sinusoidal excitation are much more time-consuming than measurements with random excitation and a precise resonance frequency cannot be found without a high resolution in the frequency of the sinusoidal excitation. Similarly, a greater number of steps in the range of vibration magnitudes may assist understanding by producing a more precise measure of the variations in the resonance frequency with vibration magnitude.

The human body system can be represented as a highly damped dynamic system with various coupled modes giving one dominant resonance in the frequency response functions. One or more of these modes has a significant nonlinear characteristic. An improved understanding of the nonlinearity may contribute to an improved understanding of the primary resonance of the human body.

5. Conclusions

The six most relevant studies of nonlinear biodynamic response to whole-body vertical vibration are reviewed. Four variables influencing the characteristic nonlinearity have been identified: posture, muscle tone, dynamics of the buttocks tissue, and geometry of the body. Muscle tone and geometric nonlinearity may make fundamental contributions to the nonlinearity. Pressure on the buttocks tissue has been observed to influence the nonlinearity and posture may also make a minor contribution.

Due to the limited number of studies of human body nonlinearity, the wide variety of possible test conditions, and the diverse objectives of experimental studies, it is not yet possible to quantify the effects of the identified variables. Further investigations to quantify the influences of these variables are needed.

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