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Effect of voluntary periodic muscular activity on nonlinearity in the apparent mass of the seated human body during vertical random whole-body vibration

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Abstract

The principal resonance frequency in the driving-point impedance of the human body decreases with increasing vibration magnitude—a nonlinear response. An understanding of the nonlinearities may advance understanding of the mechanisms controlling body movement and improve anthropodynamic modelling of responses to vibration at various magnitudes. This study investigated the effects of vibration magnitude and voluntary periodic muscle activity on the apparent mass resonance frequency using vertical random vibration in the frequency range 0.5–20 Hz. Each of 14 subjects was exposed to 14 combinations of two vibration magnitudes (0.25 and 2.0 m s^{-2} root-mean square (rms)) in seven sitting conditions: two without voluntary periodic movement (A: upright; B: upper-body tensed), and five with voluntary periodic movement (C: back-abdomen bending; D: folding-stretching arms from back to front; E: stretching arms from rest to front; F: folding arms from elbow; G: deep breathing). Three conditions with voluntary periodic movement significantly reduced the difference in resonance frequency at the two vibration magnitudes compared with the difference in a static sitting condition. Without voluntary periodic movement (condition A: upright), the median apparent mass resonance frequency was 5.47 Hz at the low vibration magnitude and 4.39 Hz at the high vibration magnitude. With voluntary periodic movement (C: back-abdomen bending), the resonance frequency was 4.69 Hz at the low vibration magnitude and 4.59 Hz at the high vibration magnitude. It is concluded that back muscles, or other muscles or tissues in the upper body, influence biodynamic responses of the human body to vibration and that voluntary muscular activity or involuntary movement of these parts can alter their equivalent stiffness.

1. Introduction

The principal resonance frequency in the driving-point impedance of the human body decreases with increasing vibration magnitude—a nonlinear softening effect during whole-body vibration. This nonlinearity is seen in the vertical and the fore-and-aft responses of the seated human body exposed to vertical whole-body vibration (e.g. Refs. [1–6]), in the fore-and-aft and vertical response to fore-and-aft excitation of the seated body (e.g. Refs. [7–10]), and in the response of the standing body (e.g. Ref. [10]). The absolute difference between resonance frequencies at two vibration magnitudes appears to be greater between two low vibration

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magnitudes than between two high vibration magnitudes (e.g. Refs. [2,4]). The mechanisms causing the nonlinearity are not understood, and this restricts the modelling of biodynamic responses and the prediction of responses to whole-body vibration, including injury, at different magnitudes of vibration.

In attempts to identify factors influencing the nonlinearity, the effects of different seating conditions have been explored, but the nonlinearity has been found in all postures previously investigated. Mansfield and Griffin [3] exposed 12 subjects to three vibration magnitudes with nine sitting postures and found that the change in resonance frequency (over three vibration magnitudes) was similar in all postures. With postures involving varying degrees of contact between the thighs and a rigid seat, Nawayseh and Griffin [6] found reductions in nonlinearity when decreasing the thigh contact area with a rigid seat by raising the foot height (from feet-hanging, to feet supported with maximum thigh contact, feet supported with average thigh contact, and feet supported with minimum thigh contact), but the nonlinearity was clear in all conditions. With both sinusoidal and random vibration, Masumoto and Griffin [5] observed reduced nonlinearity when subjects were asked to tense muscles in the buttocks and the abdomen, although the nonlinearity was not eliminated.

Huang [11] summarised six studies of the nonlinear response of the human body and identified three variables that had been considered responsible for the nonlinearity: the geometry of the body, the dynamic properties of the buttocks tissue, and muscle activity. If the nonlinearity is caused by the geometric characteristics of the human body, it should be possible to model the nonlinear behaviour with a passive dynamic system with fixed parameters, but such a model has not been found. The dynamic properties of the buttocks tissue have been associated with the vertical mode of the body at the primary resonance in some mathematical models [12,13], but variation in pressure at the buttocks has little affect on the nonlinearity [6], consistent with pressure at the ischial tuberosities having little effect on the resonance frequency [3]. Reduced stiffness of muscles with increased vibration magnitude might be the cause of the reduced resonance frequency. During static sitting, many muscles can be involved in supporting the body with 'tonic' activity. When exposed to oscillatory motion, the muscle activity varies with a 'phasic' response, so it is assumed that during vibration excitation, muscle activity has both 'tonic' and 'phasic' components. Studies have found that the phasic muscular activity varies with vibration magnitude [14–16]. Assuming the erector spinae muscles influence the biodynamic responses of the body, or that they are typical of muscles that are involved, these studies imply that a nonlinearity, possibly the nonlinear softening effect, is associated with the phasic muscle response.

The published studies often assume that the nonlinearity is caused by reduced effective stiffness at higher vibration magnitudes. Alternatively, the nonlinearity could arise from increased effective stiffness at low vibration magnitudes. The studies of phasic muscle activity suggest that, relative to a static sitting condition, the muscle forces are increased during parts of a cycle of vibration and decreased during other parts. With increases in the vibration magnitude, the peaks and troughs tend to change nonlinearly and there may be variations in the timing of the forces. Without a dynamic model, it is not possible to predict whether the force variations corresponding to the observed variations in EMG response with vibration magnitude will increase the effective stiffness or reduce the effective stiffness. However, the known variation in muscle activity with vibration magnitude is such that it can be assumed to have a nonlinear effect. The reduction in resonance frequency of the body with increased vibration magnitude suggests that either the phasic muscle activity increases stiffness at low magnitudes or the muscle activity decreases stiffness at high magnitudes, or both.

If the phasic activity of the muscles increases the effective stiffness of the body at low vibration magnitudes, the resonance frequency at low magnitudes will be reduced if the phasic activity is reduced. If the phasic activity of the muscles reduces the effective stiffness of the body at high vibration magnitudes, the resonance frequency at high magnitudes will be increased if the phasic activity is reduced.

The phasic activity of muscles arising from whole-body vibration, and therefore the nonlinearity, will be altered if the relevant muscles contract in response to other stimuli. Studies which involve voluntary steady-state contraction have found little change in the nonlinearity, possibly because such contractions involve other muscles or because the contractions are voluntary [3,5]. There have been no reported studies of the effects of periodic muscular contractions on the nonlinearity.

This experiment was designed to investigate whether voluntary periodic muscular activity affects the nonlinearity in the apparent mass resonance frequency. It was hypothesised that periodic muscle activity would reduce body stiffness at low vibration magnitudes, so reducing the resonance frequency at low magnitudes and reducing the difference in the resonance frequency at low and high vibration magnitudes.

2. Method

2.1. Apparatus

The experiment was conducted using a rigid flat horizontal seat (600×400 mm) without backrest mounted on the platform of a 1 m stroke electro-hydraulic vertical vibrator. A footrest 310 mm below the seat surface moved with the seat. A loose lap strap was fastened around the subjects.

A force platform (Kistler 9281 B21) was secured to the supporting surface of the seat and the four vertical force signals from the corners of the platform were summed and conditioned using a Kistler 5011 charge amplifier. The acceleration of the seat surface was measured using a Setra 141A accelerometer attached directly to the rigid seat surface. The force and acceleration signals were acquired at 200 samples per second via 67 Hz anti-aliasing filters.

Subjects were exposed to random vertical vibration with an approximately flat constant-bandwidth acceleration power spectrum over the frequency range 0.5–20 Hz. The duration of each exposure was 90 s. There were 14 combinations of two vibration magnitudes (0.25 and 2.0 $m\,s^{-2}$ root-mean square (rms)) and seven sitting conditions.

2.2. Experimental design

Fourteen fit and healthy male subjects with mean (standard deviation, SD) stature 1.75 m (0.07 m) and total body mass 70.3 kg (8.7 kg) participated in the experiment.

Subjects adopted an upright sitting posture as a reference condition (A: upright, Fig. 1), broadly similar to the minimum thigh contact condition used by Nawayseh and Griffin [9]. The minimum thigh contact condition was adopted so as to minimise inter-subject variability—less variation in the apparent mass resonance frequency has been found in this posture [9]. Sitting conditions B, C, D, E, F and G (Fig. 1) were based on condition A. In condition B (upper-body tensed), subjects were asked to tense their upper-body while holding their breath (to assist maintenance of tension) and exhaling-inhaling every 15 s or longer. There were five conditions with periodic movements of the body: C (back-abdomen bending), D (back-to-front), E (rest-to-front), F (arm folding), and G (deep breathing). In these five conditions, subjects were instructed to move smoothly and continuously with 3 s per complete cycle. Back muscle activity produced by the cyclical movements was expected to decrease from condition C (back-abdomen bending) to condition G (deep breathing). Condition C (back-abdomen bending) required alternate flexing of the trunk with abdominal contraction and extension of the trunk with back muscle contraction. Conditions D (back-to-front), E (rest-to-front) and F (arm folding) required subjects to make normal arm movements without otherwise unnecessary muscular activity in the remainder of the body. Condition G (deep breathing) required subjects to use their maximum lung capacity. Subjects practiced the conditions for 20 min prior to commencing the experiment. Subjects counted the number of cycles completed during each session so as to encourage a constant 3-s per cycle rate of movement.

The seven sitting conditions and the two vibration magnitudes were presented in a single session lasting approximately 45 min. The seven sitting conditions were presented in a balanced random order. The 14 subjects were divided into two equal groups, so that for each sitting condition, one group was tested in the order low-to-high vibration magnitude and the other group was tested in the order high-to-low vibration magnitude.

The experiment was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

2.3. Analysis

Mass cancellation was carried out in the time domain so as to subtract the force caused by the mass of platform above the force transducers:

$$F_s(t) = F_t(t) - (M_{\mathrm{top}} \times a_s(t)), \tag{1}$$

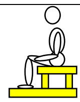
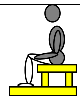
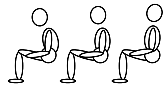
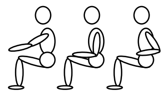
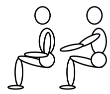
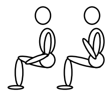
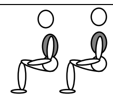
Condition	Description	Illustration
A. Upright	Upright with reduced thigh contact	
B. Upper-body tensed	Upright with reduced thigh contact – upper-body tensed	
C. Back-abdomen bending	Upright with reduced thigh contact – back-abdomen bending	
D. Back-to-front	Upright with reduced thigh contact – folding-stretching arms from back to front	
E. Rest-to-front	Upright with reduced thigh contact – stretching arms from rest to front	
F. Arm folding	Upright with reduced thigh contact – folding arms from elbow	
G. Deep breathing	Upright with reduced thigh contact – deep breathing	

Fig. 1. Seven sitting conditions—two stationary sitting conditions (A and B) and five with voluntary periodic movement (C, D, E, F and G).

where $F_s(t)$ is the vertical force generated by the subject, $F_t(t)$ is the total measured vertical force, M_{top} is the mass of the platform above the force transducers (determined dynamically over the range 0.5–20 Hz without a subject), and $a_s(t)$, is the measured vertical acceleration on the seat surface. The time histories of the vertical force generated by the subject, $F_s(t)$, and the vertical acceleration of the surface supporting the subject, $a_s(t)$, were used to calculate the apparent mass of the subject, $M(f)$, in the frequency domain using the cross-spectral density method:

$$M(f) = S_{af}(f)/S_{aa}(f), \tag{2}$$

where $M(f)$ is the apparent mass, $S_{af}(f)$ is the cross spectral density between the vertical seat acceleration and the vertical force at the seat surface (after mass cancellation), and $S_{aa}(f)$ is the power-spectral density of the vertical seat acceleration. The cross-spectral density method assumes that the output (vertical force) is linearly related to the input (vertical acceleration) excluding nonlinear effects including noise.

The moduli and phases of the apparent masses of the 14 subjects were calculated for each condition. The normalised apparent masses of the subjects were calculated by dividing their individual apparent masses by their apparent mass at 0.5 Hz. It was assumed that the body acts rigidly at 0.5 Hz such that the apparent mass at this frequency can be considered as the sitting weight of the subjects. Median normalised apparent masses and phases were calculated.

The resonance frequencies in the individual apparent masses and the median normalised apparent masses were obtained by curve-fitting the measured apparent masses and phases (over the frequency range 2–20 Hz) to a two degree-of-freedom (2dof) mathematical model [17] (Fig. 2). The 'resonance frequency' was defined as the frequency where the modulus of the apparent mass had a maximum value in the fitted curve.

The curve-fitting method used a MATLAB (version 7.0.1.24704, R14) optimisation command (fmincon()) to minimise a target error. When fitting to an individual apparent mass, the target error was calculated by

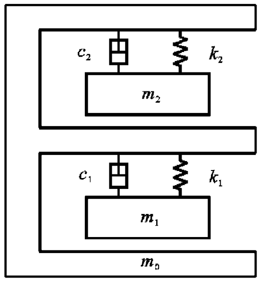


Fig. 2. Two degree-of-freedom model [17].

using both the apparent mass modulus (kg) and phase (rad). When fitting to the median normalised apparent mass, the median normalised apparent mass was multiplied by the median static weight of the subjects (estimated from the apparent mass at 0.5 Hz) and the target error was calculated using the modulus (kg) and phase (rad) of the median normalised apparent mass. For both the individual and the median normalised apparent masses, the target errors were calculated by summing the square of the errors in the modulus and the phases at each frequency. Before the summation, the modulus error was scaled to have the same error as the phase error by multiplying the modulus of the apparent mass (at each frequency from 2 to 20 Hz) by the normalisation factor P:

$$P = |PH_s|_{\max}/|AM_s|_{\max}, \tag{3}$$

where $|AM_s|_{\max}$ is the maximum value of the modulus of the measured apparent mass (kg) at any frequency and $|PH_s|_{\max}$ is the maximum absolute value of the measured phase (rad) at any frequency. The normalisation was based on the values at two frequencies: one giving the maximum modulus and the other giving the maximum absolute phase.

The errors in the moduli of the individual apparent masses and the median normalised apparent mass were summed over the frequency range 2–20 Hz, and divided by the number of frequency points, to produce normalised apparent mass modulus errors. The phase errors were similarly processed except that they were not normalised but amplified by a phase weighting factor, Q, (given a value of 10.0) to produce the best fit. The target errors for both the individual apparent masses and the median normalised apparent mass were of the form:

$$E = (1/N_f) \times \sum_{N_f} (P \times (AM_m(f) - AM_s(f))^2) + (1/N_f) \times \sum_{N_f} (Q \times (PH_m(f) - PH_s(f))^2), \tag{4}$$

where E is the target error between the model and measured apparent masses, N_f is the number of frequency steps in the measured apparent mass, $AM_m(f)$ and $PH_m(f)$, are the apparent mass modulus and phase in the model at each frequency, $AM_s(f)$ and $PH_s(f)$ are the measured apparent mass modulus and phases at each frequency, P is the normalisation factor for the apparent mass modulus error as defined in Eq. (3), Q is the phase weighting factor (= 10.0), and f is the frequency range of the curve-fitting (2–20 Hz).

The MATLAB optimisation produced the seven parameters of the two degree-of-freedom mathematical model (i.e. m_0, m_1, k_1, c_1, m_2, k_2 and c_2).

The frequency range was restricted to frequencies greater than 2 Hz because the periodic movements of the body (in conditions C–G) resulted in low coherency between resultant force and input acceleration at frequencies less than 2 Hz.

Statistical analysis was performed using non-parametric tests: Friedman two-way analysis of variance for k-sample cases and Wilcoxon matched-pairs signed ranks tests for two-sample cases.

3. Results

An example of the moduli and phases of the apparent mass of an individual subject with two magnitudes of vibration in the seven sitting conditions is shown in Fig. 3. The median normalised apparent masses of the group of 14 subjects are shown in Figs. 4 and 5, and the resonance frequencies are shown in Table 1.

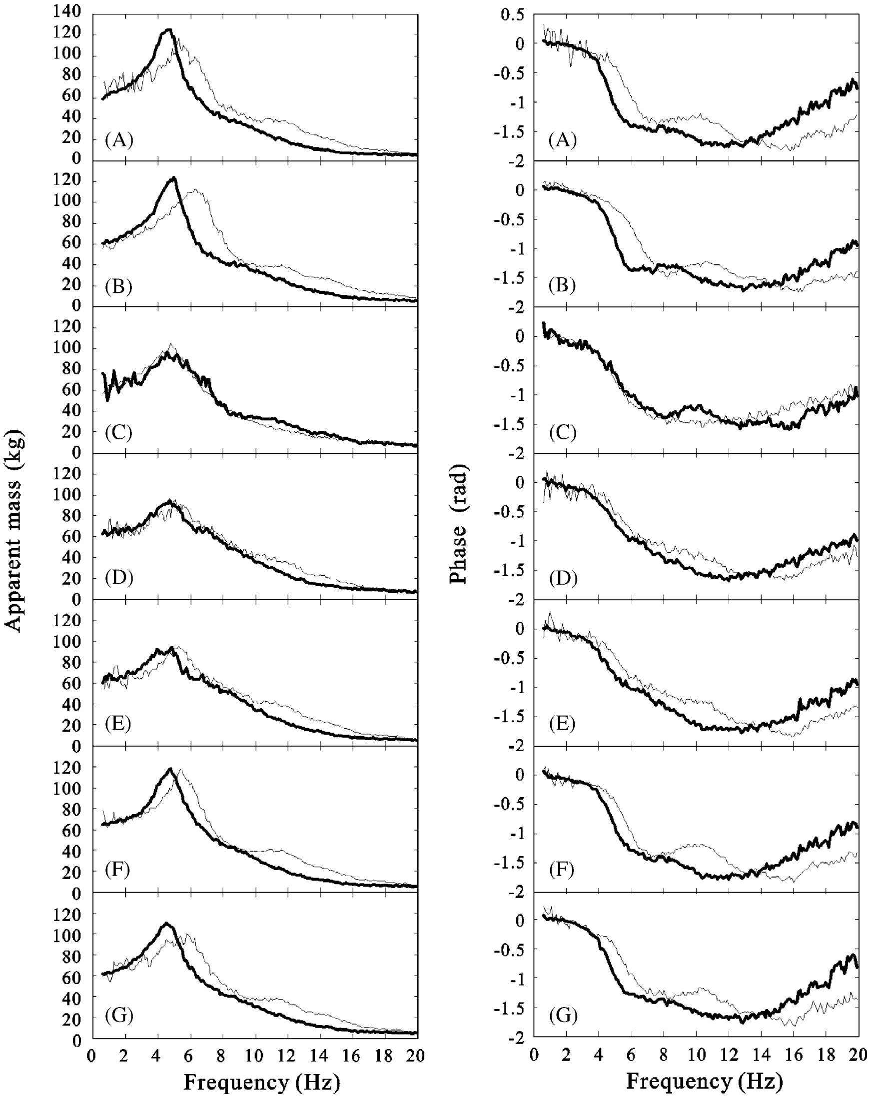


Fig. 3. Apparent masses and phases for a single subject in seven sitting conditions: (A) upright; (B) upper-body tensed; (C) back-abdomen bending; (D) back-to-front; (E) rest-to-front; (F) arm folding; (G) deep breathing at two vibration magnitudes (—— $0.25\,m\,s^{-2}$ rms; ▬▬ $2.0\,m\,s^{-2}$ rms).

The coherency varied between conditions but was generally in excess of 0.7 in the frequency range 3–20 Hz. Condition D (back-to-front) showed the lowest coherency.

As in previous studies [17], the 2dof model provided a good fit to the moduli and phases of all 14 subjects at both vibration magnitudes and in all seven sitting conditions. An example of the fitting for one subject in sitting conditions A (upright) and C (back-abdomen bending) is shown in Fig. 6. The model also provided a good fit to the scaled normalised apparent mass (Fig. 7).

3.1. Individual apparent mass resonance frequencies

The resonance frequencies at the high vibration magnitude were significantly less than the resonance frequencies at the low vibration magnitude in the two static sitting conditions (A: upright; B: upper-body tensed) and in two of the periodic moving conditions (F: arm folding; G: deep breathing) ($p<0.05$, Wilcoxon matched-pairs signed ranks test). The resonance frequencies at the two vibration magnitudes were not

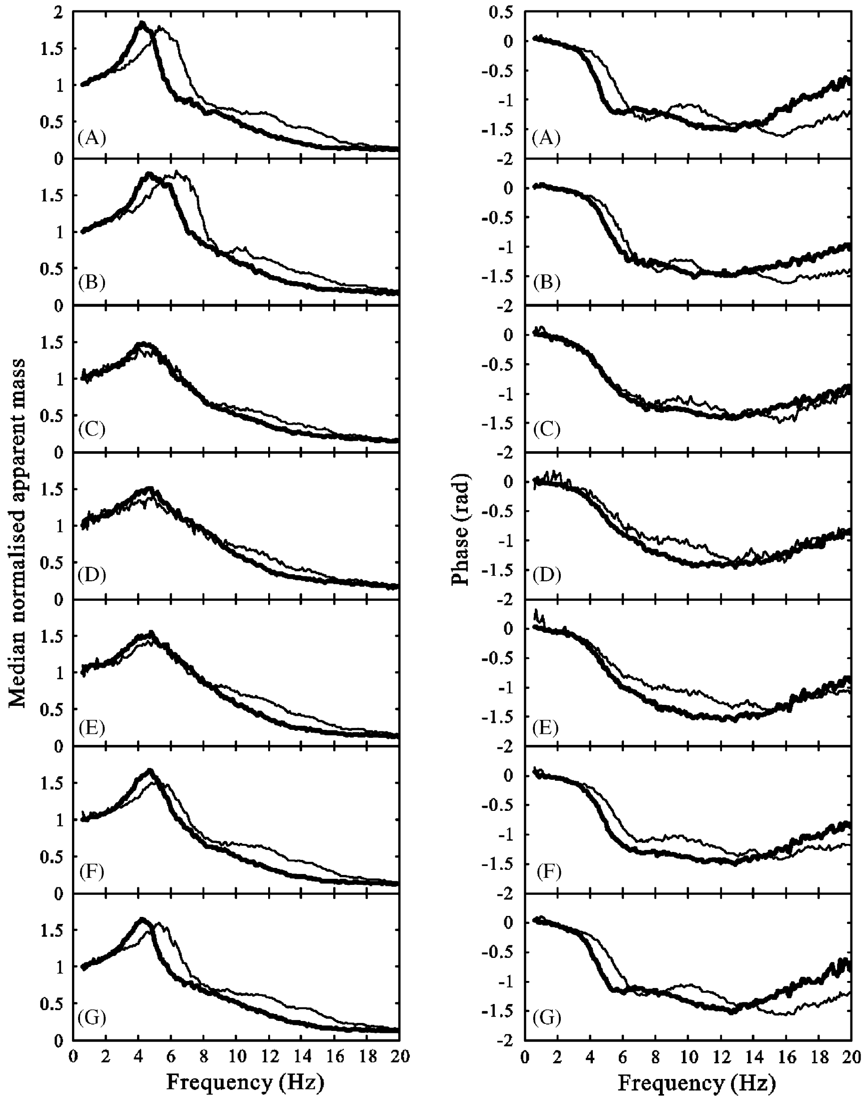


Fig. 4. Median normalised apparent masses and phases of 14 subjects in seven sitting conditions: (A) upright; (B) upper-body tensed; (C) back-abdomen bending; (D) back-to-front; (E) rest-to-front; (F) arm folding; (G) deep breathing at two vibration magnitudes (—— $0.25\,m\,s^{-2}$ rms; ▬▬ $2.0\,m\,s^{-2}$ rms).

significantly different for three of the periodic movement conditions (C: back-abdomen bending; D: back-to-front; E: rest-to-front) ($p > 0.2$, Wilcoxon).

Sitting condition B (upper-body tensed) gave a significantly greater resonance frequency than sitting condition A (upright) at both vibration magnitudes ($p < 0.01$, Tables 2 and 3, Wilcoxon), indicating an effect of static posture on the biodynamic response of the body.

Over the seven sitting conditions, there were significant differences in the resonance frequencies at $0.25\,m\,s^{-2}$ rms ($p < 0.01$, Friedman) and at $2.0\,m\,s^{-2}$ rms ($p < 0.01$, Friedman). When sitting condition B (upper-body tensed) was removed, an overall significant difference remained at both $0.25\,m\,s^{-2}$ rms and at $2.0\,m\,s^{-2}$ rms ($p < 0.01$). At $0.25\,m\,s^{-2}$ rms, the resonance frequencies did not differ between conditions A and F, C and D, C and E, D and E, and F and G ($p > 0.05$, Table 2, Wilcoxon). At $2.0\,m\,s^{-2}$ rms, the resonance frequencies did not differ between conditions A and G, C and E, D and E, D and F, and E and F ($p > 0.05$, Table 3).

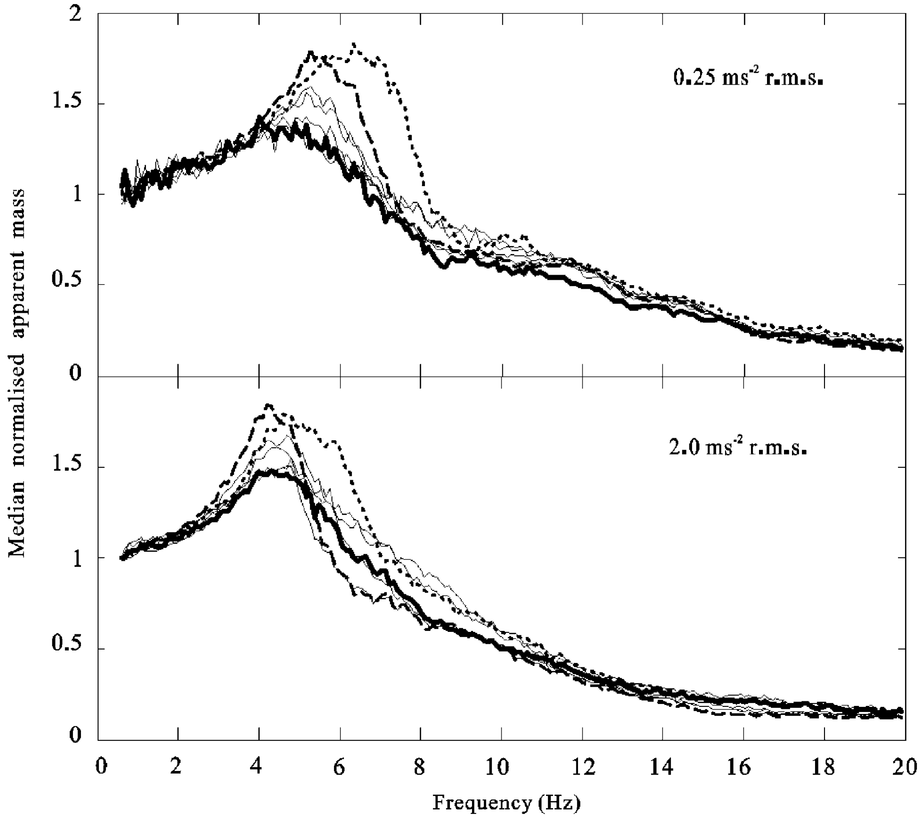


Fig. 5. Median normalised apparent masses and phases of 14 subjects in seven sitting conditions ((A) upright -----; (B) upper-body tensed ······; (C) back-abdomen bending ▬▬▬; (D) back-to-front ———; (E) rest-to-front ———; (F) arm folding ———; (G) deep breathing ———) at two vibration magnitudes (0.25 m s^{-2} rms (top); 2.0 m s^{-2} rms (bottom)).

Table 1
Median resonance frequencies of the apparent mass for seven sitting conditions at two vibration magnitudes

Condition	Vibration magnitude (m s^{-2} rms)		Absolute difference (Hz)	Resonance difference ratio
	0.25 $f_{0.25}$ (Hz)	2.0 $f_{2.0}$ (Hz)	$\Delta f = f_{0.25} - f_{2.0}$ (Hz)	$\Delta f / f_{2.0}$ (%)
(A) Upright	5.47	4.39	1.08	24.60
(B) Upper-body tensed	5.96	5.08	0.88	17.32
(C) Back-abdomen bending	4.69	4.59	0.10	2.18
(D) Back-to-front	5.08	4.59	0.49	10.68
(E) Rest-to-front	4.98	4.69	0.29	6.18
(F) Arm folding	5.27	4.69	0.58	12.37
(G) Deep breathing	5.27	4.30	0.97	22.56

$f_{0.25}$ and $f_{2.0}$: resonance frequencies at two magnitudes (0.25 and 2.0 m s^{-2} rms). Δf: ($f_{0.25} - f_{2.0}$), absolute difference of two resonance frequencies.

There was a significant overall effect of sitting condition on the absolute difference in resonance frequency at the two vibration magnitudes ($p < 0.01$, Friedman). In four conditions with voluntary periodic movement (C: back-abdomen bending; D: back-to-front; E back-to-front; F: arm folding) the difference in resonance frequency was significantly less than in condition A (upright) ($p < 0.05$, Wilcoxon; Table 4). There was no significant difference in the change in resonance frequency between low and high magnitudes in the two static

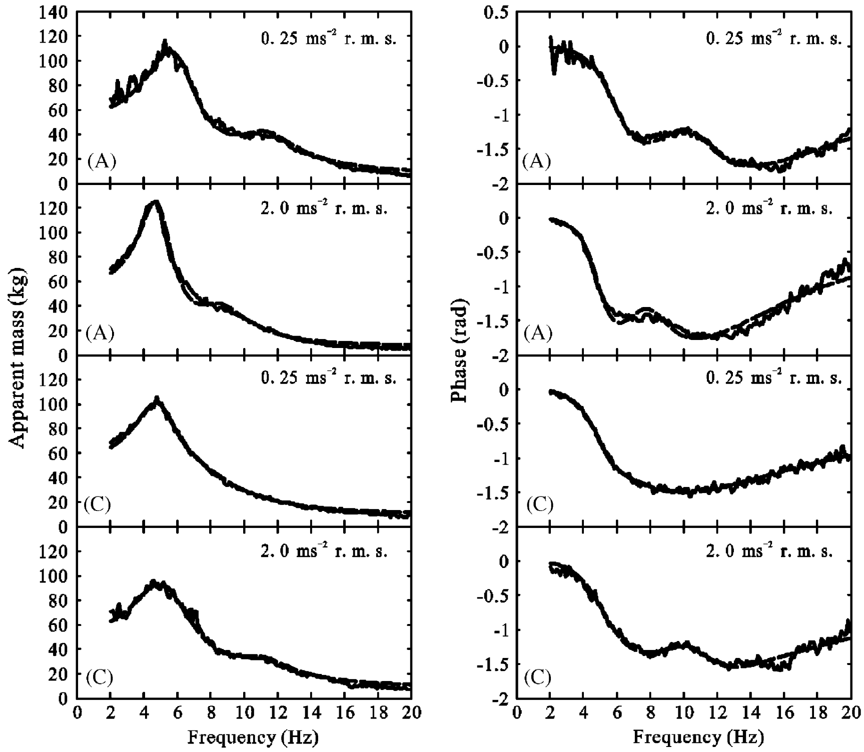


Fig. 6. Curve-fitting (—— measurement; – – – fitting curve) the apparent mass and phase to obtain the resonance frequency of the apparent mass for a single subject in condition A (upright) and C (back-abdomen bending) at the low vibration magnitude ($0.25\,\mathrm{m\,s^{-2}}$ rms) and the high vibration magnitude ($2.0\,\mathrm{m\,s^{-2}}$ rms).

sitting conditions (A: upright; B: upper-body tensed) ($p>0.5$, Wilcoxon; Table 4), or between condition G (deep breathing) and condition A ($p>0.05$, Wilcoxon). There was no significant difference in the change in resonance frequency between low and high magnitudes between conditions C (back-abdomen bending) and D (back-to-front) ($p>0.2$, Wilcoxon; Table 4), or between conditions C (back-abdomen bending) and E (rest-to-front) ($p>0.8$, Wilcoxon).

3.2. Median normalised apparent mass resonance frequencies

The median normalised apparent masses and phases of the 14 subjects in the seven conditions at the two vibration magnitudes are shown in Fig. 4. Table 1 and Fig. 8 show that the difference in the resonance frequencies at the two vibration magnitudes decreased markedly in the periodic moving conditions, especially C (back-abdomen bending), E (rest-to-front) and D (back-to-front) compared with condition A (upright), G (deep breathing) and B (upper-body tensed). Condition C (back-abdomen bending) produced the least change in median resonance frequency (0.10 Hz, 2.18%) compared with condition A (upright) that produced the greatest change (1.08 Hz, 24.60%).

3.3. Parameters in an equivalent 2dof model

The parameters of the 2dof model fitted to the rescaled median normalised apparent masses are shown in Table 5. The ranges of the parameters of the 2dof model fitted to the individual subject apparent masses are shown in Table 6.

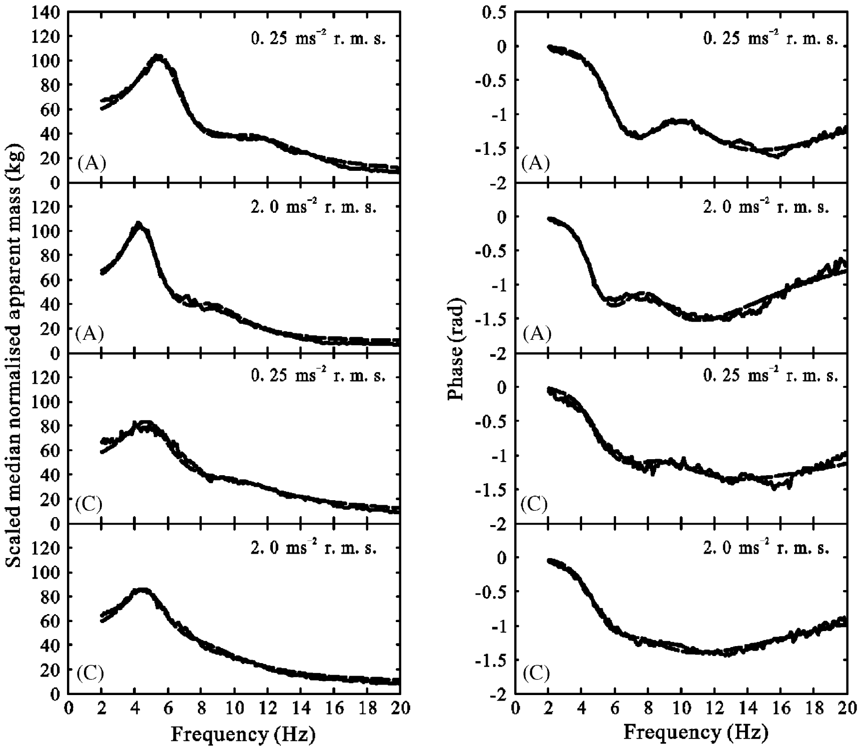


Fig. 7. Curve-fitting (▬▬▬ measurement; ▬ ▬ ▬ fitting curve) the scaled median normalised apparent mass and phase to obtain the resonance frequency of the median normalised apparent mass in conditions A (upright) and C (back-abdomen bending) at the low vibration magnitude ($0.25\,\mathrm{m\,s^{-2}}$ rms) and the high vibration magnitude ($2.0\,\mathrm{m\,s^{-2}}$ rms).

Table 2
Statistical significance of the difference in apparent mass resonance frequencies at the low vibration magnitude ($0.25\,\mathrm{m\,s^{-2}}$ rms) between the seven sitting conditions (p values for Wilcoxon matched-pairs signed ranks test)

	A (upright)	B (upper-body tensed)	C (back-abdomen bending)	D (back-to-front)	E (rest-to-front)	F (arm folding)	G (deep breathing)
A (upright)	—	0.001*	0.000*	0.000*	0.000*	0.060	0.004*
B (upper-body tensed)	—	—	0.000*	0.000*	0.000*	0.000*	0.000*
C (back-abdomen bending)	—	—	—	0.397	0.087	0.000*	0.001*
D (back-to-front)	—	—	—	—	0.088	0.001*	0.000*
E (rest-to-front)	—	—	—	—	—	0.004*	0.002*
F (arm folding)	—	—	—	—	—	—	0.278
G (deep breathing)	—	—	—	—	—	—	—

*$p < 0.05$.

Since the 2dof model provided a good fit to the modulus and phase of all 14 individual subjects at both vibration magnitudes and in all seven sitting conditions it seems appropriate to investigate which parameters in this model changed with vibration magnitude and sitting condition (Fig. 9).

Table 3
Statistical significance of the difference in apparent mass resonance frequencies at the high vibration magnitude (2.0 m s^{-2} rms) between the seven sitting conditions (p values for Wilcoxon matched-pairs signed ranks test)

	A (upright)	B (upper-body tensed)	C (back-abdomen bending)	D (back-to-front)	E (rest-to-front)	F (arm folding)	G (deep breathing)
A (upright)	—	0.000*	0.037*	0.002*	0.002*	0.000*	0.218
B (upper-body tensed)	—	—	0.001*	0.016*	0.009*	0.006*	0.000*
C (back-abdomen bending)	—	—	—	0.027*	0.066	0.005*	0.002*
D (back-to-front)	—	—	—	—	0.201	0.648	0.002*
E (rest-to-front)	—	—	—	—	—	0.408	0.002*
F (arm folding)	—	—	—	—	—	—	0.000*
G (deep breathing)	—	—	—	—	—	—	—

*$p<0.05$.

Table 4
Statistical significance of the size of the absolute difference in apparent mass resonance frequencies at the low and the high vibration magnitudes ($\Delta f = f_{0.25} - f_{2.0}$) between the seven sitting conditions (p values for Wilcoxon matched-pairs signed ranks test)

	A (upright)	B (upper-body tensed)	C (back-abdomen bending)	D (back-to-front)	E (rest-to-front)	F (arm folding)	G (deep breathing)
A (upright)	—	0.484	0.001*	0.001*	0.001*	0.001*	0.059
B (upper-body tensed)	—	—	0.010*	0.002*	0.004*	0.064	0.814
C (back-abdomen bending)	—	—	—	0.208	0.814	0.020*	0.001*
D (back-to-front)	—	—	—	—	0.007*	0.004*	0.002*
E (rest-to-front)	—	—	—	—	—	0.010*	0.002*
F (arm folding)	—	—	—	—	—	—	0.002*
G (deep breathing)	—	—	—	—	—	—	—

*$p<0.05$.

3.3.1. *Frame mass, m_0*

3.3.1.1. Effect of vibration magnitude. The vibration magnitude had little effect on the frame mass (m_0). However, m_0 was significantly greater at the high vibration magnitude than at the low magnitude in conditions A (upright) and G (deep breathing) ($p<0.05$, Wilcoxon). There was no significant change in the frame mass with vibration magnitude in any other condition.

3.3.1.2. Effect of sitting condition. Over the seven sitting conditions, there were significant differences in m_0 at both 0.25 and 2.0 m s^{-2} rms ($p<0.05$, Friedman). At 0.25 m s^{-2} rms, m_0 differed between conditions C and A, E and A, E and B, F and E, and G and E ($p<0.05$, Wilcoxon). At 2.0 m s^{-2} rms, m_0 differed between conditions B and A, C and A, D and A, E and A, F and A, D and C, G and C, E and D, and G and D ($p<0.05$, Wilcoxon).

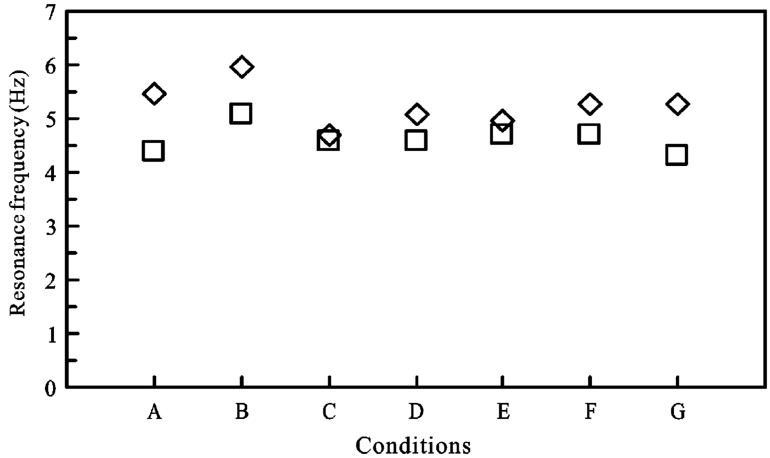


Fig. 8. Resonance frequencies of median normalised apparent masses—effect of two vibration magnitudes (◇, 0.25 m s^{-2} rms and □, 2.0 m s^{-2} rms) and seven sitting conditions ((A) upright; (B) upper-body tensed; (C) back-abdomen bending; (D) back-to-front; (E) rest-to-front; (F) arm folding; (G) deep breathing).

Table 5
Parameters generated by fitting the two degree-of-freedom model in Fig. 2 to the scaled median normalised apparent masses and phases of 14 subjects at two vibration magnitudes with seven sitting conditions

Condition	Vibration magnitude (m s^{-2} rms)	m_0 (kg)	m_1 (kg)	k_1 (N m^{-1})	c_1 (N s m^{-1})	m_2 (kg)	k_2 (N m^{-1})	c_2 (N s m^{-1})	f_r (Hz)
(A) Upright	0.25	9.13	36.00	49440	615	10.45	54444	367	5.47
	2.0	10.45	36.64	32513	522	9.46	29816	236	4.39
(B) Upper-body tensed	0.25	7.14	38.48	61707	718	11.51	56144	501	5.96
	2.0	9.59	37.41	44119	644	11.18	33976	376	5.08
(C) Back-abdomen bending	0.25	8.26	34.58	38039	719	9.89	41598	411	4.69
	2.0	8.78	34.08	34519	655	10.17	28736	352	4.59
(D) Back-to-front	0.25	12.83	29.28	38179	653	11.72	48585	405	5.08
	2.0	10.11	31.99	33388	658	14.24	36868	406	4.59
(E) Rest-to-front	0.25	10.39	31.66	39402	727	12.81	53238	505	4.98
	2.0	9.12	32.83	34757	611	12.88	33569	339	4.69
(F) Arm folding	0.25	9.71	33.08	44068	669	11.06	53900	449	5.27
	2.0	9.32	35.23	36631	567	8.83	27264	266	4.69
(G) Deep breathing	0.25	8.60	34.19	44969	641	10.45	54684	387	5.27
	2.0	10.04	34.79	30676	538	9.52	30391	253	4.30

3.3.2. The first segmental mass, m_1

3.3.2.1. Effect of vibration magnitude. There was only one significant change in the first segmental mass, m_1: in condition F (arm folding), m_1 was significantly greater at the high vibration magnitude than at the low vibration magnitude ($p < 0.05$, Wilcoxon).

Table 6
Inter-subject variability—ranges of parameters generated by fitting the two degree-of-freedom model in Fig. 2 to individual subject apparent masses and phases of 14 subjects at two vibration magnitudes with seven sitting conditions

Condition	Vibration magnitude ($m\,s^{-2}$ rms)		m_0 (kg)	m_1 (kg)	k_1 ($N\,m^{-1}$)	c_1 ($Ns\,m^{-1}$)	m_2 (kg)	k_2 ($N\,m^{-1}$)	c_2 ($Ns\,m^{-1}$)	f_r (Hz)
(A) Upright	0.25	Max	5.65	26.46	31453	476	6.35	31951	154	4.30
		Min	12.53	43.68	62262	773	12.90	69587	536	6.35
	2.0	Max	6.70	23.48	20742	276	4.92	19611	92	3.61
		Min	12.25	41.29	42910	706	11.06	34189	423	5.18
(B) Upper-body tensed	0.25	Max	3.90	21.03	30145	282	3.70	28237	225	4.49
		Min	12.62	44.14	73527	764	16.71	86562	663	7.42
	2.0	Max	2.96	26.58	28378	453	2.19	11632	42	4.00
		Min	10.92	41.47	74593	1052	31.50	57066	678	7.03
(C) Back-abdomen bending	0.25	Max	3.82	23.94	20455	565	6.48	19791	239	3.32
		Min	12.01	37.70	44716	927	14.14	58575	737	5.37
	2.0	Max	4.51	23.90	23662	494	2.83	12648	53	3.81
		Min	11.69	44.22	59810	1441	13.32	33137	936	5.08
(D) Back-to-front	0.25	Max	2.65	21.36	22957	567	2.50	11943	38	3.81
		Min	13.23	35.50	44782	791	16.30	74923	689	5.47
	2.0	Max	4.60	21.79	27368	448	5.79	19871	128	4.30
		Min	11.87	33.22	35005	857	19.16	42043	586	5.57
(E) Rest-to-front	0.25	Max	3.60	22.48	25209	588	4.34	22416	89	3.91
		Min	11.72	34.34	45654	799	15.78	70354	711	5.57
	2.0	Max	3.57	23.16	26334	431	5.28	18158	100	4.20
		Min	11.02	36.99	56578	1067	15.86	42247	604	5.47
(F) Arm folding	0.25	Max	4.19	24.46	32383	524	7.00	28035	222	4.39
		Min	13.57	38.25	58108	839	14.82	72467	592	6.25
	2.0	Max	6.84	25.78	26672	422	4.99	14373	111	4.00
		Min	11.64	40.12	62726	995	12.49	40426	544	5.96
(G) Deep breathing	0.25	Max	5.49	26.32	29639	538	7.41	34879	195	4.20
		Min	11.58	41.53	51480	739	15.31	76284	593	5.86
	2.0	Max	7.00	25.95	22213	369	4.99	16558	101	3.71
		Min	12.79	40.99	37674	617	11.56	35470	356	4.69

3.3.2.2. Effect of sitting condition. Over the seven sitting conditions, there were significant differences in m_1 at 0.25 $m\,s^{-2}$ rms and at 2.0 $m\,s^{-2}$ rms ($p<0.05$, Friedman). At 0.25 $m\,s^{-2}$ rms, m_1 differed between conditions C and A, D and A, E and A, F and A, G and A, D and B, E and B, D and C, E and C, G and C, F and D, G and D, F and E, and G and E ($p<0.05$, Wilcoxon). At 2.0 $m\,s^{-2}$ rms, m_1 differed between conditions D and A, E and A, G and A, D and B, E and B, G and B, D and C, E and C, E and D, F and D, G and D, F and E, and G and E ($p<0.05$, Wilcoxon).

3.3.3. The first segmental stiffness, k_1

3.3.3.1. Effect of vibration magnitude. At the high vibration magnitude, the first segmental stiffness, k_1 was significantly less than at the low vibration magnitude in conditions A (upright), B (upper-body tensed), F (arm folding), and G (deep breathing) ($p<0.05$, Wilcoxon).

3.3.3.2. Effect of sitting condition. Over the seven sitting conditions, there were significant differences in k_1 at 0.25 $m\,s^{-2}$ rms ($p<0.05$, Friedman) and at 2.0 $m\,s^{-2}$ rms ($p<0.05$, Friedman). At 0.25 $m\,s^{-2}$ rms, k_1 differed

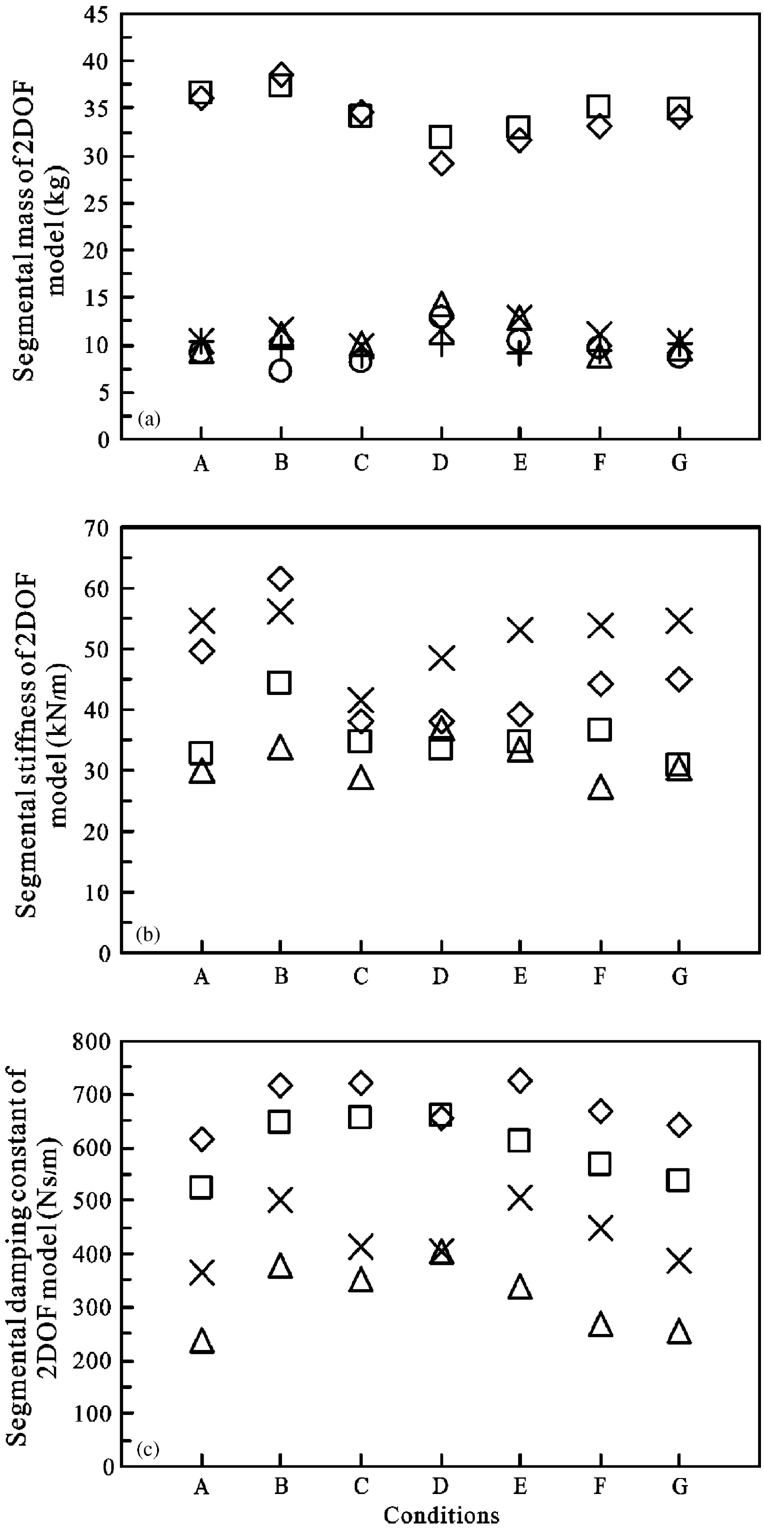


Fig. 9. Parameters of the 2dof (segmental mass: m_0, m_1 and m_2; segmental stiffness: k_1 and k_2; segmental damping constant: c_1 and c_2) —effect of two vibration magnitudes (0.25 and $2.0\,\mathrm{m\,s^{-2}}$ rms) and seven sitting conditions ((A) upright; (B) upper-body tensed; (C) back-abdomen bending; (D) back-to-front; (E) rest-to-front; (F) arm folding; (G) deep breathing). (a) segmental mass: ○, m_0 at $0.25\,\mathrm{m\,s^{-2}}$ rms; +, m_0 at $2.0\,\mathrm{m\,s^{-2}}$ rms; ◇, m_1 at $0.25\,\mathrm{m\,s^{-2}}$ rms; □, m_1 at $2.0\,\mathrm{m\,s^{-2}}$ rms; ×, m_2 at $0.25\,\mathrm{m\,s^{-2}}$ rms; △, m_2 at $2.0\,\mathrm{m\,s^{-2}}$ rms (b) segmental stiffness: ◇, k_1 at $0.25\,\mathrm{m\,s^{-2}}$ rms; □, k_1 at $2.0\,\mathrm{m\,s^{-2}}$ rms; ×, k_2 at $0.25\,\mathrm{m\,s^{-2}}$ rms; △, k_2 at $2.0\,\mathrm{m\,s^{-2}}$ rms (c) segmental damping constant: ◇, c_1 at $0.25\,\mathrm{m\,s^{-2}}$ rms; □, c_1 at $2.0\,\mathrm{m\,s^{-2}}$ rms; ×, c_2 at $0.25\,\mathrm{m\,s^{-2}}$ rms; △, c_2 at $2.0\,\mathrm{m\,s^{-2}}$ rms.

between all conditions ($p<0.05$, Wilcoxon), except between conditions D and C, E and C, E and D, G and F ($p>0.1$, Wilcoxon). At $2.0\,\mathrm{m\,s^{-2}}$ rms, k_1 did not differ between condition C and A, D and A, E and A, G and A, D and C, E and C, E and D, or G and D ($p>0.05$, Wilcoxon). This shows that voluntary movement had less effect on the first segmental stiffness, k_1, at the high vibration magnitude than at the low vibration magnitude.

3.3.4. The first segmental damping constant, c_1

3.3.4.1. Effect of vibration magnitude. At the high vibration magnitude, the first segmental damping constant, c_1, was significantly less than at the low vibration magnitude in condition A (upright), D (back-to-front), E (rest-to-front), F (arm folding), and G (deep breathing) ($p<0.05$, Wilcoxon).

3.3.4.2. Effect of sitting condition. Over the seven sitting conditions, there were significant changes in c_1 at both 0.25 and $2.0\,\mathrm{m\,s^{-2}}$ rms ($p<0.05$, Friedman). At $0.25\,\mathrm{m\,s^{-2}}$ rms, c_1 differed between conditions C and A, D and A, E and A, D and B, E and B, G and C, F and D, G and D, and G and E ($p<0.05$, Wilcoxon). At $2.0\,\mathrm{m\,s^{-2}}$ rms, c_1 differed between conditions B and A, C and A, D and A, E and A, F and A, F and B, G and B, F and C, G and C, E and D, F and D, G and D, and G and E ($p<0.05$, Wilcoxon).

3.3.5. The second segmental mass, m_2

3.3.5.1. Effect of vibration magnitude. At the high vibration magnitude, the second segmental mass, m_2, was significantly less than that at the low vibration magnitude in condition F (arm folding) and G (deep breathing) ($p<0.05$, Wilcoxon).

3.3.5.2. Effect of sitting condition. Over the seven sitting conditions, there were significant changes in m_2 at $0.25\,\mathrm{m\,s^{-2}}$ rms ($p<0.05$, Friedman) and at $2.0\,\mathrm{m\,s^{-2}}$ rms ($p<0.05$, Friedman). At $0.25\,\mathrm{m\,s^{-2}}$ rms, m_2 differed between conditions B and A, C and A, D and A, E and A, F and A, G and A, G and D, and G and E ($p<0.05$, Wilcoxon). At $2.0\,\mathrm{m\,s^{-2}}$ rms, m_2 differed between conditions D and A, E and A, D and C, E and D, F and D, G and D, and F and E ($p<0.05$, Wilcoxon).

3.3.6. The second segmental stiffness, k_2

3.3.6.1. Effect of vibration magnitude. At the high vibration magnitude, the second segmental stiffness, k_2, was significantly less than at the low vibration magnitude in all conditions A to G ($p<0.01$, Wilcoxon).

3.3.6.2. Effect of sitting condition. Over the seven sitting conditions, there were significant differences in k_2 at both 0.25 and $2.0\,\mathrm{m\,s^{-2}}$ rms ($p<0.05$, Friedman). At $0.25\,\mathrm{m\,s^{-2}}$ rms, k_2 differed between conditions C and A, C and B, D and B, E and B, E and C, F and C, G and C, E and D, and G and D ($p<0.05$, Wilcoxon). At $2.0\,\mathrm{m\,s^{-2}}$ rms, k_2 differed between conditions D and A, C and B, F and B, D and C, E and C, F and D, and F and E ($p<0.05$, Wilcoxon).

3.3.7. The second segmental damping constant, c_2

3.3.7.1. Effect of vibration magnitude. At the high vibration magnitude, the second segmental damping constant, c_2, was significantly less than at the low vibration magnitude in all conditions A–G ($p<0.05$, Wilcoxon).

3.3.7.2. Effect of sitting condition. Over the seven sitting conditions, there were significant differences in c_2 at both 0.25 and $2.0\,\mathrm{m\,s^{-2}}$ rms ($p<0.05$, Friedman). At $0.25\,\mathrm{m\,s^{-2}}$ rms, c_2 differed between conditions B and A, C and A, D and A, E and A, F and A, G and B, G and D, and G and E ($p<0.05$, Wilcoxon). At $2.0\,\mathrm{m\,s^{-2}}$ rms, c_2 differed between conditions B and A, C and A, D and A, E and A, F and A, F and B, G and B, E and D, F and D, and G and D ($p<0.05$, Wilcoxon).

4. Discussion

The results show that voluntary periodic movement can affect the nonlinearity in the apparent mass resonance frequency. The changes in nonlinearity found here are far greater than those found as a result of postural changes in previous studies. Conditions involving periodic movement significantly reduced the difference in resonance frequencies between low and high vibration magnitudes compared with the difference during static sitting in the same posture. The voluntary periodic movements primarily reduced the resonance frequency at low vibration magnitudes, with little change in the resonance frequency at high vibration magnitudes (Fig. 5).

Voluntary periodic body movement reduced the effective stiffness of the body at the low vibration magnitude, but had less effect on the effective stiffness of the body at the high vibration magnitude. This is apparent in the stiffness of both k_1 and k_2 in the equivalent 2dof model (Table 5, Fig. 9). At the low vibration magnitude, there were also increases in the damping, as reflected in c_1 and c_2 of the equivalent model, although the pattern of changes in damping over the conditions with voluntary movement differs from the changes in stiffness. Although there were also some statistically significant changes in the masses in the equivalent 2dof model as a result of voluntary movement, the nonlinearity is most obviously reflected in the changes in stiffness.

Compared to a normal sitting posture (A: upright), a voluntary sustained increase in muscle tension (B: upper-body tensed) increased the resonance frequency at both low and high vibration magnitudes, and this was reflected in significant increases in the stiffness k_1 in the equivalent model at both vibration magnitudes. However, the stiffness k_2 in the equivalent model did not increase significantly with the increased voluntary sustained muscle tension in condition B. The damping, as reflected in c_1 and c_2 of the equivalent model also increased with increased voluntary muscle tension.

The results suggest that body movement influences the effective stiffness of the body but that voluntary steady-state tensing of the body and voluntary movements have different effects. Whereas tensing increased stiffness at both high and low magnitudes of vibration, periodic voluntary muscular contractions primarily affected the dynamic response of the body at low magnitudes.

Condition C (back-abdomen bending) had the least nonlinearity in the apparent mass resonance frequency and had similar resonance frequencies at the two vibration magnitudes. The variation in the characteristic nonlinearity with the different involvement of back muscles in the different sitting conditions may suggest that back muscles, or other muscles involved in making the voluntary periodic movements, influence the biodynamic responses of the body and are in some way responsible for the nonlinearity.

The nonlinearity might be caused by muscular activity that acts differently at high and low vibration magnitudes. Limitations to muscles might restrict their force at high magnitudes, but the addition of voluntary movement as in this experiment would then be expected to change response at high magnitudes more than low magnitudes. The timing of the phasic muscle activity may vary with vibration magnitude so that the peak muscle force occurs at different times during high magnitude and low magnitude vibration, but if voluntary muscle activity alters the timing of phasic muscular activity this might be expected to alter response with both high and low magnitudes of vibration.

The greater effect of periodic body movement at low vibration magnitudes suggests the nonlinearity arises from a change at low magnitudes rather than a change at high magnitudes. At high magnitudes the inertial forces are greater, so it will require greater muscular force to influence the apparent mass, whereas at low magnitudes the inertial forces are less and it will require less muscle activity to influence the apparent mass. If the phasic muscle activity results in low forces that do not increase in proportion to vibration magnitude, they will influence the equivalent stiffness of the body more at low magnitudes than at high magnitudes. Voluntary periodic muscular activity may activate these same muscles, modify their phasic activity and reduce their contribution to the nonlinearity.

Periodic voluntary body movement might change the dynamic response of relevant body parts without muscle activity. For example, the thixotropy of tissues might allow both whole-body vibration and voluntary body movements to reduce the equivalent stiffness of the body. This would reduce the resonance frequency of the body if the movements occur in the soft tissues contributing to the stiffness of the body that controls the resonance frequency. High vibration magnitudes or increased voluntary movement would then reduce the resonance frequency of the body. The nonlinearity would be less evident when the stiffness of relevant body tissues has been reduced by voluntary body movements, as found in the present experiment.

5. Conclusion

The nonlinearity in apparent mass resonance frequency during static sitting can be significantly reduced by suitable voluntary periodic muscular activity.

Voluntary periodic muscle activity alters the equivalent stiffness of the body more at low vibration magnitudes (e.g. $0.25\,m\,s^{-2}$ rms) than at high vibration magnitudes (e.g. $2.0\,m\,s^{-2}$ rms).

Active control, or alternatively some passive property (e.g. thixotropy), of muscles, or other tissues involved during movement of the back and the upper body, significantly influence the biodynamic responses of the body to vibration.

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