ROLE OF THE THIGHS IN THE BIODYNAMIC RESPONSE OF THE HUMAN BODY SITTING ON A RIGID SEAT EXPOSED TO VERTICAL VIBRATION

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Abstract

Dynamic vertical forces at the ischial tuberosities and along the thighs of a seated person exposed to vertical vibration can be expected to reflect the dynamic characteristics of the body at these locations as well as more distant locations, including the upper body. Understanding the biodynamic responses at different locations over the contact surfaces, and the contribution of these responses to the overall apparent mass of the body, should assist understanding of the resonance behaviour of the whole body. With vertical vibration excitation, this study investigated biodynamic responses measured beneath the ischial tuberosities, the middle thighs, and the front thighs in terms of the vertical apparent masses (i.e., ratios of vertical force to vertical acceleration at these locations). Fourteen male subjects sat on a rigid seat with feet hanging while exposed to random vertical vibration (0.5 to 20 Hz) at three vibration magnitudes (0.25, 0.5, and 1.0 ms^{-2} r.m.s.). The frequency of the principal resonance in the vertical apparent mass was higher at the front thighs (8 to 10 Hz) than at the ischial tuberosities (around 5 Hz). There was greater nonlinearity in the vertical apparent mass measured at the front thighs than at the ischial tuberosities.

1 Introduction

Dynamic forces over the interfaces between a seat and the human body can contribute to the perception of discomfort caused by vibration. Understanding the variation in biodynamic responses over these surfaces, and the contribution of each response to the overall apparent mass of the body sitting on a seat, will advance understanding of biodynamic responses to whole-body vibration and may contribute to improving sitting comfort.

The biodynamic responses of the human body exposed to vertical vibration have been studied in terms of the driving point apparent mass. The vertical in-line apparent mass (i.e., the complex ratio between the vertical driving force and the vertical acceleration at the same point) has a principal resonance around 5 Hz and a secondary resonance around 8 to 10 Hz (Fairley and Griffin, 1989). The fore-and-aft cross-axis apparent mass of the seated human body exposed to vertical vibration (i.e., the complex ratio between the fore-and-aft force to the vertical acceleration at the driving point) also shows a principal resonance around 5 Hz (Nawayseh and Griffin, 2003).

Experimental and analytical modal analyses of the seated human body have suggested that the deformation of the soft tissues beneath the pelvis contributes to the principal resonance in the apparent mass around 5 Hz and the secondary resonance around 8 Hz (Kitazaki and Griffin, 1997;

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Kitazaki and Griffin, 1998; Matsumoto and Griffin, 2001). In previous studies, the total force at the seat surface has been measured, so how the soft tissues at the ischial tuberosities and the thighs are involved in the apparent mass could not be distinguished. The roles of the soft tissues at the ischial tuberosities and the thighs may be studied by measuring the responses at these locations. Different principal resonance frequencies might be expected at the ischial tuberosities and the thighs if the deformation of the soft tissues at the ischial tuberosities and the thighs are involved in different modes of vibration. However, the dynamic response of the body is complex and the principal resonance evident at a location can be caused either by a mode of the body at that location or a mode of the body at distant locations. When the feet are unsupported (i.e., hanging), the thighs may bounce on the muscles and other soft tissues beneath the femur and produce a local mode of vibration at the thighs that differs from the principal mode of vibration of the human body. If the body tissues beneath the thighs and the ischial tuberosities have broadly similar stiffness, it would be expected that the principal resonance at the thighs will be at a higher frequency than the resonance at the ischial tuberosities, because less mass is supported at the thighs than at the ischial tuberosities.

The apparent mass of the body depends on the vibration magnitude, with the principal resonance frequency decreasing as the vibration magnitude increases (e.g., Fairley and Griffin, 1989; Huang and Griffin, 2008). This nonlinearity in the biodynamic responses may be a property of the soft tissues. The nonlinearity in the vertical apparent mass increases as thigh contact increases (Nawayseh and Griffin, 2003). This suggests that in postures with greater thigh contact the apparent mass is more influenced by a mode of vibration with greater nonlinearity, possibly due to a difference in the nonlinearity of the tissues at the thighs and the ischial tuberosities. With the human body sitting on a rigid flat surface, there are greater pressures beneath the ischial tuberosities than beneath the thighs (Verver *et al*., 2004). The differences in pressures, tissue types, and tissue thicknesses make it reasonable to suppose there will also be differences in the nonlinearity of tissues at the ischial tuberosities and the thighs.

The objective of this study was to investigate the biodynamic responses at the ischial tuberosities, the middle thighs, and the front thighs of the human body sitting on a rigid seat with feet hanging while exposed to vertical vibration. The study was designed to identify the contributions of the biodynamic responses at different locations to the overall apparent mass of the human body. It was hypothesised that the response at the thighs would have a higher principal resonance frequency than that at the ischial tuberosities. It was also hypothesised that the nonlinearity in the response at the thighs would differ from that at the ischial tuberosities.

2 Method

2.1 Equipment

A rigid seat with a flat horizontal surface was secured to the platform of a 1-m vertical electro-hydraulic vibrator (Figure 1). An accelerometer (Entran EGCSY-240D-10) was mounted beneath the centre of the seat pan to measure the vertical vibration acceleration. A force plate (Kistler 9281B) was secured to the seat frame to measure the overall vertical forces on the seat surface. Two load cells (Kistler 9602) supported a rectangular wooden plate at the front area of the force plate to measure the vertical forces beneath the distal parts of the thighs. Another two load cells (Kistler 9602) supported a rectangular wooden plate in the middle area of the force plate to measure the vertical forces beneath the proximal thighs. A wooden block was secured on the rear of the force plate to provide a surface to take the weight at the ischial tuberosities. The upper surface of this wooden block was level with the upper surfaces of the two wooden plates supported by the two pairs of load cells.

Forces in the vertical direction were measured in this study. Signals from the accelerometer and the load cells were acquired at 512 samples per second via anti-aliasing filters at 50 Hz.

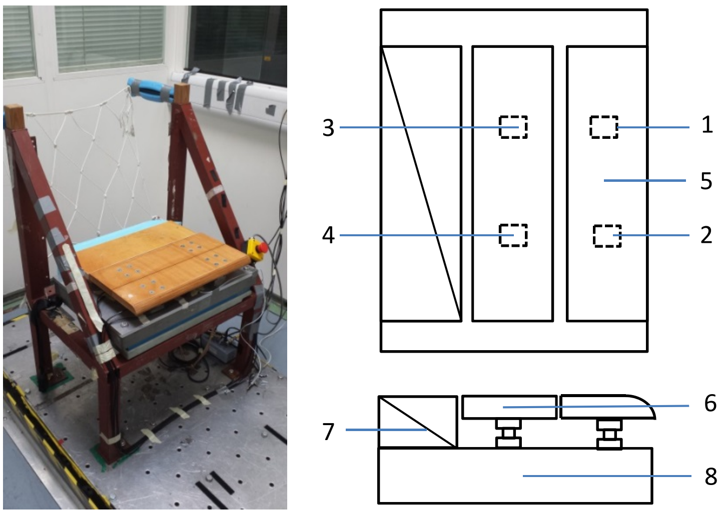

Figure 1 Force cells for measuring forces at different locations. 1 to 4: Kistler 9602 load cells; 5 and 6: wooden plates to support thighs; 7: wooden block to support the ischial tuberosities; 8: Kistler 9281B force plate.

Figure 2 Feet hanging posture.

Table 1 Characteristics of the 14 male subjects: median (range).

Age [Year]	Weight [kg]	Stature [cm]	Sitting height* [cm]	Knee height** [cm]	Buttock-knee length*** [cm]
28.4 (24-40)	74.2 (65.5-85.5)	179 (165-188)	91 (86-94)	57.6 (50-62.5)	60.6 (56-66)

*: Vertical distance from the sitting surface to the top of the head;
**: Vertical distance from the footrest surface to the upper surface of the knee;
***: Horizontal distance from the rearmost surface of the buttocks to the front of the knee.

2.2 Subjects and stimuli

Fourteen male subjects sat on the seat with their ischial tuberosities supported by the wooden block at the rear of the seat, their feet hanging, and their upper-body in a normal upright posture (Figure 2). The characteristics of the subjects are listed in Table 1.

The subjects were exposed to vertical random vibration with an approximately flat constant bandwidth acceleration power spectrum between 0.5 and 20 Hz at three magnitudes (0.25, 0.5, and 1.0 ms^{-2} r.m.s.), each with a duration of 60 s.

The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (approval number 7931).

2.3 Analysis

The total vertical dynamic force on the whole body was determined by subtracting the inertia forces due to the 50.5-kg mass above the force sensing elements of the Kistler 9281B force plate from the vertical force measured by this force plate. This 'mass cancellation' was performed in the time-domain.

The vertical force at the front thighs was obtained by summing the forces from the two front Kistler 9602 load cells and then subtracting the inertia force due to the 0.7-kg mass above these load cells in the time-domain. The same procedure was applied to obtain the vertical force at the middle thighs. The force at the ischial tuberosities of the seated human body was obtained by subtracting in the time-domain the vertical forces at the front and middle thighs from the total vertical force for the whole body as calculated from the signals given by the Kistler 9281B force plate.

The complex ratios between the vertical acceleration at the seat and the vertical force at each location (front thighs, middle thighs, and ischial tuberosities) were calculated using the cross-spectral density method, and are referred to as the vertical in-line apparent mass at the appropriate measurement position:

$$M(\omega) = S_{af}(\omega) / S_{aa}(\omega), \qquad \text{Equation 1}$$

where $M(\omega)$ is the apparent mass, $S_{af}(\omega)$ is the cross-spectral density between the acceleration and the force, and $S_{aa}(\omega)$ is the power spectral density of the acceleration.

The complex ratio between the total force in the vertical direction and the vertical acceleration at the seat was also calculated using the cross-spectral density method, and is referred to as the overall vertical in-line apparent mass of the human body.

The degree of nonlinearity in the response at different locations is quantified by the ratio, R, of the resonance frequencies in response to vibration at 0.25 ms^{-2} r.m.s. and 1.0 ms^{-2} r.m.s.:

$$R = f_{0.25} / f_{1.0} \qquad \text{Equation 2}$$

where $f_{0.25}$ is the frequency of resonance in response to vibration at 0.25 ms^{-2} r.m.s. and $f_{1.0}$ is the frequency of resonance in response to vibration at 1.0 ms^{-2} r.m.s. A greater R value indicates greater nonlinearity.

3 Results

3.1 Characteristics in the vertical apparent masses

The overall vertical apparent mass showed principal resonances in the region of 5 Hz for the majority of the subjects but with variability between subjects (Figure 3). Twelve of the fourteen subjects showed another resonance at about 8 to 10 Hz and eight subjects showed a third broad resonance around 13 Hz.

The vertical apparent masses showed principal resonances around 5 Hz at the ischial tuberosities, around 5 Hz with a secondary resonance in the range 8 to 10 Hz at the middle thighs, and around 8 to 10 Hz at the front thighs.

The overall apparent masses presented similar resonance frequencies to the responses at the ischial tuberosities (Figure 4), with no significant difference in the resonance frequencies at any vibration magnitude (Wilcoxon, $p>0.05$). With all three vibration magnitudes, the apparent masses presented significantly higher resonance frequencies at the front thighs than at the other locations (Figure 4; Wilcoxon, $p<0.005$).

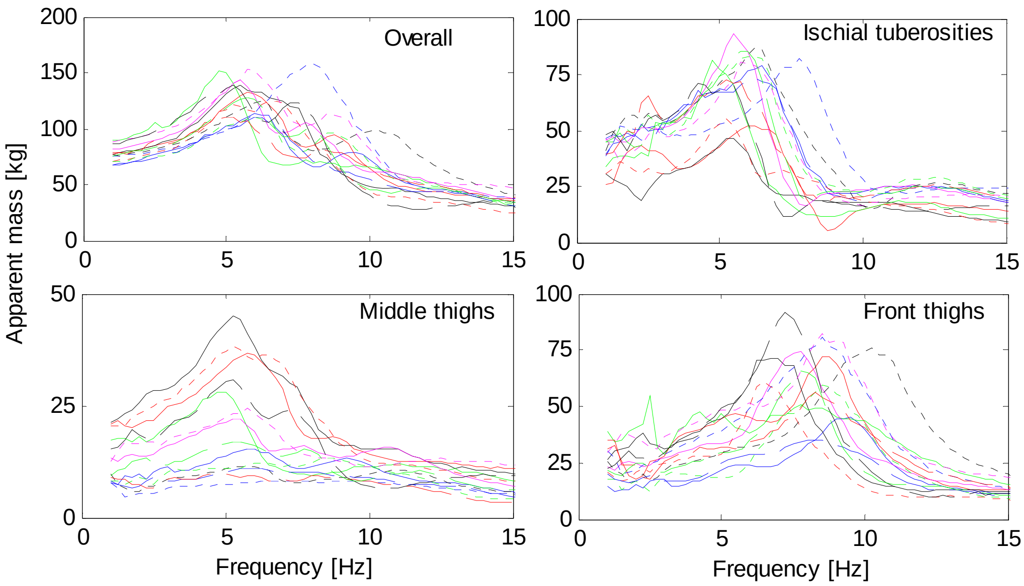

Figure 3 Overall vertical apparent masses and vertical apparent masses at the ischial tuberosities, the middle thighs, and the front thighs with a vibration magnitude of 0.25 ms^{-2} r.m.s. Individual data from 14 subjects.

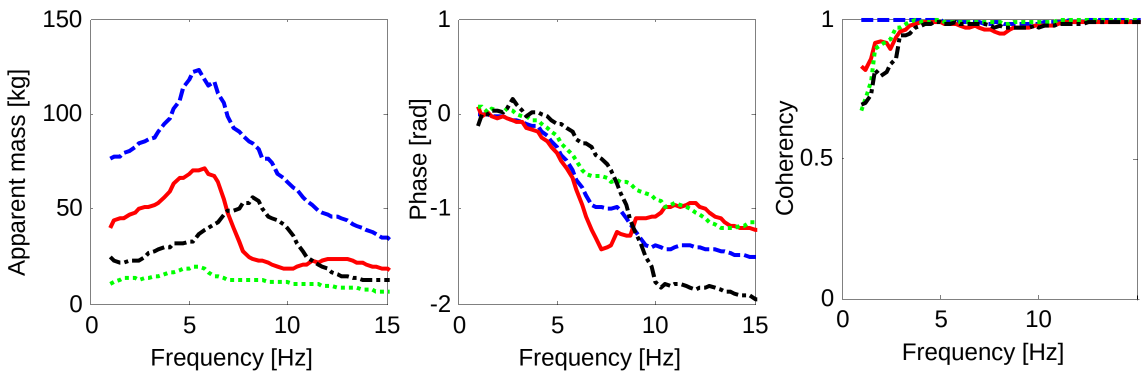

Figure 4 Overall vertical apparent mass and vertical apparent masses at the ischial tuberosities, the middle thighs, and the front thighs with a vibration magnitude of 0.25 ms^{-2} r.m.s.: – – – overall apparent mass; ——— apparent mass at the ischial tuberosities; ········ apparent mass at the middle thighs; –·–·– apparent mass at the front thighs. Median data from 14 subjects.

Table 2 Statistical comparison of the vertical apparent masses between locations at frequencies from 1 to 16 Hz at all three vibration magnitudes (Wilcoxon matched-pairs signed ranks test).

Frequency (Hz)	ischial tuberosities versus middle thighs			ischial tuberosities versus front thighs			front thighs versus middle thighs		
	Vibration magnitude (ms^{-2} r.m.s.)			Vibration magnitude (ms^{-2} r.m.s.)			Vibration magnitude (ms^{-2} r.m.s.)		
	0.25	0.5	1.0	0.25	0.5	1.0	0.25	0.5	1.0
1.0	****B	****B	****B	***B	****B	****B	****F	****F	****F
2.0	****B	****B	****B	***B	****B	****B	****F	****F	****F
3.25	****B	****B	****B	****B	****B	****B	****F	****F	****F
4.0	****B	****B	****B	****B	****B	****B	****F	****F	****F
5.0	****B	****B	****B	****B	****B	***B	****F	****F	****F
6.25	****B	****B	****B	*B	-	-	****F	****F	****F
8.0	***B	***B	****B	**F	****F	*F	****F	****F	****F
10	****B	****B	****B	***F	-	-	****F	****F	****F
12.5	****B	****B	****B	-	-	*B	****F	****F	****F
16	****B	****B	****B	*B	*B	***B	****F	****F	****F

*p<0.05; **: p<0.01; ***: p<0.005; ****: p<0.001; -: p>0.05
B: median apparent mass at the ischial tuberosities greater than that at the other location;
F: median apparent mass at the front thighs greater than that at the other location.

The apparent masses were greater at the ischial tuberosities than at the middle thighs at all frequencies (Figure 4, Table 2). The apparent masses were greater at the ischial tuberosities than at the front thighs at all frequencies, except around 8 to 10 Hz (Figure 4, Table 2). The apparent masses were less at the middle thighs than at the front thighs at all frequencies (Table 2).

3.2 Nonlinearity in the vertical apparent masses

The resonance frequencies in the overall vertical apparent mass and the apparent masses at all three locations decreased with increasing vibration magnitude (Friedman, p<0.05; Figure 5).

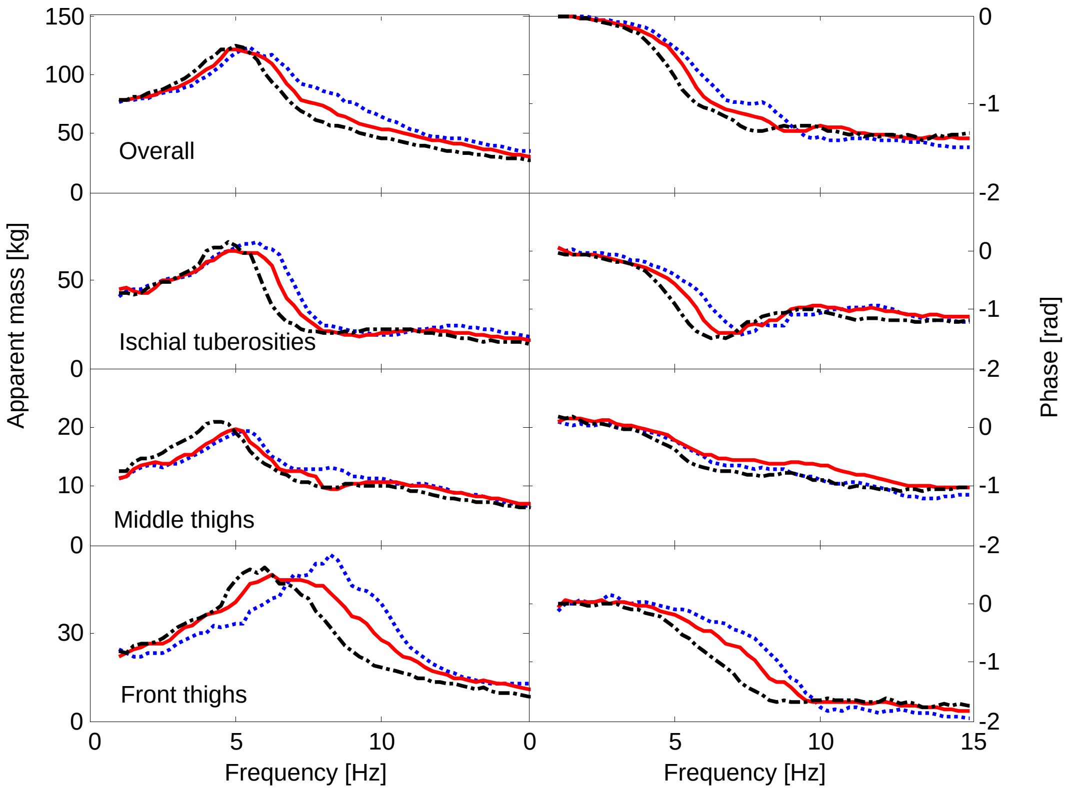

Figure 5 Effect of vibration magnitude on the overall vertical apparent mass and the vertical apparent masses at the ischial tuberosities, the middle thighs, and the front thighs: ········ 0.25 ms^{-2} r.m.s.; ——— 0.5 ms^{-2} r.m.s.; –·–·– 1.0 ms^{-2} r.m.s. Median values for 14 subjects.

When the vibration magnitude increased from 0.25 to 1.0 ms^{-2} r.m.s., the median ratio, R, calculated with Equation 2, was 1.18, 1.18, and 1.25 for the overall vertical apparent mass, the apparent mass at the ischial tuberosities, and the apparent mass at the front thighs, respectively. The ratio was significantly greater for the front thighs than for both the overall apparent mass and the apparent mass at the ischial tuberosities (Wilcoxon, p<0.001).

4 Discussion

4.1 Characteristics in the vertical apparent masses

Previous studies have suggested that the mode associated with the principal whole-body resonance of the human body involves deformation of the soft tissues beneath the ischial tuberosities (Kitazaki and Griffin, 1997; Matsumoto and Griffin, 2001; Zheng *et al*., 2011). In this study, the vertical apparent mass at the ischial tuberosities showed a similar resonance frequency to the overall vertical apparent mass, consistent with soft tissue deformation at the ischial tuberosities contributing to the resonance. In contrast, the resonance evident at the front of the thighs occurred at a frequency that was higher than the principal resonance of the body, showing that deformation of the front thighs was not primarily responsible for the major resonance of the whole-body. It may be concluded that soft tissues beneath the ischial tuberosities are more involved in the principal resonance in the vertical apparent mass of the human body than the soft tissues at the thighs.

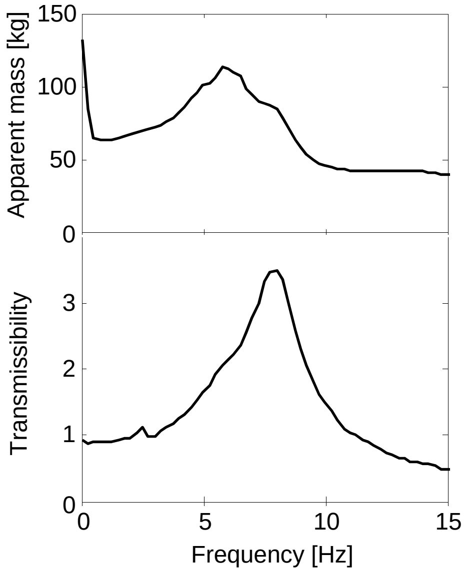

Figure 6 Vertical apparent mass and vertical transmissibility to the upper-surface of the knee. Data from one subject.

With feet hanging, the vertical apparent mass showed a higher resonance frequency at the front thighs than at other locations (Figure 4). This is similar to the apparent mass measured at the feet when subjects sit with their heels just in contact with a footrest (Nawayseh and Griffin, 2003). The vertical force at the feet presented a principal resonance around 10 Hz, higher than the principal resonance frequency in the vertical apparent mass at the seat. At frequencies around 8 Hz in the present study, the apparent mass at the front thighs was greater than the apparent masses at the ischial tuberosities and the middle thighs (Figure 4, Table 2). This indicates that the response at the front thighs can make an appreciable contribution to the overall vertical apparent mass of the body, and that around 8 Hz the soft tissues at the front thighs are more involved than the soft tissues at the ischial tuberosities.

The resonance in the apparent mass measured at the front thighs around 8 Hz might arise from the masses (of the thighs, legs, and feet) being supported on the thighs and the femurs undergoing a pitch mode about the hip joints. This is consistent with the vertical transmissibility from the seat to the knee having the same principal resonance frequency as the second peak in the vertical apparent mass, when the feet were hanging (Figure 6).

The vertical apparent mass of the whole-body often shows a secondary peak around 8 to 10 Hz (e.g., Fairley and Griffin, 1989). Some biodynamic models have suggested that a mode in which the viscera moves vertically out of phase with axial deformation of the soft tissues of the buttocks and thighs is associated with this secondary peak in the vertical apparent mass of the whole-body (e.g., Kitazaki and Griffin, 1997; Matsumoto and Griffin, 2001). It is expected that the resonance of the thighs found around 8 Hz in the present study may also contribute to this secondary peak when the feet are not well supported by a footrest.

4.2 Nonlinearity in the vertical apparent masses

When the vibration magnitude increased from 0.25 to 1.0 ms^{-2} r.m.s., the nonlinearity (as indicated by the ratio, *R*, calculated with Equation 2), was greater at the front thighs than at the ischial tuberosities. Since the principal resonance at the front thighs may be caused by the thighs bouncing on the soft tissues beneath the femurs, as discussed above, the nonlinearity measured at the front thighs may be related to the compression properties of the soft tissues in the thighs. The cause of the non-linearity associated with the principal resonance in the vertical apparent mass around 5 Hz is less clear and may reflect the characteristics of the soft tissues beneath the ischial tuberosities and the tissues of the upper-body. This study shows that the soft tissues at the thighs can introduce greater nonlinearity than the soft tissues beneath the ischial tuberosities.

5 Conclusions

When sitting with the feet hanging, the vertical apparent mass measured at the ischial tuberosities makes a greater contribution to the overall vertical apparent mass at the 5-Hz resonance of the body than the apparent mass measured at the middle of the thighs or the front of the thighs.

With the feet hanging, the vertical apparent mass measured at the front thighs exhibits a principal resonance around 8 Hz and can be the principal contribution to the overall vertical in-line apparent mass at 8 Hz. This resonance may involve pitch motion of the femurs about the hip joints, with the legs bouncing on the soft tissues of the thighs.

As the vibration magnitude increases, the resonance frequencies in the apparent masses measured at all three locations (i.e., ischial tuberosities, middle thighs, and front thighs) decrease. With the feet hanging, there was greater nonlinearly in the vertical apparent mass at the thighs than at the ischial tuberosities.

6 References

Fairley TE and Griffin MJ (1989) The apparent mass of the seated human body: vertical vibration. Journal of Biomechanics, 22, 81-94.

Huang Y and Griffin MJ (2008) Non-linear dual-axis biodynamic response of the semi-supine human body during vertical whole-body vibration. Journal of Sound and Vibration 312 (1-2), 296 – 315.

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

Kitazaki S and Griffin MJ (1998) Resonance behaviour of the seated human body and effects of posture. Journal of Biomechanics 31 (2), 143 – 149.

Matsumoto Y and Griffin MJ (2001) Modelling the dynamic mechanisms associated with the principal resonance of the seated human body. Clinical Biomechanics, 16, 31-44.

Nawayseh N and Griffin MJ (2003) Non-linear dual-axis biodynamic response to vertical whole-body vibration. Journal of Sound and Vibration 268 (3), 503 – 523.

Verver MM, Van HJ, Oomens CWJ, Wismans JSHM and Baaijens FPT. (2004) A finite element model of the human buttocks for prediction of seat pressure distributions. Computer Methods in Biomechanics and Biomedical Engineering, 7 (4), 193-203.

Zheng G, Qiu Y and Griffin MJ (2011) An analytical model of the in-line and cross-axis apparent mass of the seated human body exposed to vertical vibration with and without a backrest. Journal of Sound and Vibration, 330 (26), 6509-6525.