UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT
Institute of Sound and Vibration Research

FACTORS AFFECTING THE DYNAMIC RESPONSE OF THE BODY AND THE VIBRATION TRANSMITTED THROUGH SEATS

by

Martin GR Toward

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ABSTRACT

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Doctor of Philosophy

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The vibration transmitted through a seat is influenced by the dynamics of the seat and the dynamics of the occupant. The principal objective of this thesis is to understand how the dynamics of the body and factors affecting the dynamics of the body influence the vibration transmitted through seats. Previous studies have shown that the apparent mass of the body and seat transmissibility are affected by the seating environment (e.g. vibration input spectra, backrest, hands position, foot position) and variability between people (i.e. physical characteristics), but these effects have not previously been systematically explored for realistic seating conditions.

The apparent masses of 12 subjects were measured during exposure to random vertical vibration (from 0.125 to 40 Hz) to investigate the effects of the seat backrest, the footrest and steering wheel, and input spectra. In a rigid seat with no backrest, there were resonances in the apparent mass of the body around 5 and 10 Hz (with 1.0 ms^{-2} r.m.s broadband vibration). In the same seat with a rigid backrest, the median resonance frequency in the apparent mass increased from 5.47 to 6.35 Hz as the backrest was reclined to 30 degrees in 5 degrees increments; with a 100-mm foam backrest, the median resonance frequency decreased from 5.18 to 4.49 Hz as the backrest was reclined to 30 degrees. When subjects held a steering wheel, the mass supported on the seat surface decreased and there was an additional resonance at 4 Hz in the apparent mass. Moving the steering wheel away from the body reduced the apparent mass at resonance and increased the apparent mass around the 4 Hz resonance. As the feet moved forward, the mass supported on the seat surface increased, indicating that the backrest and footrest supported a lesser proportion of the subject weight. Applying force (0, 50, 100, 150, 200 N) to either the steering wheel or the footrest reduced the apparent mass at resonance and decreased the mass supported on the seat surface. Narrowband inputs at ½-octave intervals (from 1 to 16 Hz) presented at five magnitudes (0.25, 0.4, 0.63, 1.0 and 1.6 ms^{-2} r.m.s.) showed that the extent of nonlinearity previously observed with broadband vibration was frequency-dependent: the magnitude of vibration at frequencies less than 4 Hz had the greatest effect on the apparent mass at resonance, while vibration at frequencies less than 8 Hz had the greatest effect on the resonance frequency.

A simple lumped parameter model was used to demonstrate that changes in the apparent mass with backrest contact, backrest inclination, hand position, foot position and vibration magnitude could be closely represented by changing the parameters in the model. Trends in model parameters, the damping ratios, and the damped natural frequencies were identified as a function of the model variables.

A study was designed to determine how the physical characteristics of 80 seated adults (41 males and 39 females aged 18 to 65) affected their apparent mass and the transmission of vibration through a seat. Multiple regression models showed that while the strongest predictor of the vertical apparent mass at 0.6 Hz, at resonance, and at 12 Hz was bodyweight, weight was not strongly associated with seat transmissibility. A lumped parameter seat-person model was used to show that the dynamic stiffness of the seat increased with increased loading so as to compensate for increases in apparent mass associated with increased sitting weight. As age increased from 18 to 65 years, the apparent mass resonance frequency increased by up to 1.7 Hz. This change was greater than the 0.9-Hz increase in resonance frequency between sitting without a backrest and sitting with a backrest reclined to 15° and greater than the 1.0-Hz reduction in resonance frequency when the magnitude of vibration increased from 0.5 to 1.5 ms^{-2} r.m.s. Subject age was much the strongest predictor of the seat transmissibility resonance frequency and the transmissibility at resonance. The model was used to show that changes in the seat transmissibility with age could be predicted from changes in the apparent mass with age.

CONTENTS

DECLARATION OF AUTHORSHIP

I, MARTIN TOWARD

declare that the thesis entitled

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and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

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Toward and Griffin (2009). Apparent mass of the human body in the vertical direction: Effect of seat backrest. Journal of Sound and Vibration 327, 657-669.

Toward and Griffin (2010a). Apparent mass of the human body in the vertical direction: Effect of steering wheel and footrest. Journal of Sound and Vibration 329, 1586-1596.

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

Toward and Griffin (2010c). Apparent mass of the human body in the vertical direction: inter-subject variability. Journal of Sound and Vibration 330, 827–841.

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CHAPTER 1: INTRODUCTION

In a wide variety of transport environments the vibration transmitted through seats is associated with discomfort. This vibration discomfort can either be reduced or increased due to the influence of the seat. The efficiency of a seat in terms of vibration discomfort depends on three factors that can vary independently: (i) the seat transmissibility (ratio of the magnitude of vibration on the seat surface to the magnitude at the seat base), (ii) the sensitivity of the body to the spectrum of vibration on the seat surface, and (iii) the spectrum of vibration at the seat base. It is obvious that the construction of a seat can influence the manner in which it amplifies or attenuates the vibration. Additionally, because the seat and the body supported on the seat form a coupled dynamic system, the vibration transmitted through seats is also influenced by the dynamic response of the human body.

Mostly, seat transmissibilities are measured with 'representative' people sitting in the seats, but this means different transmissibilities are obtained according to the people selected. Furthermore, this involves exposing the selected people to vibration, with attendant costs and risks. A convenient alternative would be to either replace the person with a dynamic dummy having dynamic characteristics similar to the 'average person', or to calculate the transmissibility from the measured dynamic characteristics of the seat and the known dynamic characteristics of appropriate people. Both approaches need information on the relevant dynamic characteristics of the human body in representative conditions.

Apparent mass (i.e. the complex ratio of the force to acceleration on the seat surface) is the most commonly used driving point response function used to describe the dynamic characteristics of the seated body. Previous studies have shown that the apparent mass of the body is affected by the seating environment (e.g. vibration spectrum, backrest, hands position, foot position) and variability between subjects (e.g. physical characteristics) but these effects have not been systematically defined for realistic seating conditions. Knowledge of the influence of these factors will advance understanding of the dynamic mechanisms of the body under vibration, and assist the development of biodynamic models of the human body.

Factors affecting the dynamic responses of the occupant may also affect the dynamic properties of the seat. For instance, heavier subjects tend to have higher apparent masses at all frequencies, but the contact area with the seat surface and hence the compression and dynamic stiffness of the seat cushion are also likely to be related to body weight. The influence of changes in the seat dynamic stiffness on seat transmissibility is not well understood. Knowledge of how the dynamic properties of the seat are affected by the apparent mass of the body will help to develop more accurate models to predict the transmission of vibration through seats.

This thesis sets out to answer three main questions: (i) How does the seating environment affect the apparent mass of the seated body, (ii) How do subject physical characteristics affect the apparent mass of the body, and (iii) How does the apparent mass of the body affect the vibration transmitted through a seat?

The thesis is divided into ten chapters. Following this chapter, Chapter 2 is a literature review, in which the current state of knowledge relating to the driving point impedance of the body and the vibration transmitted through seats is summarised and discussed; from this discussion the scope of the research is defined. Chapter 3 describes the apparatus and analysis methods used in the experimental aspects of the research. Chapters 4 to 6 contain experimental studies investigating the effects of the seat backrest, posture and input spectra on the apparent mass of the body. In Chapter 7 a model is developed to represent effects of posture and vibration magnitude on apparent mass. Chapters 8 and 9 describe studies showing how the physical characteristics of people affect their apparent mass and the transmission of vibration through seats respectively. General conclusions and recommendations are presented in Chapter 10.

Preliminary studies are presented in the appendices. Appendix A describes a study investigating the use of an anthropodynamic dummy to measure seat transmissibility. Appendix B describes a study examining effects of backrest interaction on seat transmissibility.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

The aim of this chapter is to review the state of knowledge relating to measurements and modelling of factors affecting the apparent mass of the seated body and the transmission of vibration through seats.

Vibration transmitted to the occupant of a seat can enter the body through each supporting surface (e.g. seat pan, backrest, steering wheel, etc.). At each location, vibration can occur in one or more axis and may vary in magnitude. The sensitivity of the body also depends on the body location and the frequency and direction of vibration. Notwithstanding these considerations, in most seating environments vertical vibration transmitted to the seat surface is often of greatest significance in terms of discomfort (Griffin, 1990). Accordingly, the scope of this review has been restricted to point responses of the seated body exposed to vertical vibration. Likewise, studies relating to the transmission of vibration through seats are largely restrained to those relating to the transmission of vertical vibration to the seat surface.

In some vehicles, suspension seats are used, often where there is significant low frequency vibration. These seats offer lower stiffness and thus lower resonance frequencies compared to conventional foam cushion seats. The dynamics of suspension seats are complex with numerous non-linearities associated (e.g. end-stop impacts, friction, damper properties; Gunston, 2002). As such, it is likely that the influence of factors affecting the transmission of vibration through conventional seats will be different to suspension seats. While the findings of these studies may be of significance to the further understanding of suspension seat dynamics, the scope of this research is mainly focussed on the transmission of vibration through conventional foam cushion seats without separate mechanical suspensions.

The literature review is divided into three main sections: factors affecting the seated driving point response of the human body to vertical vibration, factors affecting the transmission of vertical vibration through seats, and modelling of the seat and person.

2.1.1 Description and calculation of transfer functions

Measures of the dynamic responses of a system are represented by transfer functions. A transfer function of a mechanical system is defined as the ratio of an input signal to an output signal as a function of frequency, where the input and output signals may be acceleration, velocity, displacement, force, and so on. These input and output signals can either occur at the same location on the structure or at different locations on the structure.

It is possible to determine the transfer function by using sinusoidal excitation - the modulus and phase of the transfer function is simply given by the ratio and phase difference between the input and output signals. However, transfer functions over a frequency range can be more quickly calculated using random excitation and transferring the input and output signals into the frequency domain using a Fourier transform (Fahy and Walker, 1998). The transfer function, $H(f)$, can then be given by:

$$H(f) = Y(f) / X(f) \qquad \textbf{2.1}$$

where f is the frequency, and $X(f)$ and $Y(f)$ are the Fourier transforms of the input and output, respectively. In practice there is always some noise on the input and output signals, so there is always some inaccuracy in the calculation of the transfer function according to Equation 2.1. The effect of this noise can be minimized by using alternative transfer functions based on the cross spectra and power spectra of the input and output. The cross-spectral density (CSD) method calculates the transfer function as:

$$H(f) = S_{xy}(f) / S_{xx}(f) \qquad \textbf{2.2}$$

where $S_{xy}(f)$ is the cross-spectral density between the output signal and the input signal, and $S_{xx}(f)$ is the power-spectral density of the input signal. Alternatively the power-spectral density (PSD) method can be used to calculate the frequency response function:

$$H(f) = S_{yy}(f) / S_{xx}(f) \qquad \textbf{2.3}$$

where $S_{yy}(f)$ is the power-spectral density of the output. The CSD method calculates the transfer function between the input and the part of the output that is linearly related to the output. The PSD method calculates the transfer function between the input and output including all ‘noise’ between the input and output. If there is no noise in the system then the two methods will yield identical transfer functions. However, where there is noise in the system then the modulus of the transfer function calculated using the CSD method will be lower. An advantage of the CSD method is that because it is a complex function it gives both the modulus and the phase of the transfer function. In contrast, the PSD method gives only the modulus.

To estimate how the output motions are related to the input motions, the coherence function, $\gamma_{xy}^2(f)$, may be determined:

$$\gamma_{xy}^2(f) = |S_{xy}(f)|^2 / (S_{xx}(f)\ S_{yy}(f)) \qquad \textbf{2.4}$$

The coherency takes a value between 0 and 1 - in an ideal linear system with no noise the output and input will be perfectly correlated and the coherency will have a value of unity at all frequencies. Lower coherency can be caused by noise, non-linearity of the structure, and the presence of other inputs (Fahy and Walker, 1998).

2.1.2 Driving point response functions

Driving point response functions are used to define the relation between input and output signals at the same point of a system. When measuring the driving point responses of a seated person this point is usually at the seat surface. The mechanical impedance, $Z(f)$, and the apparent mass, $M(f)$, are the most widely used driving point responses for whole-body vibration, given by:

$$Z(f) = F(f)\ /\ V(f) \qquad \textbf{2.5}$$

$$M(f) = F(f)\ /\ A(f) \qquad \textbf{2.6}$$

where $F(f)$ is the Fourier transform of the response force measured at the seat surface, and $V(f)$ and $A(f)$ are the Fourier transforms of the excitation velocity and acceleration respectively. In practice, the transfer functions are often calculated using the CSD or PSD methods described in Section 2.1.1, to minimize the effect of noise.

An advantage of using apparent mass over mechanical impedance is that the apparent mass can be obtained directly from measurements by accelerometers and force transducers. A further advantage is that Newton’s second law of motion gives apparent mass an intuitive meaning: ‘a force applied to a body accelerates the body by an amount proportional to the force, the constant of proportionality being the mass of the body’. For a rigid body the apparent mass is equal to the static mass at all frequencies. For a non-rigid body such as a human subject the apparent mass is equal to their supported static weight at 0 Hz where the body is effectively rigid (Griffin, 1990).

As the apparent mass is a function of the supported weight, it can be desirable to normalise the data to remove the influence of subject weight, so that the responses of different subjects can be directly compared. The normalised apparent mass is usually determined by dividing the measured apparent mass by the sitting weight of the subjects (i.e. the apparent mass at 0 Hz).

The frequency of the peak in the mechanical impedance is always either the same or higher than that observed for the apparent mass. This was illustrated by Mansfield (2005), who compared the resonance frequencies in both the mechanical impedance and the apparent mass for a simple single-degree-of-freedom model fitted to the average apparent mass response of a group of 60 subjects. For measurements of mechanical impedance the model had a resonance at 5.50 Hz, compared to a resonance frequency of 4.25 Hz for measurements of apparent mass with the same model parameters. The resonance frequency in transmissibility between the base mass in the model and the moving mass of the model was the same as that in the apparent mass. This equivalence in the frequency of the apparent mass and transmissibility peaks illustrates that the apparent mass gives a more direct indication of the biomechanical response of the structure compared to mechanical impedance.

To obtain the apparent mass of a subject, the influence of the mass of the force transducer 'above' the force sensing elements must be removed from the apparent mass. This 'mass cancelation' can either be done in the time domain or in the frequency domain. In the time domain the inertial force of the effective mass of the transducers is subtracted from the measured force to give the true force:

$$f(t) = f_m(t) - m_e a(t) \qquad \textbf{2.7}$$

where $f(t)$ is the true force, $f_m(t)$ is the measured force, m_e is the effective mass of the force transducer, and $a(t)$ is the excitation acceleration. The alternative frequency domain method is to subtract the real and imaginary parts of the apparent mass measured without a subject, $M_e(f)$, from the measured apparent mass with a subject, $M_m(f)$, to give the true apparent mass, $M(f)$:

$$M(f) = M_m(f) - M_e(f) \qquad \textbf{2.8}$$

If the apparent mass of the force transducer differs with and without a subject, the apparent masses measured using the frequency domain method may be inaccurate. This might occur if the excitation at the seat surface, or if the support structure beneath the force platform, is influenced by loading. In practice, most researchers have found that the moduli of the apparent masses obtained using both methods are not greatly different (e.g. Huang; 2008). However, errors in the phase of the apparent mass, particularly at high frequencies, where the apparent mass of the body is relatively small, can be of significance. A further advantage of the time domain method is that the derived coherency reflects the true coherency as the effect of the effective mass of the force transducer is removed before the coherency is calculated.

2.1.3 Seat transmissibility

Seat transmissibility represents the amount of motion transmitted between the base of a seat and the surface of a seat. These motions can be expressed in displacement, velocity or acceleration. For convenience, acceleration is often used. The transmissibility can be calculated by simply dividing the Fourier transforms of the motions for example:

$$\mathrm{T}(f) = a_{\mathrm{s}}(f) \;/\; a_{\mathrm{b}}(f) \qquad \mathbf{2.9}$$

where $T(f)$, is the seat transmissibility, $a_s(f)$ is the acceleration on the seat, and $a_b(f)$ is the acceleration at the seat base (Griffin, 1990). However, in practice the CSD or PSD methods discussed in Section 2.1.1 are normally used to minimize the effects of noise.

2.2 FACTORS AFFECTING THE APPARENT MASS OF THE SEATED BODY

2.2.1 Introduction

Studies measuring the apparent mass of the seated body during vertical vibration have generally shown a resonance[1] at around 5 Hz (e.g. Fairley and Griffin, 1989). In Figure 2.1 the moduli of the apparent masses of 60 subjects, sitting in a seat with no backrest exposed to 1.0 ms^{-2} r.m.s. broadband random vertical vibration, are compared. At low-frequencies, where the body is effectively rigid, each apparent mass curve approaches

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[1]Usually a peak in the apparent mass of a system is referred to as an 'anti-resonance' (Fahy and Walker, 1998) as it represents a peak in the force required to drive the system and hence a minimum in the system response. The term 'resonance' is used throughout this thesis (as is conventional in this field (e.g. Griffin, 1990). The peak in the apparent mass of the body is known to occur at the same frequency as the principal peak in the seat-to-head transmissibility of the body (e.g. Kitazaki, 1994), and therefore this peak might be considered to be a peak in the response of the body for a given velocity input. This can be illustrated by representing the body as a single degree-of-freedom mass-spring system; moreover if this system is blocked at the base it will have a resonance at the same frequency as the peak in the apparent mass of the system when excited at the base.

the static mass of the subject supported on the seat. At resonance, the response is in the region of 1.3 to 2.0 times the static mass. A second resonance can be seen in some subjects in the region of 10 Hz. The frequency and magnitude of this second resonance varies considerably between subjects and so is not always clear in mean or median results.

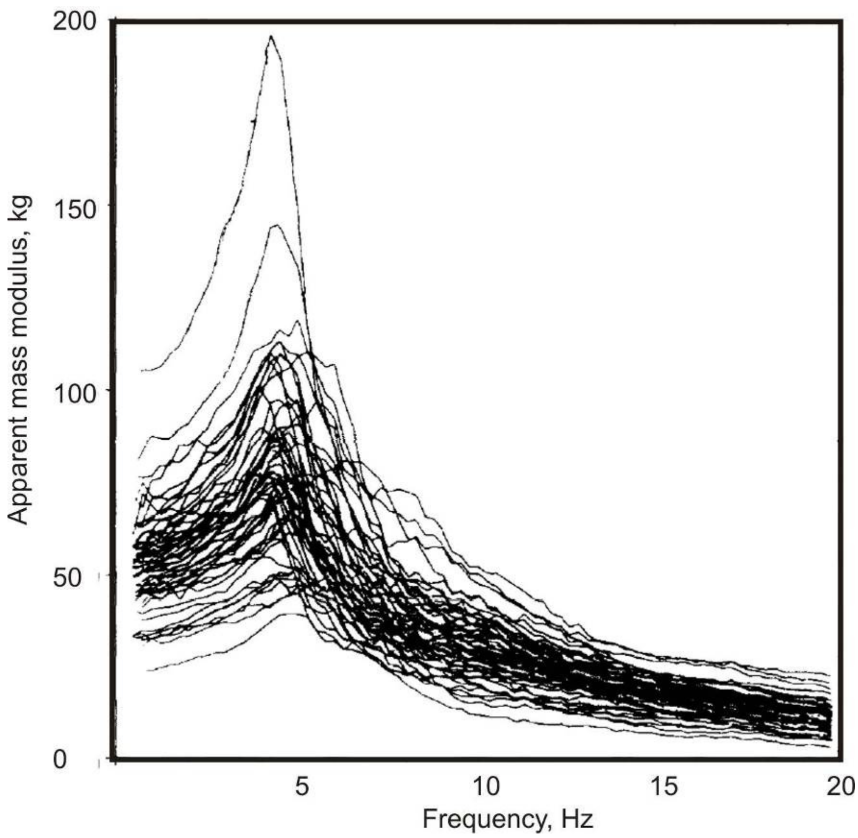

Figure 2.1 Apparent masses of 60 seated people in the vertical direction (from Fairley and Griffin, 1989).

2.2.2 Posture and muscle tension

There can be considerable variability in the apparent mass responses of subjects in the same nominal sitting conditions (e.g. Figure 2.1). While much of this variability may be accounted for by subject physical characteristics (see Section 2.2.5), some of this variability may arise from variations in posture and muscle tension between subjects – studies relating to the effects of these variables are summarised in Table 2.1 and are described in the subsections below.

Some studies have found subjects have a higher resonance frequency when they adopt either a more erect posture (e.g. Figure 2.2; Kitazaki and Griffin, 1998) or a more tense posture; however some studies have found little or no difference with these postural variations (e.g. Miwa, 1975; Mansfield and Griffin, 2002).

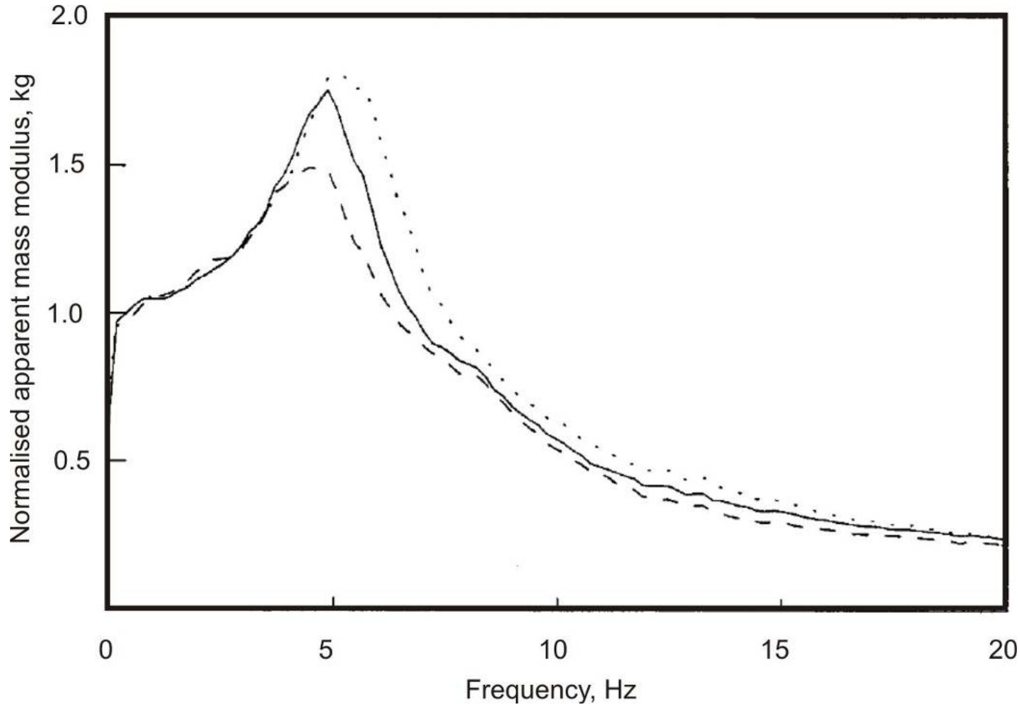

Figure 2.2 Effect of posture on mean normalised apparent masses of eight subjects (1.7 ms^{-2} r.m.s random vibration, no backrest support): ·····, erect posture; ——, normal posture; - - - - slouched posture (from Kitazaki and Griffin, 1998).

Fairley and Griffin (1989) found that increases in resonance frequency varied considerably between eight subjects adopting a more erect posture, and while for some subjects the resonance magnitude increased in the 'erect' posture, for others it decreased (Figure 2.3). The effect of posture was further investigated with one subject as he changed posture from 'slouched' to 'very erect' in five steps. They found the resonance frequency of this subject increased by 1.5 Hz and the resonance magnitude also increased as the posture became more erect.

Of the nine postures investigated in a study by Mansfield and Griffin (2002), the 'kyphotic' (slouched) posture resulted in the lowest resonance magnitude (see Table 2.1 for description of postures), consistent with the differences observed by Kitazaki and Griffin (1998) between similar conditions, and indicating a higher degree of damping when the body is more relaxed. However, contrary to other studies, Mansfield and Griffin found little evidence of changes in posture affecting the primary resonance frequency. Mansfield and Griffin concluded that changes in apparent mass caused by variations in posture were smaller than those caused by changes in vibration magnitude.

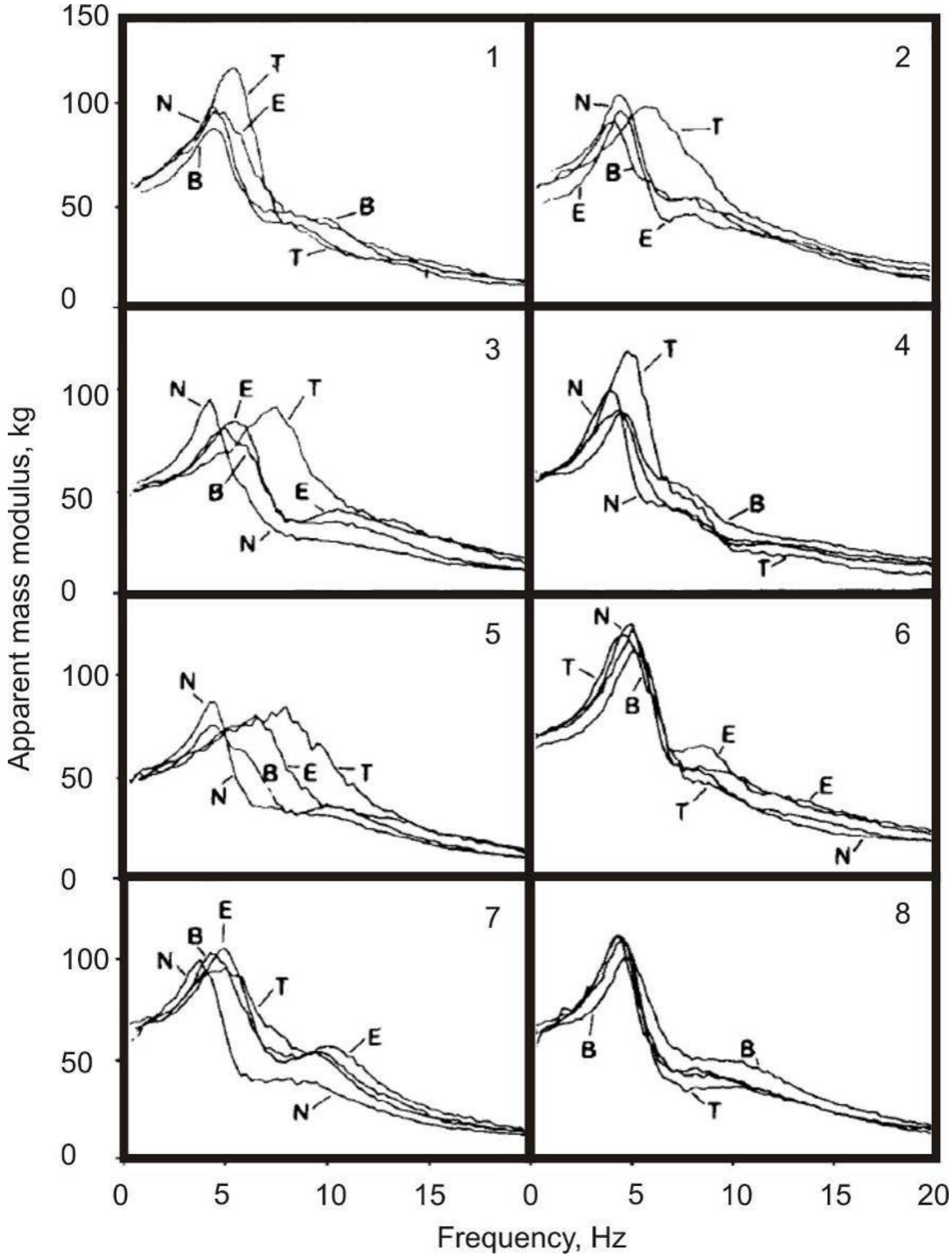

Figure 2.3 Effect of posture and muscle tension on the apparent masses of eight people: N, normal; E, erect; B, backrest; T, tense (from Fairley and Griffin, 1989).

Increasing the steady-state muscle tension of various body parts has generally been found to increase the apparent mass resonance frequency compared to a 'normal' posture (e.g. Figure 2.4). This increase in resonance frequency has been observed when subjects tensed their buttocks or abdomen (e.g. Figure 2.4) or upper-body (e.g. compare Conditions A and B in Figure 2.5).

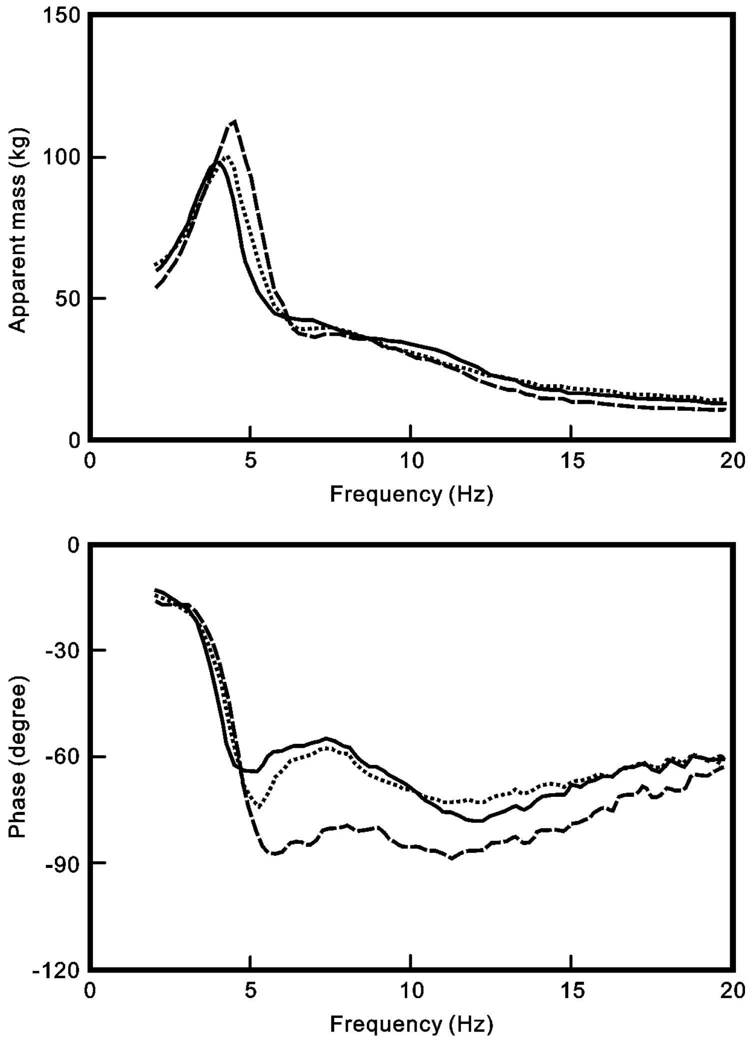

Figure 2.4 Effect of muscle tension on apparent masses of a single seated subject; 1.4 ms^{-2} r.m.s. random vibration: ——— , normal upright; — — — , buttocks tensed; ········ , abdomen minimized (adapted from Matsumoto and Griffin, 2002a).

Changing from a 'relaxed' to 'erect' posture (see Section 2.2.2) increases the activity of the muscles used to stabilise the body (e.g. Blüthner *et al.*, 2002) and consequently increased muscle tension as well as geometric changes may explain the increase in resonance frequency when subjects move to a more erect posture.

The differences in postural effects between studies and between subjects within the same study might be attributed to a number of causes including: variability in subject's interpretation of the postures (e.g. ‘erect’ and ‘normal’), differences in postural control capabilities and strategies, and biomechanical differences between subjects.

Some of the extremes in postures examined in the studies described above and in Table 2.1 are unlikely to be representative of the postures adopted by people in most vehicles. So, while some postures have been shown to affect the apparent mass of some subjects compared to a ‘normal’ posture, the contribution of postural variations to the variability in apparent masses of subjects adopting the same nominal posture (e.g. Figure 2.1) is not clear.

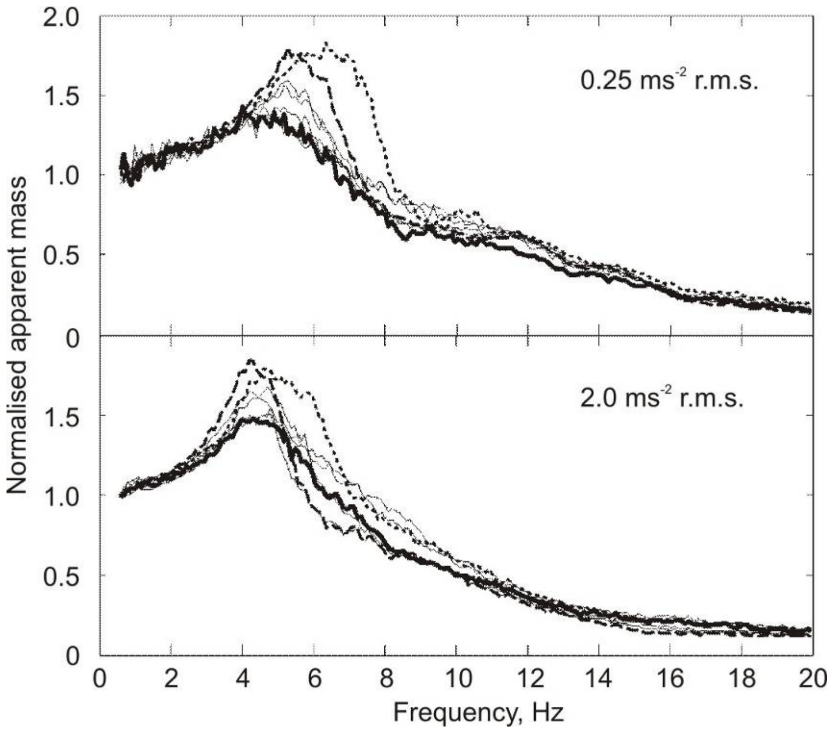

Figure 2.5 Median normalised apparent masses of 14 subjects in seven sitting conditions (A: upright - - - - ; B: upper-body tensed · · · · · ; C: back-abdomen bending ——— ; D: back-to-front ——— ; E: rest-to-front ——— ; F: arm folding ——— ; G: deep breathing ———) at two vibration magnitudes (from Huang and Griffin, 2006).

2.2.3 Buttock pressure and constraints

Movements of the viscera and deformation of the tissue under the pelvis contribute to the primary resonance of the body (Kitazaki, 1994; Matsumoto, 1999). It has been hypothesized that constraining the motion of the soft tissue in these areas would affect the response around resonance.

Kitazaki (1994) hypothesized that increasing the pressure under the buttocks by sitting subjects on 50 x 50 x 10 mm wooden blocks would increase the stiffness of the system, assuming a nonlinear force deflection relationship of the buttock tissue. He found that while with some subjects the resonance frequency increased when subjects sat on the blocks, for other subjects there were no clear effects. More recent studies have found no significant effects of varying buttock pressure on resonance frequency (Nawayseh and Griffin 2003, Mansfield and Griffin, 2002). Nawayseh and Griffin raised the height of the footrest relative to the seat to reduce thigh contact and increase pressure under the ischial tuberosities, while Mansfield and Griffin sat subjects on an 'inverted SIT-bar'. Variability between subjects may explain different findings between studies, differences may also be attributed to postural factors: Nawayseh and Griffin used a footrest attached to the moving platform while Kitazaki used a stationary footrest (see Section 2.2.4.2 – Effect of foot position).

The effects of constraining the movements of the viscera have been studied by a number of researchers. Kitazaki (1994) found that the apparent mass resonance frequency increased when subjects wore a wide belt wrapped tightly around the abdomen and were exposed to vibration at 1.6 ms^{-2} r.m.s. With vibration magnitudes of 0.2 or 2.0 ms^{-2} r.m.s Mansfield and Griffin (2002) found that the resonance frequency increased when subjects wore an elasticated belt compared to an 'upright' posture, but no effect of the belt was found with 1.0 ms^{-2} r.m.s vibration. It was noted by Mansfield and Griffin that the changes in apparent mass between the nine postures examined in their study were less than the changes observed within each posture in responses to variations in vibration magnitude (from 0.2 to 2.0 ms^{-2} r.m.s.).

Table 2.1 Summary of some principal studies on the effects of posture, muscle tension, buttock pressure, and constraints on apparent mass. Unless stated, subjects sat in a relaxed upright posture with no backrest support, hands in lap and horizontal seat pan. Claimed results not statistically tested in italics.

Authors	Subjects, Conditions, Stimuli	Findings
Fairley and Griffin (1989) Fairley (1986)	**Subjects**: 8 male; 24 to 38 yrs 1 subject for investigation into the 'erect posture' **Postures**: 'normal', 'erect', 'tense' **Vibration**: 1.0 ms^{-2} r.m.s.	- *Resonance frequency higher for 'erect', and 'tense' (largest change) postures compared to 'normal' posture* - *Resonance frequency increased by 1.5 Hz when posture of single subject changed from 'slouched' to 'very erect' in 5 steps*
Huang and Griffin (2006) Huang (2008)	**Subjects**: 14 male **Postures**: 'upright', 'upper-body tensed' **Vibration**: 0.25 and 2.0 ms^{-2} r.m.s.	- Increases in resonance frequency in 'upper-body tensed' posture compared to 'upright' posture
Kitazaki (1994)	**Subjects**: 7 male **Postures**: 'upright', 'buttocks constrained' (sat on two wooden blocks (5cm x 5cm x 1cm)), 'Visceral constrained' (wide belt around abdomen) **Vibration**: 1.6 ms^{-2} r.m.s.	- Resonance frequency higher and/or decrease in the modulus in the constrained conditions - Effects varied considerably between subjects
Kitazaki and Griffin (1998)	**Subjects**: 8 male; 20 to 35 yrs **Postures**: 'erect', 'normal', 'slouched' (all with stationary footrest) **Vibration**: 1.7 ms^{-2} r.m.s.	- *Resonance frequency decreased from 5.2 Hz in 'erect' posture to 4.4 Hz in 'slouched' posture* - *Greater shear deformation of the buttock tissue in the 'slouched' posture in the whole-body mode at resonance*
Mansfield and Griffin (2002) Mansfield (1998)	**Subjects**: 12 male **Postures**: 'upright', 'anterior lean', 'posterior lean', 'kyphotic', 'pelvis support', 'inverted sit-bar', 'bead cushion', 'belt' **Vibration**: 0.2, 1.0 and 2.0 ms^{-2} r.m.s.	- Only small changes in apparent mass between postures - Peaks were lower in the 'kyphotic' posture - Resonance frequencies decreased with increasing magnitude in all postures
Matsumoto and Griffin (2002a) Matsumoto (1999)	**Subjects**: 8 male **Postures**: 'upright', 'buttocks tensed', 'abdomen tensed' **Vibration**: 0.35 to 1.4 ms^{-2} r.m.s.	- Mean resonance frequency increased in tensed postures

2.2.4 Seating

Early measurements of the point impedance of the body tended to be made with subjects sitting on a flat rigid seat with no backrest support, with feet in front of them and hands in lap. These conditions do not represent the seating environment of most 'real world' exposures to vibration. Some more recent studies have investigated the effects of the seating environment on the apparent mass of the body. The principal findings of these are summarised in Table 2.2.

2.2.4.1 Seat backrest

For most subjects, making contact with an upright rigid backrest slightly increases the frequency of the primary resonance in the apparent mass compared to a 'no backrest' posture (e.g. Figure 2.3 and Figure 2.6). Fairley and Griffin (1989) suggested that this was caused by an increase in body stiffness when in contact with a backrest. The apparent mass at very low frequencies, where the response tends toward the static mass supported on the platform, decreases when contact is made with an upright rigid backrest, with the mass supported by the backrest increasing by a corresponding amount (e.g. Figure 2.6). This suggests that the vertical backrest is able to support some of the subject weight in shear. After normalisation, the apparent mass between 4 and 10 Hz has been found to be higher when the back is supported by a rigid backrest (e.g. Wang *et al.*, 2004).

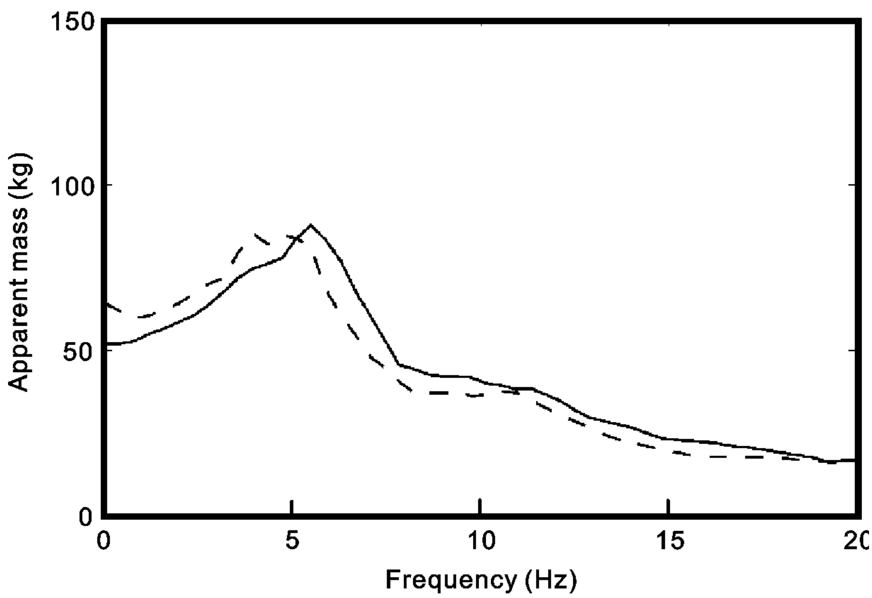

Figure 2.6 Effect of backrest contact on median vertical apparent mass of 11 upright seated subjects (1.25 ms^{-2} r.m.s. random vibration, average thigh contact posture): ——— , with an upright backrest; — — — , without the backrest (from Nawayseh and Griffin, 2004).

Wei (2000) suggested that the resonance frequency was slightly lower when subjects were supported by an upright foam backrest compared to an upright rigid backrest, and that at frequencies greater than the resonance frequency, the apparent mass was lower with a foam backrest than with a rigid backrest, consistent with the foam backrest having less 'stiffening' effect on the body.

The apparent mass resonance frequency increases when a rigid backrest is reclined. With subjects supported by a backrest reclined to 24°, Rakheja *at al.* (2002) found that the mean resonance frequency occurred at 7.8 Hz, considerably higher than reported for studies where there was no backrest support or when subjects were supported by an upright backrest, where the resonance frequency has typically been around 5 Hz (e.g. Fairley and Griffin, 1989). Wei (2000) observed a trend for the resonance frequency to increase and the mass supported on the seat surface to decrease as a rigid backrest was reclined from 0 to 20° (Figure 2.7), but these observations were not statistically tested. A supine posture (i.e. lying down with the face up) might be considered a posture in which the backrest is reclined to 90°. Huang and Griffin (2008) found the mean resonance frequency to be between 7.8 and 9.6 Hz in a semi-supine posture where the upper-body was horizontal, the legs raised and the lower legs horizontal.

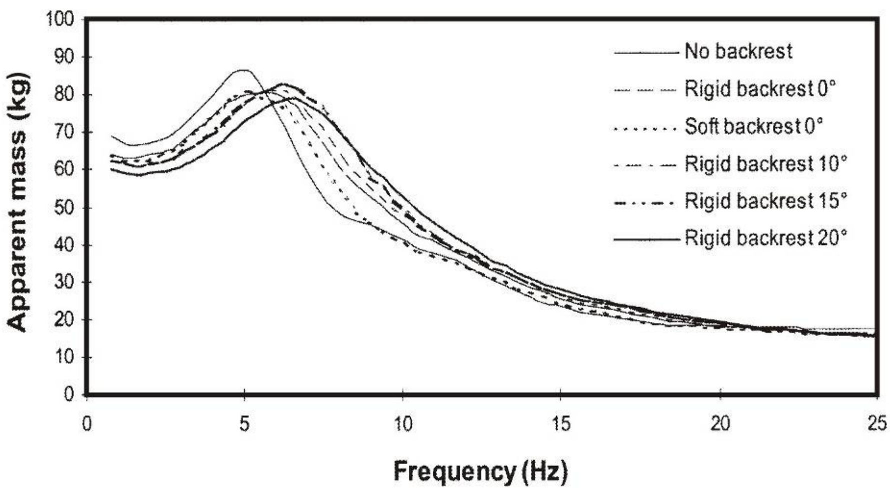

Figure 2.7 Effect of backrest type and inclination on the mean apparent mass of 10 subjects; 0.5 ms^{-2} r.m.s random excitation (from Wei, 2000).

There are no known studies investigating the effect of reclining a foam backrest on the apparent mass. However, it might be expected that there will be greater compressive force acting on a backrest as it is reclined and consequently the dynamic properties of the backrest will have more influence on the apparent mass measured at the seat surface.

2.2.4.2 *Foot position*

Fairley and Griffin (1984) compared the apparent masses of 10 men sitting with and without the support of a stationary footrest. They found that the modulus of the apparent mass at all frequencies was lower for a feet supported posture compared to a feet unsupported posture, but that the resonance frequency was unchanged. They also observed with the feet supported posture that at low frequencies the apparent mass on the seat tended towards a lower value than the weight supported on the seat. In response to this somewhat surprising observation a later study was conducted investigating the height of a stationary footrest on the apparent mass of a single subject (Figure 2.8; Fairley and Griffin, 1989). In the highest foot position (0.28 m above their unsupported level) the apparent mass at 1 Hz was 60 kg (close to static weight supported on the platform), but it was only about 20 kg with the lowest footrest position (where the feet were just touching the footrest). They hypothesized that this effect was caused by the thighs being able to exert a force on the platform in the opposite direction to the force applied by the body at some frequencies, with the effect dependent on the stiffness of the thighs and hence the footrest height. These findings might suggest that the apparent mass on a compliant seat may be different to that on a rigid seat. With conventional foam cushion seats the resonance is typically in the region of 4 Hz, and consequently less than 2 Hz where the effect of a stationary footrest was evident, the seat surface is largely in phase with the motion at the base of the seat. This phenomenon is more likely to be evident with suspension seats where the relative displacements are larger.

Increasing the height of a footrest moving in phase with the seat decreases the mass supported on the seat surface and, as a consequence, reduces the apparent mass at resonance (Nawayseh and Griffin, 2003). A similar reduction in apparent mass at frequencies below resonance was found when increasing the seat height relative to the feet from 410mm to 510mm (Wang *et al.*, 2004). In both of these studies there was no effect of footrest height on the resonance frequency.

Varying the horizontal position of a footrest by 0.15 m has been found to have a negligible effect on the apparent mass (Rakheja *et al.*, 2002). The lack of an effect of horizontal position of the footrest in that study might be explained by the limited range of footrest positions, resulting in the degree of thigh contact and distribution of weight on the seat and footrest being little affected.

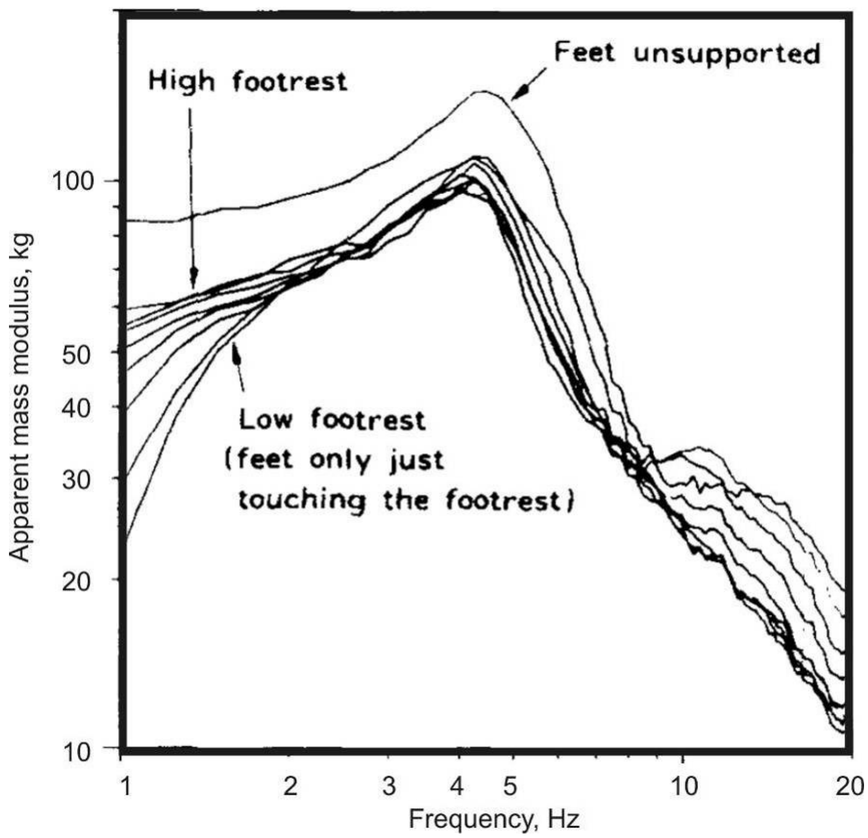

Figure 2.8 Effect of the height of a stationary footrest on the apparent mass of a single subject (from Fairley and Griffin, 1989).

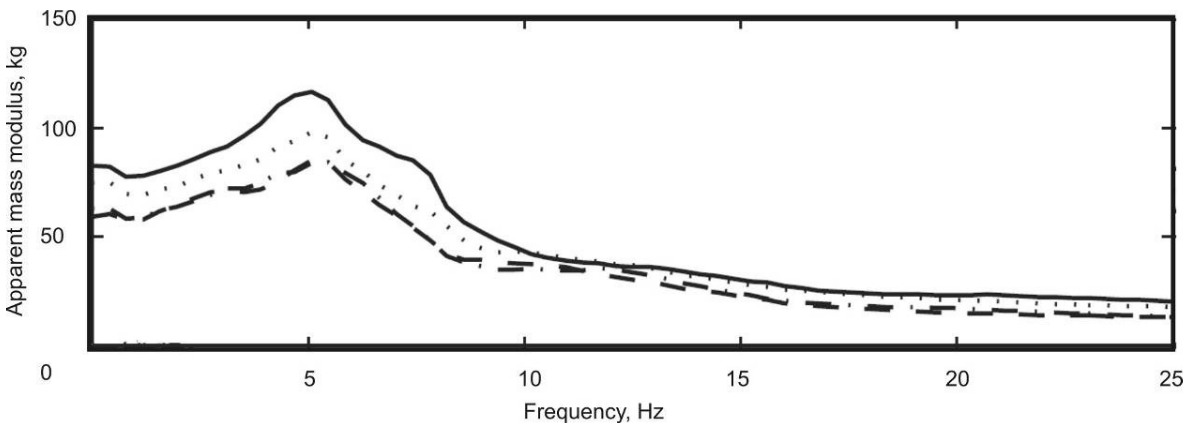

Figure 2.9 Effect of foot position on median apparent mass of 12 subjects with feet moving in phase with seat; 0.625 ms^{-2} random vibration: ——, feet hanging; · · · ·, maximum thigh contact; – · – ·, average thigh contact; - - - - -, minimum thigh contact (from Nawayseh and Griffin, 2003).

2.2.4.3 Hand position

When holding a steering wheel, the peak in the apparent mass of subjects sitting in an 'automotive' posture (inclined backrest and seat pan) decreases slightly both in magnitude and frequency compared to a hand in lap posture (Rakheja *et al.*, 2002; Wang *et al.*, 2004). However when sitting upright with no backrest contact, differences between subjects holding a steering wheel or placing their hands in their laps are much reduced, suggesting an interaction between backrest contact and hand position (Figure 2.10; Wang *et al.*, 2004).

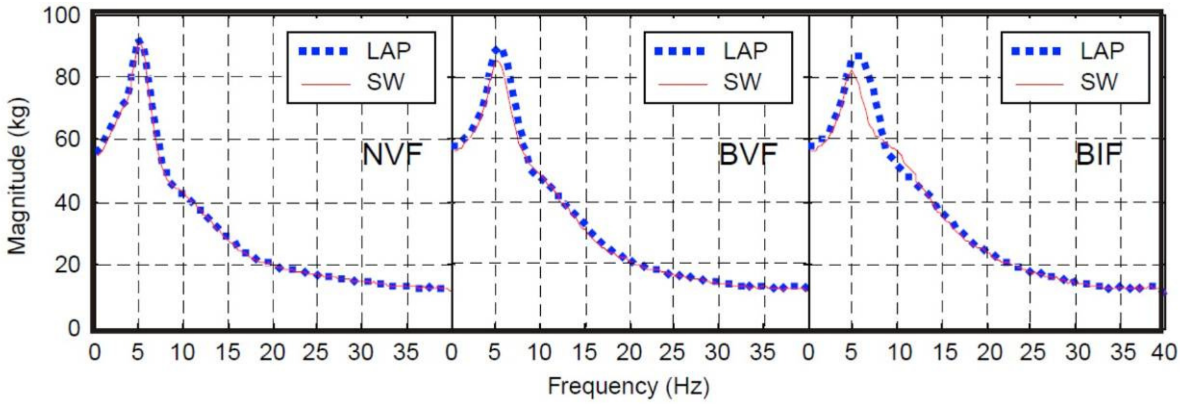

Figure 2.10 Influence of hand position (LAP = hands on lap; SW = hands on steering wheel) and back support condition (NVF = no backrest; BVF = vertical backrest; BIF = inclined backrest (12°)) on the mean apparent mass of 27 subjects; 1.0 ms^{-2} r.m.s. random vibration (from Wang *et al.*, 2004).

Mansfield and Maeda (2005a) measured the apparent mass of subjects in a 'move' posture: twisting to the left and right with arms outstretched unsupported by a backrest. The principal peak in the apparent mass was reduced or eliminated for subjects in this 'move' posture compared to the three other static postures where subjects' hands were placed in their laps (Figure 2.11). They offered two explanations for this reduction in the peak apparent mass: (i) the body movement in the 'move' posture influenced the dynamic response; (ii) that the out of phase movement of the arms relative to the body could have acted to reduce the resultant force at the seat surface. Studies of the vibration transmitted from the seat surface to various body parts may suggest a resonance of the arms in the vicinity of the primary resonance, tending to support the second of Mansfield and Maeda's hypotheses. While sitting upright with arms outstretched, Paddan and Griffin (1995) showed a peak in the transmissibility to the hand between 5 and 6 Hz coinciding with the peak in the apparent mass. Nishiyama *et al.* (2000) observed that the transmissibility to the arms, thighs, and shins was influenced by the angle between the forearm and upper-arm of subjects holding a steering wheel. There are no known studies investigating the effects of varying the extension of the outstretched arms on the apparent mass of the body.

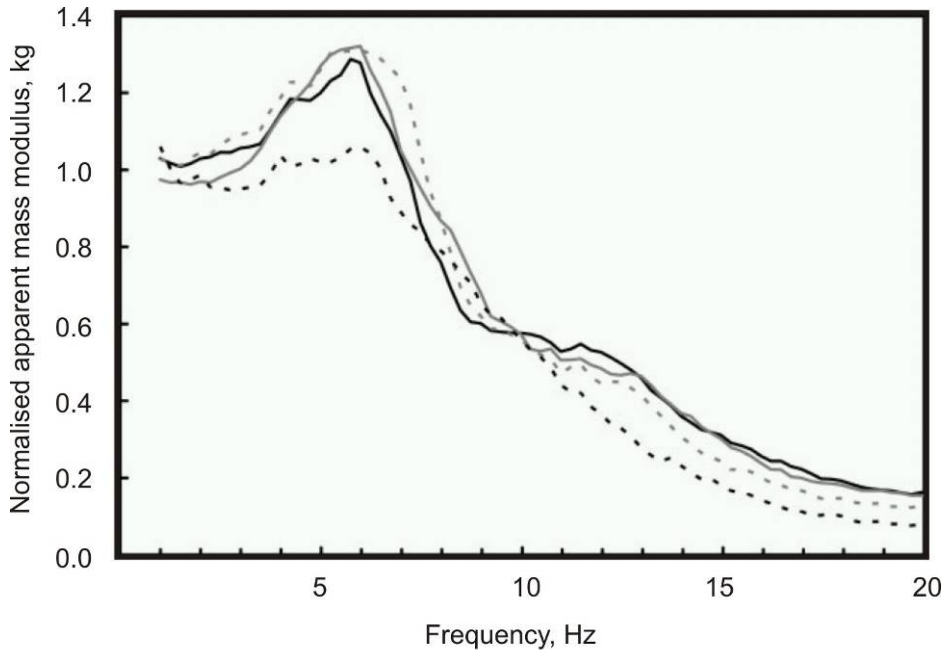

Figure 2.11 Median normalised apparent mass in four postures; 0.4 ms^{-2} r.m.s. random vibration: ——, back off; ——, back on; - - - -, twist; **- - - -**, move (from Mansfield and Maeda, 2005a).

2.2.4.4 Seat pan inclination

The angle of the seat pan is often non-horizontal and varies between vehicles and seats. However, no significant effects on apparent mass have been reported from inclining the seat pan from 0 to 15° when subjects are supported by an upright backrest (Nawayseh and Griffin, 2005) or from varying the seat pan angle from 0 to 7.5° with subjects supported with a reclined backrest (Wang *et al*., 2004). While it might be expected that increasing the seat pan inclination might increase the shear stiffness of the tissue under the ischial tuberosities leading to reduced nonlinearity in the resonance frequency, this effect was not evident in the studies cited above. This suggests that the increase in resonance frequency seen when subjects tense their buttock muscles (see Section 2.2.2 above) was caused by an increase in the axial stiffness of the tissues rather than an increase in the shear stiffness. Alternatively, the range of seat pan inclinations in the studies cited above may not have been sufficient to substantially increase the shear stiffness of the buttock tissue.

2.2.4.5 Seat compliance

Most measurements of the apparent mass of the body have been made on flat rigid seats. However, it has been hypothesized that the response of the body may be different on compliant seats (e.g. Fairley and Griffin, 1986).

The apparent mass of subjects sitting on an automotive was compared to their apparent mass sitting on a rigid seat by Fairley and Griffin (1986), with both seats subjects sat with no backrest support. The apparent mass on the soft seat was determined from the force and acceleration at the seat-person interface. The force at the seat surface was derived by subtracting the dynamic force of the mass of the seat attached to the platform from the dynamic force measured at the base of the seat, the moving mass of the seat was assumed to be negligible. The acceleration on the surface of the soft seat was corrected for the seat response to ensure a flat frequency spectrum. They found that the apparent masses of the people on the soft seat were not significantly different from those on the rigid seat, except for frequencies between 12.25 Hz and 18.25 Hz, where the responses on the soft seat tended to be higher (Figure 2.12).

An alternative to measuring force using a force platform is to use a compliant pressure mat positioned on the seat surface. Pressure mats have been used to measure the static pressure distributions on seats (e.g. Wu *et al.*, 1999) however pressure mats are now also available capable of measuring dynamic pressure. A 'pliance' system (Novel gmbh), comprised of 16 x 16 sensors with each sensor having an area of 6 cm^2, was used in an experiment by Hinz *et al.* (2006) to compare dynamic pressures on a rigid and a soft seat. The measurements indicate that the contact area was less with the rigid seat and the pressure under the ischial tuberosities higher compared to a soft seat (Figure 2.13). Some studies have suggested that the apparent mass can be influenced by increased pressure under the ischial tuberosities, with some subjects having a higher resonance frequency (e.g. Kitazaki, 1994; see Section 2.2.3). This might suggest that the differences in pressure distribution between seats may lead to differences in the apparent mass.

The 'pliance' system was used to measure the apparent masses of subjects on a foam cushion seat where subjects sat supported by a backrest reclined to 10 degrees (Hinz *et al.*, 2006). These apparent masses were compared to those measured with a force platform on a flat rigid seat with no backrest. The authors claimed that the moduli of the apparent masses derived for the soft seat were lower than those determined for the rigid seat, and that the apparent masses on the soft seat showed a similar dependence on the vibration magnitude as the apparent masses on the rigid seat. However, direct comparisons are difficult to establish due to the differences in input spectra, postures, and measurement techniques used with the two seats. The use of pressure mats to measure apparent mass has the potential attraction that it might enable measurements in real seats and vibration environments. However, there is a need for further understanding of the performance and limitations of these devices for making dynamic measurements.

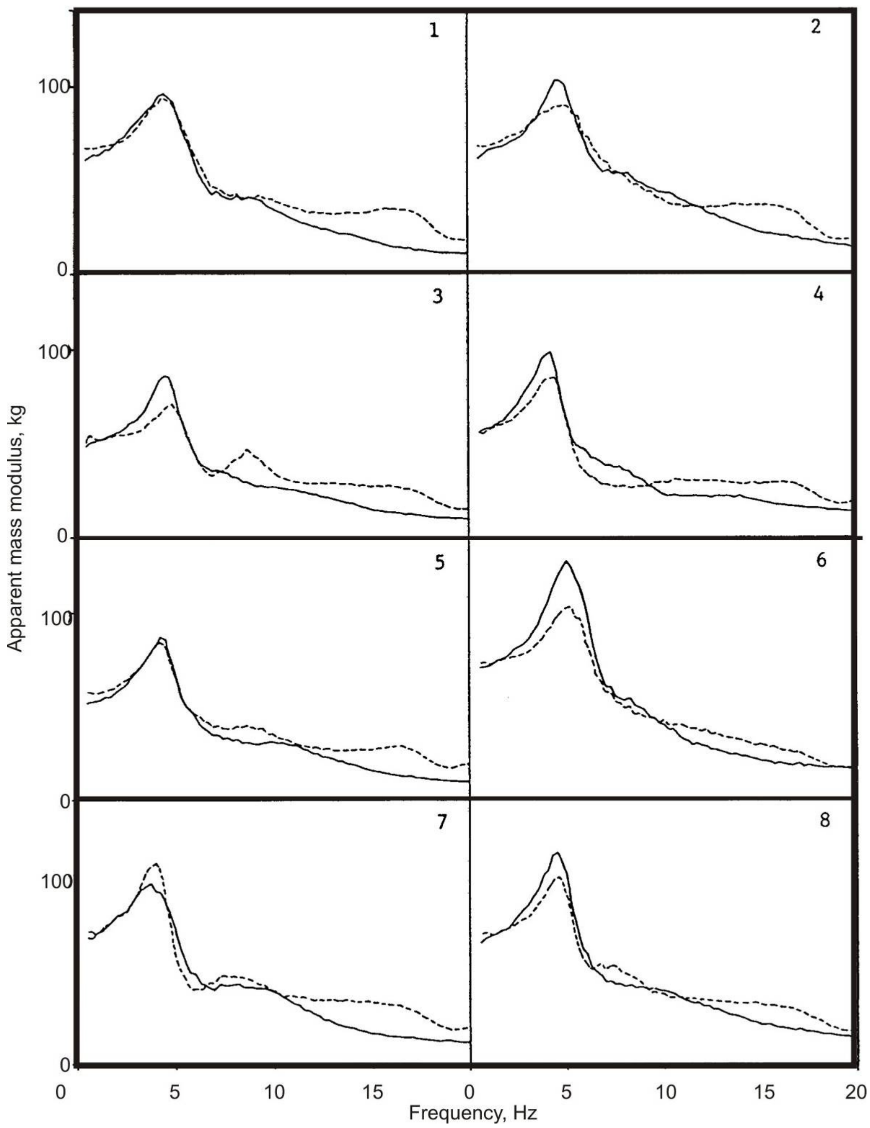

Figure 2.12 Apparent masses of eight people measured on a hard seat (——) and a soft seat (- - - -) (from Fairley and Griffin, 1986).

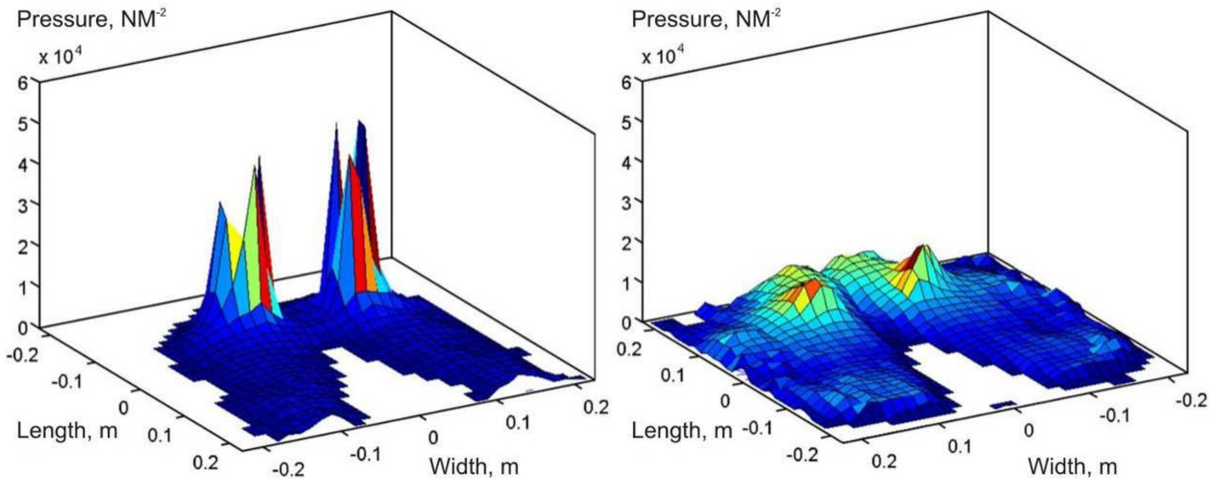

Figure 2.13 Averaged dynamic pressure distributions of one subject measured on a rigid seat with 1.6 ms^{-2} r.m.s. random vibration (left), and on a soft seat (right) with 1.4 ms^{-2} r.m.s. random vibration at the seat base (from Hinz *et al.*, 2006).

Table 2.2 Summary of some principal studies on the effects of seating (backrest, hand position, foot position, and seat) on apparent mass. Unless stated, subjects sat in a relaxed upright posture with no backrest support, hands in lap and horizontal seat pan. Claimed results not statistically tested in italics.

Authors	Subjects, Conditions, Stimuli	Findings
Fairley and Griffin (1986) Fairley (1986)	**Subjects**: 8 male; 24 to 38 yrs **Vibration**: 1.0 ms^{-2} r.m.s. **Posture:** Apparent mass measured on rigid seat and soft seat	- Foam backrest gave higher apparent mass from 12.25 to 18.25 Hz - No difference between resonance frequency or magnitude between rigid and soft seat
Fairley and Griffin (1989) Fairley (1986)	**Subjects**: 8 male; 24 to 38 yrs **Foot position**: ‘Vibrating footrest’ at different heights, ‘Stationary footrest’ **Hand position:** In lap **Backrest:** ‘Upright backrest’ and ‘No backrest’ **Vibration**: 1.0 ms^{-2} r.m.s.	- *Relative movement between stationary feet and seat reduced response below 2 to 3 Hz. Reduction was greatest with the lowest footrest position.* - *Resonance frequency higher for ‘backrest’ posture compared to ‘no backrest’ posture*
Huang and Griffin (2008) Huang (2008)	**Subjects**: 12 male subjects (20 to 42 yrs) **Posture:** ‘Semi-supine posture’ (upper body horizontal, legs raised, lower legs horizontal). **Stimuli:** *z*-axis (*x*-axis relative to subject) at 0.125, 0.25, 0.5, 0.75, and 1.0 m s^{-2} r.m.s	- Resonance frequency of semi supine subjects was between 7.81 and 9.62 Hz - higher than previously reported for seated subjects
Mansfield and Maeda (2005a)	**Subjects**: 12 male subjects (20 to 42 yrs) **Posture:** ‘back on’, ‘back off’, ‘twist’ (hands on laps upper body twisted), ‘move’ (arms outstretched performing moving task) **Vibration**: 0.40 ms^{-2} r.m.s.	- Similar apparent masses in the ‘back on’, ‘back off’ and ‘twist’ postures - Resonance peak attenuated in ‘move’ posture
Nawayseh and Griffin (2003) Nawayseh (2004)	**Subjects**: 12 male; 20 to 47 yrs **Foot position**: 4 vertical foot positions (‘feet hanging’ to ‘minimum thigh contact’). Lower legs vertical **Hand position:** In lap **Vibration**: 0.125, 0.25, 0.625 and 1.25 ms^{-2} r.m.s.	- Resonance frequency unaffected by foot position - Mass supported on seat surface decreased as feet were raised - Nonlinearity least with minimum thigh contact

Nawayseh and Griffin (2004) Nawayseh (2004)	**Subjects**: 12 male; 20 to 46 yrs **Foot position**: 4 vertical foot positions ('feet hanging' to 'minimum thigh contact') with lower legs vertical **Backrest**: 'Upright backrest' and 'No backrest' (from Nawayseh and Griffin,2003) **Vibration**: 0.125, 0.25, 0.625 and 1.25 ms^{-2} r.m.s.	- Higher resonance frequency with back supported - Backrest supported some of the subject mass in shear - Backrest contact did not affect linearity of the body
Nawayseh and Griffin (2005) Nawayseh (2004)	**Subjects**: 12 male, 24 to 47 yrs **Seat pan:** 0, 5, 10, 15° to horizontal **Vibration:** 0.125, 0.25, 0.625 and 1.25 ms^{-2} r.m.s.	- Seat angle had a negligible effect on the apparent mass
Patra *et al.* (2008)	**Subjects**: 27 male subjects **Hand position:** In lap, on steering wheel **Backrest**: No backrest and backrest reclined to 13° **Vibration**: 0.50, 1.0 and 2.0 ms^{-2} r.m.s.	- *Nonlinearity less for back supported posture* - *Hand position had negligible effect on apparent mass*
Rakheja *et al.* (2002)	**Subjects**: 24 (12 male, 12 female); 21 to 53 yrs **Foot position**: 3 horizontal foot positions Δ15cm **Hand position:** In lap, on steering wheel **Seat pan:** 13° to horizontal **Backrest**: 24° to vertical **Vibration**: 0.25, 0.50, 1.0 and 1.07 (road) ms^{-2} r.m.s.	- *Mean resonance 7.8 Hz in 'automotive posture' higher than 'no backrest' studies* - *Peak response lower with 'hands on steering wheel'* - *Horizontal foot position had negligible effect*
Wang *et al.* (2004)	**Subjects**: 24 (13 male, 14 female); 21 to 53 yrs **Hand position:** In lap, on steering wheel **Seat pan:** 0 and 7.5° to horizontal, 3 seat heights (410-510mm) **Backrest**: 24° to vertical **Vibration**: 0.25, 0.50, 1.0 and 1.07 (road) ms^{-2} r.m.s.	- Hands 'in lap' resulted in higher resonance frequency and peak response than hands 'on steering wheel' but only when subject were supported by a backrest - Seat angle had a negligible effect on the apparent mass - Peak response increased with higher seat height - Backrest resulted in higher response above resonance
Wei (2000)	**Subjects**: 10 subjects (9 male, 1 female); 26 to 42 years **Hand position:** In lap, on steering wheel **Backrest**: No backrest, rigid backrest (0,10,15,20°), rigid backrest at 10°, foam backrest (0°) **Vibration**: 0.50 ms^{-2} r.m.s.	- *Resonance frequency lowest in no backrest posture* - *Renounce frequency increased with inclination of rigid backrest* - *Resonance magnitude unaffected by backrest inclination* - *Resonance frequency lower for foam backrest than rigid backrest*

2.2.5 Inter-subject variability

Experimental studies have shown large variability in the apparent masses of subjects measured in the same nominal seating conditions.

The most comprehensive study of the effect of subject physical characteristics on the seated response of the body was conducted by Fairley and Griffin (1989). They measured the apparent masses of 60 subjects (24 men, 24 women, and 12 children) sitting upright on a rigid flat seat with no backrest contact and with lower legs vertical. They found large variations in the apparent mass between subjects at low frequencies, but after normalisation (dividing the modulus of the apparent mass by the static mass supported by the seat) the variability was much reduced (compare Figure 2.1 with Figure 2.14). Most subjects had a principal resonance near 5 Hz, with the apparent mass at this frequency about 40% greater than the static mass. The mean normalised responses of men, women, and children were remarkably similar, suggesting that the effects of age and gender, after accounting for subject weight, were small (Figure 2.15). They used non-parametric correlation tests to determine relationships between physical characteristics and features of the apparent mass. It was found that the weight of subjects supported on the seat divided by their sitting height – thought to be a crude measure of the build of a person – was negatively correlated with their resonance frequency. Subject weight had the most significant correlation with the normalised apparent mass at the resonance frequency. Age was correlated with the normalised apparent mass at 20 Hz. There was no statistically significant effect of subject weight on resonance frequency. Some studies have claimed that the resonance frequency decreases with increasing subject mass (e.g. Rakheja *et al.*, 2002; Patra *et al.*, 2008) although with no statistical support.

Variable effects of gender on the apparent mass the body have been reported. Fairley and Griffin (1989) observed that the mean normalised apparent masses of men and women were similar at all frequencies (Figure 2.15), although this observation was not statistically verified. Wang *et al.* (2004) suggested females have a greater normalised apparent mass than men at frequencies between 15 and 40 Hz, Lundström *et al.* (1998) suggested females have a slightly lower resonance frequency, and Holmlund *et al.* (2000) claimed that females have a less distinct peak in their mechanical impedance than males. Although the effects of subject weight were controlled in these studies, either by normalising the apparent mass or by comparing groups with matched weights, the effects of other characteristics were not controlled, allowing the possibility that apparent effects of gender may have been confounded by the effects of other variables.

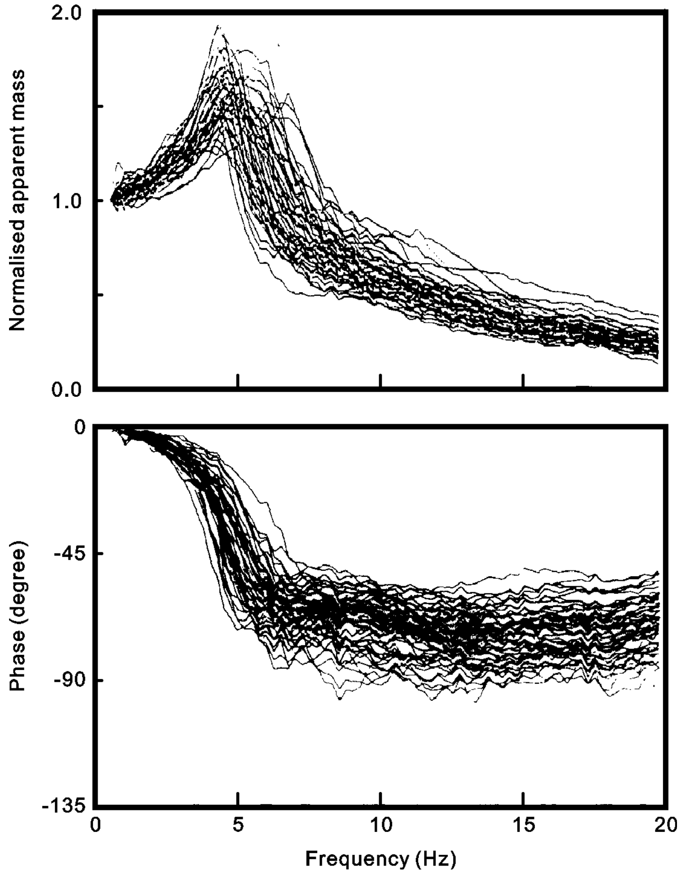

Figure 2.14 Normalised (at 0.5 Hz) apparent masses of 60 seated people (1.0 ms^{-2} r.m.s random vibration, no backrest support) (from Fairley and Griffin, 1989).

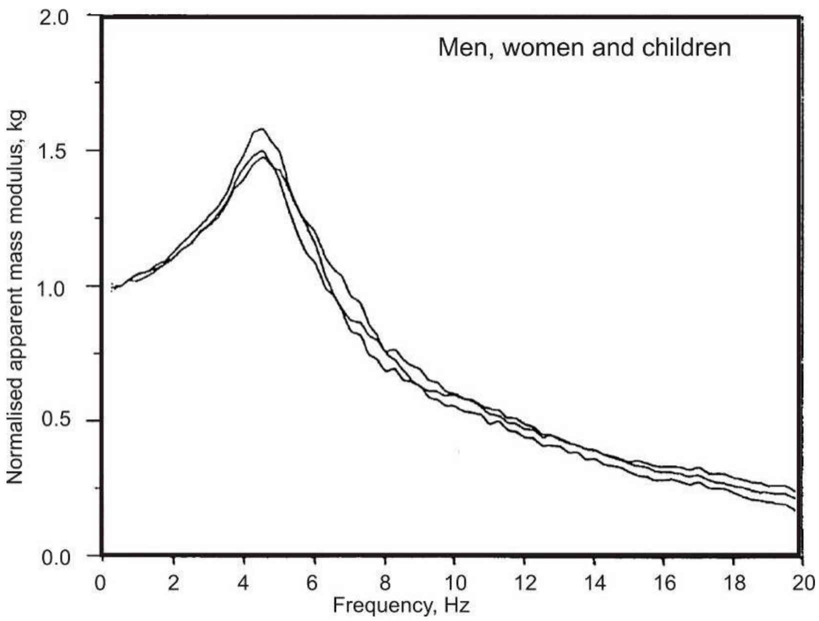

Figure 2.15 Comparison of men, women, and children: mean normalised apparent mass (from Fairley and Griffin, 1989).

While some correlations have been established between anthropometric parameters and apparent mass features, the quantitative effects of these on the apparent mass response are not well understood.

Fairley and Griffin (1989) investigated inter-subject variability in a single measurement condition (no backrest, 1.0 ms^{-2} r.m.s.). It might be expected that the seating condition (e.g. backrest contact and backrest inclination) and the input signal (e.g. magnitude) might affect the variability between subjects. For instance, it might be hypothesized that the use of a reclined backrest might control the motions of the upper-body and reduce postural variations between subjects and hence variations in apparent mass. Similarly, as the magnitude-dependent non-linearity is affected by soft tissue, it might be expected that variations in body composition will influence the degree of non-linearity between people.

2.2.6 Input signal

2.2.6.1 Vibration magnitude

Recent studies have consistently reported that the resonance frequency in the apparent mass of the human body decreases with increasing magnitude of vibration. This nonlinear response has been found for seated subjects (e.g. Fairley and Griffin, 1989), standing subjects (e.g. Matsumoto, 1999), and supine subjects (e.g. Huang, 2008).

Fairley and Griffin (1989) showed that for each of eight seated subjects their apparent mass resonance frequency decreased as the magnitude of broadband random excitation was increased. The mean resonance frequency decreased from 6 to 4 Hz as the vibration magnitude was increased from 0.25 to 2.0 ms^{-2} r.m.s. For subjects who exhibited a second resonance, the frequency of this resonance also tended to decrease with increasing vibration magnitude. Mansfield and Griffin (2000) found similar non-linear behaviour in apparent mass (Figure 2.16), they also found that resonance frequencies in transmissibilities from the seat to various locations on the body decreased with increasing input magnitude.

Mansfield and Griffin (2000) found that changes in resonance frequencies were greater at lower vibration magnitudes (Figure 2.16), with less change between the three highest magnitudes (i.e. 1.5 to 2.5 ms^{-2} r.m.s.;). The reduced nonlinear effect at higher magnitudes may help to explain why in an earlier study Sandover (1978) was led to conclude that there were no appreciable effects of vibration magnitude on apparent mass. Sandover measured the response of a single seated subject with broadband vibration at 1.0 and 2.0 ms^{-2} r.m.s. Inspection of Mansfield and Griffin's data suggest that while there was a consistent reduction in resonance frequency between 1.0 and 2.0 ms^{-2} r.m.s., the effect was small and may not have been noticed by Sandover measuring the response of a single subject.

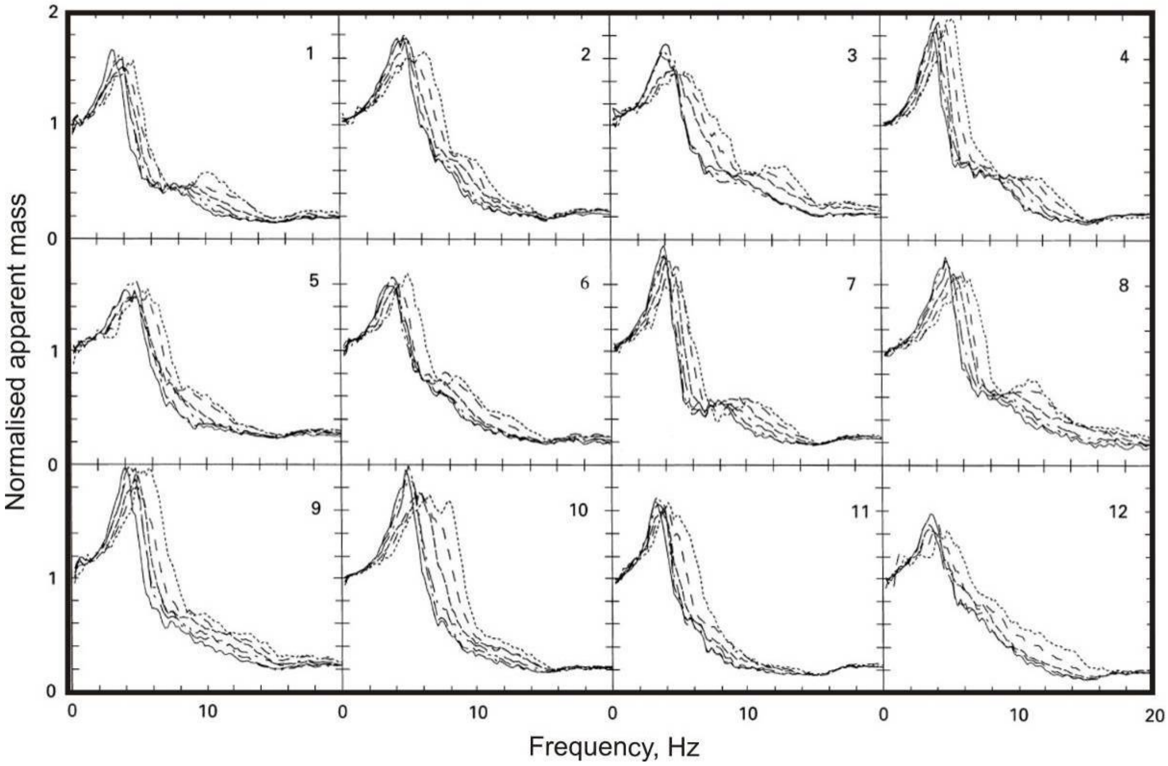

Figure 2.16 Normalised apparent masses of 12 upright seated subjects exposed to broadband (0.2 to 20 Hz) random vibration at 0.25 (·········), 0.5 (- - - -), 1.0 (- - - - -), 1.5 (–· –· –·) , 2.0 (- - ·· - -), and 2.5 (———) ms^{-2} r.m.s. (from Mansfield and Griffin, 2000).

Some studies have found that the apparent mass at resonance does not depend upon vibration magnitude (Fairley and Griffin, 1989; Mansfield and Griffin, 2002; Matsumoto and Griffin, 2002b). However, Nawayseh and Griffin (2003) found that with four different footrest heights the resonance magnitude decreased with increasing magnitude but that the extent of the increase varied between the four footrest positions. In contrast, Mansfield and Griffin (2000) reported that the individual apparent masses and the median apparent mass 'tended' to increase with increasing vibration magnitude (Figure 2.16). The reasons behind the inconsistency in findings is not clear but may be caused by postural differences between the studies as well as inter-subject variability.

2.2.6.2 Waveform

The mechanical impedances of 15 subjects were compared under swept sinusoidal vibration and broadband vibration by Donati and Bonthoux (1983) (Figure 2.17). Although some differences can be observed between the two means, they found no statistical differences between the two stimuli on the impedance at frequencies between 1 and 10 Hz, except at resonance where the sinusoidal vibration resulted in a higher peak. Similarly, few differences were found when comparing apparent masses measured using random vibration and apparent masses measured with sinusoidal vibration at discrete frequencies (1,2,4,8,16 and 32 Hz) (Mansfield and Maeda, 2005b).

Harmonic distortion in driving point force has been found when exciting the body using sinusoidal vibration, indicative of a non-linear response (e.g. Hinz and Seidel, 1987; Huang, 2008). Huang (2008) measured force distortion when subjects adopted a semi-supine posture intended to minimise muscular activity. He found that the harmonic distortion increased at frequencies close to the apparent mass resonance frequency. That the distortion was evident in a relaxed semi-supine posture, where muscular activity was minimized, was cited as evidence of thixotropy being a primary cause of non-linearity as opposed to passive or active muscular activity (see Section 2.2.6.5).

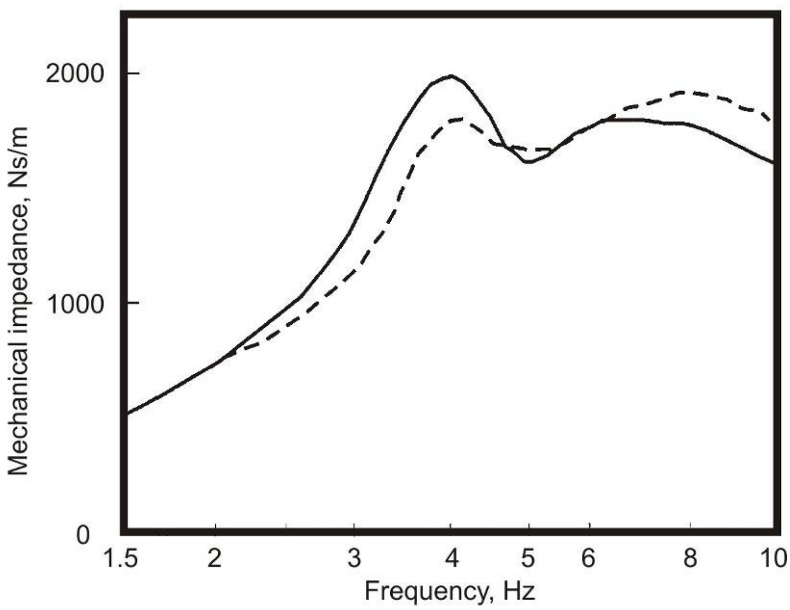

Figure 2.17 Effect of waveform on mean mechanical impedance of 15 subjects measured using broadband random vibration (——) and swept sinusoidal vibration (- - - -) (from Donati and Bonthoux, 1983).

2.2.6.3 Vibration spectra

Most studies investigating the dynamic response of the body have used inputs with equal energy across the frequency range. While these inputs ensure good coherency and repeatability they are not representative of typical exposures. The effect of the frequency composition of input spectra on the dynamic response has received little attention.

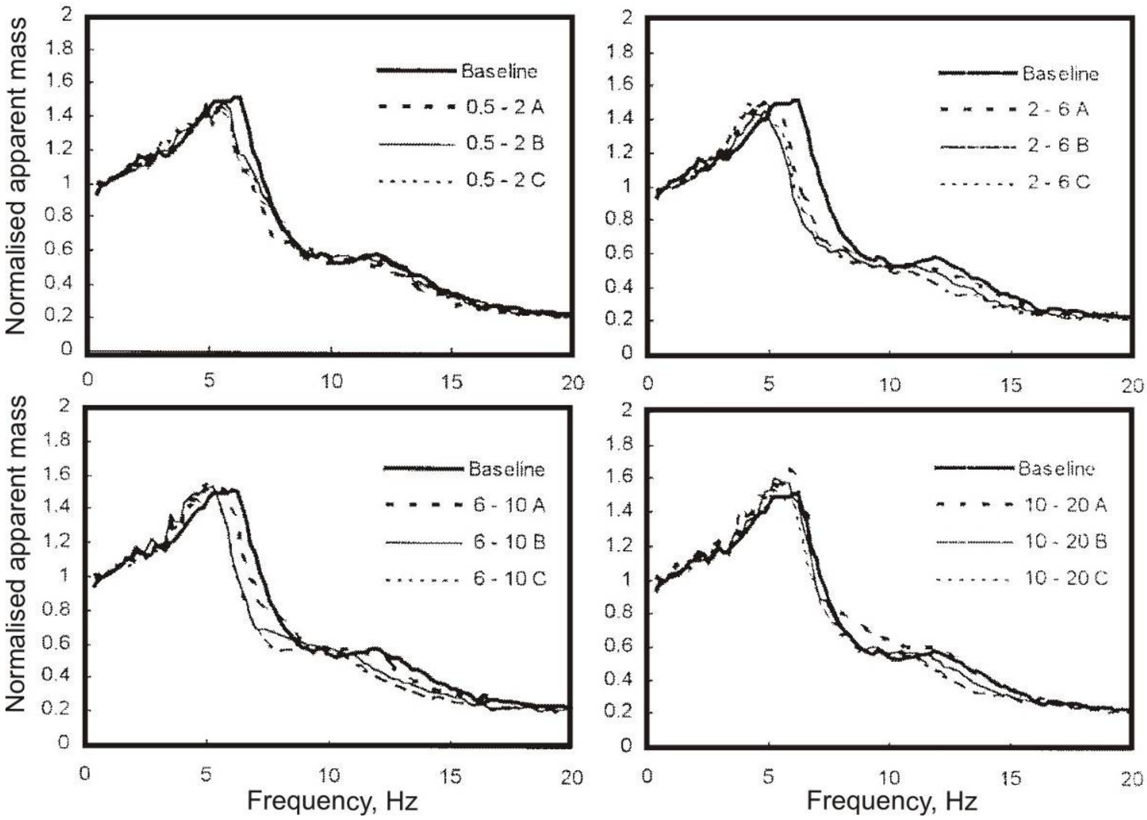

Figure 2.18 Median normalised apparent masses of 10 subjects exposed to 13 different vibration conditions. Stimuli comprised of random vibration (0.25 ms^{-2} r.m.s) with added components of 0.5 to 2.0, 2 to 6, 6 to 10, and 10 to 20 Hz frequency ranges to give overall magnitude of: A=0.5 ms^{-2} r.m.s, B=0.75 ms^{-2} r.m.s, C=1.0 ms^{-2} r.m.s. (from Mansfield, 1998).

Fairley (1986) produced some evidence that the apparent mass around resonance was affected by the input energy at other frequencies. The response of a single subject was measured using low level broadband vibration (0.25 ms^{-2} r.m.s.) with added sinusoidal components at different magnitudes and frequencies. The effects of magnitude on resonance frequency appeared greater with added 5-Hz sinusoidal vibration; the effects were still evident but less marked for added 20-Hz sinusoidal vibration. A similar study was undertaken by Mansfield (1998) using varying levels and frequencies (0.5 to 2 Hz; 2 to 6 Hz; 6 to 10 Hz; 10 to 20 Hz) of narrowband vibration. The narrowband components were added at three different magnitudes to broadband vibration (0.25 ms^{-2} r.m.s, 0.5 to 20 Hz) to give overall vibration levels of 0.5, 0.75, and 1.0 ms^{-2} r.m.s. It was found that changes in the magnitude of the narrowband components changed the apparent mass at frequencies where the magnitude did not change (Figure 2.19). It was claimed that the extent of this non-linearity was similar for all frequencies of narrowband component, leading the author to conclude the non-linearity was acceleration dependent rather than displacement or velocity dependent. Contrary to this claim, Figure 2.19 suggests that the non-linearity was most pronounced when energy was added between 2 and 6 Hz. The statistics used in this study tested for the consistency of changes in resonance frequency with input magnitude within each frequency band but did not directly compare the size of any effects. It is possible that different statistical tests may have found that the extent of the non-linearity depended on the frequency of narrowband component.

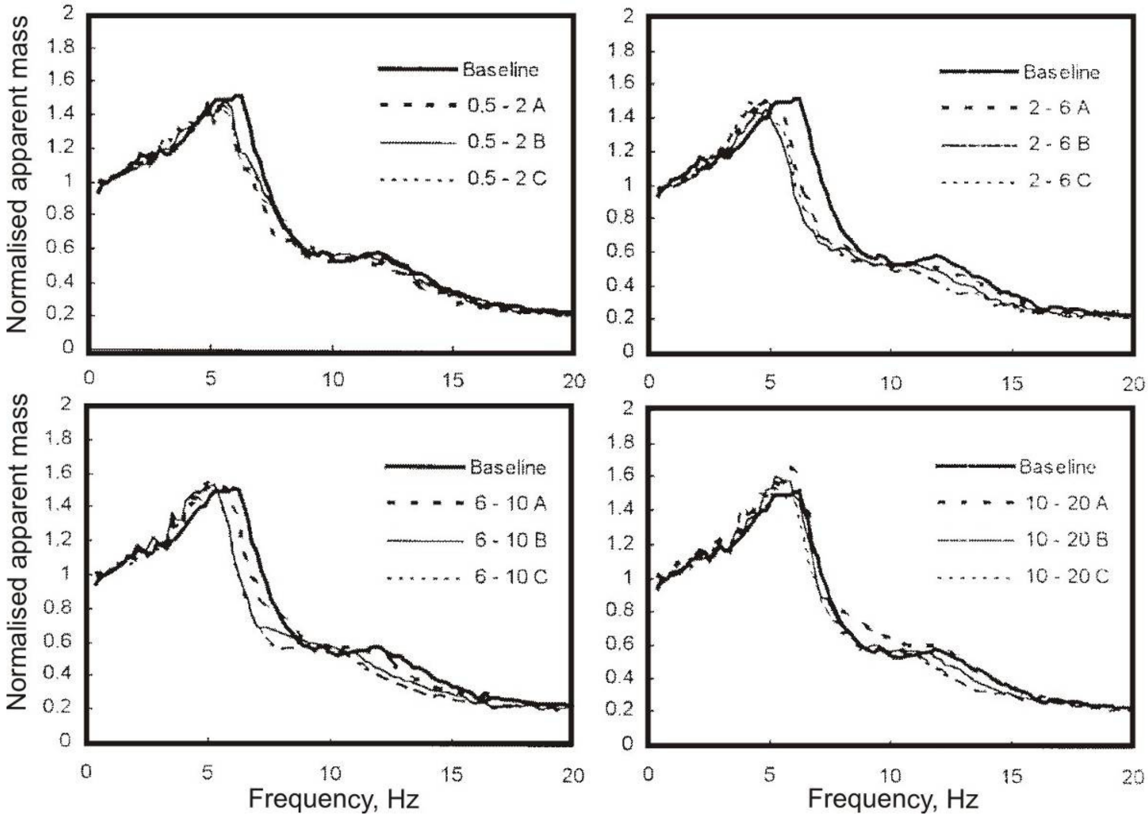

Figure 2.19 Median normalised apparent masses of 10 subjects exposed to 13 different vibration conditions. Stimuli comprised of random vibration (0.25 ms^{-2} r.m.s) with added components of 0.5 to 2.0, 2 to 6, 6 to 10, and 10 to 20 Hz frequency ranges to give overall magnitude of: A=0.5 ms^{-2} r.m.s, B=0.75 ms^{-2} r.m.s, C=1.0 ms^{-2} r.m.s. (from Mansfield, 1998).

2.2.6.4 *Influence of posture on non-linearity*

Various researchers have studied the influence of posture and sitting condition on the extent of the non-linearity in the body.

Rakheja *et al.* (2002) measured non-linearity of the body in an ‘automotive’ posture (reclined backrest and seat pan, legs outstretched) in this posture they claimed the non-linearity was greater when subjects had their hands in their laps compared to their hands on a steering wheel, however this finding was not statistically tested. Wang *et al.* (2004) measured the apparent masses of 27 subjects with three backrest conditions (no backrest, upright rigid backrest, reclined rigid backrest) with two hand positions (hands in lap, hands on steering wheel). The mean resonance frequencies in each posture are shown in Figure 2.20. The authors claimed that irrespective of hand position the reduction in resonance frequency when increasing the magnitude from 0.5 to 1.0 ms^{-2} was greatest in the ‘no back support’ posture (decrease of 0.5 Hz or 0.6 Hz) and least in the ‘inclined back support’ posture (decrease of 0.2 Hz).

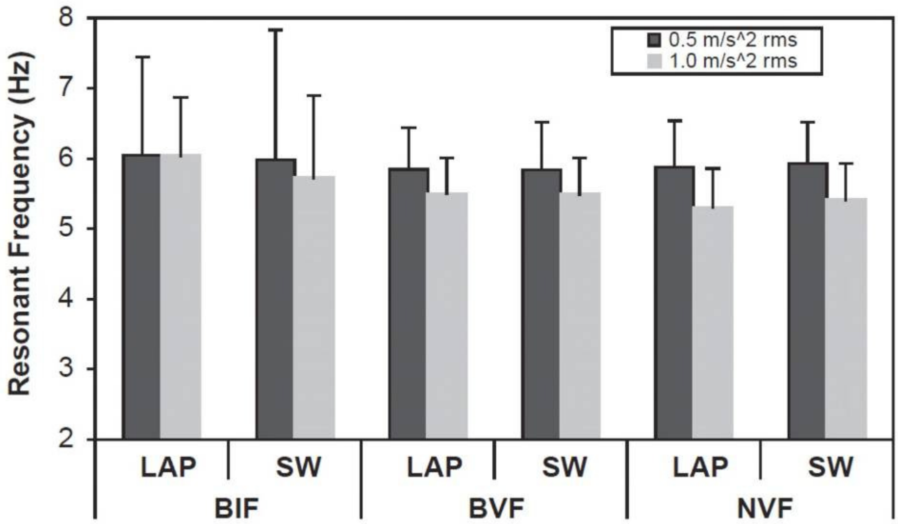

Figure 2.20 Influence of excitation magnitude on apparent mass primary resonance for different postures (mean of 27 subjects). (LAP = hands on lap; SW = hands on steering wheel; NVF = no backrest; BVF = vertical backrest; BIF = inclined backrest (12°)) (from Wang *et al.*, 2004).

Nawayseh and Griffin (2003, 2004) investigated the influence of foot position on the non-linearity with and without an upright backrest. When subjects were supported by the backrest they found that the absolute change in resonance frequency was unaffected by the height of the feet relative to the seat. However, when subjects sat unsupported by a backrest the nonlinearity was least in the highest footrest position ‘minimum thigh contact’.

The authors speculated that the muscle tension required by subjects to maintain this posture may have caused the reduction in nonlinearity, similar to the effect of voluntary increases in muscle tension observed by Matsumoto and Griffin (2002a) (see Section 2.2.2).

The effect of vibration magnitude on semi-supine subjects was investigated by Huang (2008). He found that the median resonance frequency decreased from 10.35 to 7.32 Hz as the magnitude of vertical vibration increased from 0.125 to 1.0 ms^{-2} r.m.s., confirming a non-linear response of the body in this posture. It was assumed that the semi-supine posture would require less muscular control of the body than a sitting or standing posture and therefore the consistent non-linear response in this posture led the author to conclude that the nonlinearity was unlikely to be caused by voluntary changes in tension of the muscles used to control posture.

2.2.6.5 Causes of nonlinearity

Explanations for the causes of the non-linear response of the body can be classified into three main areas: geometric considerations of the body, muscle activity (voluntary and involuntary), and passive properties of the tissues (e.g. thixotropy).

Mansfield (1998) found that a non-linear response was evident in measurements of the transmission of vibration from the seat-to-abdominal wall, seat-to-spine, and seat-to-pelvis. He suggested that the non-linearity was 'caused along a transmission path common to the spine and abdomen'. After discounting other causes of the non-linearity he concluded that the non-linearity was likely to be caused by a bending or buckling response of the spine. This geometric non-linearity was likened to the response of an inverted pendulum, with the pendulum representing the body bending about the ischial tuberosities. However in a later study, Mansfield and Griffin (2000) argued that the greater nonlinearity at low magnitudes of vibration was opposite to the expected response of an inverted pendulum. They also noted a non-linear response in the spine-to-abdominal wall transmissibility inconsistent with the inverted pendulum model. This led them to revise the likely causes of non-linearity to include a combination of factors including the response of the tissues under the ischial tuberosities, bending and buckling of the spine and active response of the muscles.

Involuntary changes in muscle tension refer to the involuntary contractions of muscles not controlled by some central mechanism. Electromyography (EMG) measurements have demonstrated that there are 'phasic' responses of the muscles during vibration. This phasic response involves the muscles trying to react and synchronise with the inertial forces of the body generated by the oscillatory motions. At frequencies greater than 2 Hz, the phasic response is thought to be largely produced by involuntary muscle activity. The phasic muscular activity does not increase proportionally with increasing vibration magnitude, indicating an upper limit in the muscular forces generated by the muscles (Robertson and Griffin, 1989). Voluntary continual contraction of postural muscles (i.e. tonic activity) is required to support the seated and standing body. At higher magnitudes of vibration, increased tonic activity in addition to increased phasic activity may be required to stabilize the body. At higher magnitudes the phasic and tonic muscular activity could effectively 'top-out' and therefore become disproportionate to the vibration magnitude, causing the non-linear response.

Various studies have demonstrated that the non-linearity can be reduced with increased muscle tension (e.g. Matsumoto and Griffin, 2002a; Huang and Griffin; 2006) or increased pressure under the ischial tuberosities (e.g. Nawayseh and Griffin, 2003) compared to a 'normal' sitting posture. These conditions were designed to decrease the involuntary changes in muscle tension during vibration. Although these studies suggest that involuntary changes in muscle tension could contribute to the non-linearity the effects were generally quite small and are contrary to findings of other studies where no effects were found (e.g. Nawayseh and Griffin, 2004). It is possible that changes in the non-linearity were small with increased muscle tension because the phasic activity was not affected.

A considerable reduction in the non-linearity was found when subjects performed voluntary periodic muscle movements (Huang and Griffin, 2006): increasing the input vibration magnitude from 0.25 to 2.0 Hz resulted in a 1.08 Hz reduction in resonance frequency in a 'normal' posture but only a 0.1 Hz reduction when subjects performed periodic back abdomen bending (see Figure 2.5). The authors noted that the periodic movements reduced the resonance frequency at low magnitudes but had little effect on the resonance frequency at high magnitudes. That the non-linearity mostly affected the low magnitudes is consistent with the muscular activity having more influence on the apparent mass where the inertial forces are low. The authors suggested that the voluntary movements may have modified the phasic activity of the muscles and reduced their contribution to the non-linearity. The authors also offered an alternative explanation: that passive properties of the tissues (e.g. thixotropy) could have accounted for the reduced non-linearity when subjects performed voluntary body movements.

Thixotropy refers to the property of some materials to reduce in stiffness during or immediately after vibration. This behaviour has been observed in body tissues (e.g. synovial fluid - found in joints between some bones, and mucus, etc.). Thixotropy has also been observed in the relaxed human finger: the stiffness of the finger decreased after a perturbation was applied, and the stiffness returning back to ‘normal’ after a period of 5 to 10 seconds (Lakie, 1986). Mansfield (1998) conducted an experiment aimed at determining whether the non-linearity in the seated body response was caused by thixotropy. He measured the apparent masses of subjects exposed to continuous random vibration (at 0.2 and 2.0 ms^{-2}) and intermittent random vibration varying between 0.2 and 2.0 ms^{-2} r.m.s. in 60-second intervals. However, he found no significant differences between the resonance frequencies measured with the continuous vibration and during equivalent magnitude periods of the intermittent vibration. This may have been because he had assumed that the stiffness recovery time was such that it would significantly affect the response measured over the 60-second period. If the recover time was much shorter (e.g. 1 second) than the measured stiffness over the 60-second vibration period would be unlikely to reflect any thixotropic response immediately after excitation. Huang and Griffin (2008) performed a similar experiment to Mansfield however they only analysed the initial 2.56 seconds of each period of intermittent random vibration continually varying between 0.25 to 1.0 ms^{-2} r.m.s. Subjects sat in relaxed semi-supine posture to reduce the muscular activity compared to a sitting or standing posture. With the intermittent vibration, the resonance frequency was higher at the higher magnitude (1.0 ms^{-2} r.m.s.) and lower during the lower magnitude (0.25 ms^{-2} r.m.s.) than during continuous vibration at the same magnitudes, consistent with thixotropy being a cause of the non-linearity (Table 2.3).

Table 2.3 Apparent mass resonance frequencies of 12 subjects at two vibration magnitudes (0.25 and 1.0 ms^{-2} r.m.s.) of both continuous and intermittent random stimuli (from Huang and Griffin, 2008).

(A) Resonance frequency (Hz)

Subject	0.25 m s^{-2} rms intermittent	0.25 m s^{-2} rms continuous	1.0 m s^{-2} rms intermittent	1.0 m s^{-2} rms continuous
s1	10.65	11.04	9.18	8.59
s2	9.38	9.47	8.20	8.01
s3	8.01	7.91	7.23	6.84
s4	8.69	8.79	7.71	7.13
s5	9.96	10.25	8.50	8.40
s6	9.18	9.38	7.91	7.62
s7	8.40	8.79	7.52	7.42
s8	10.16	10.25	8.69	8.59
s9	8.98	9.77	7.62	7.32
s10	11.13	11.82	9.77	9.18
s11	8.50	8.20	7.03	7.32
s12	9.86	10.55	8.50	8.79
Minimum	8.01	7.91	7.03	6.84
Median	9.28	9.62	8.06	7.81
Maximum	11.13	11.82	9.77	9.18

2.2.7 International standard ISO 5982 (2001)

International standard ISO 5982 (2001) presents idealized values intended to be used in the development of mathematical and mechanical models representing the dynamic responses of the body. These values take the form of driving point apparent mass (Figure 2.21) and mechanical impedance responses of the seated body. The defined responses are an amalgamation of datasets from studies where subjects were seated on a flat rigid seat with no backrest, maintaining an erect posture, their feet vibrated in phase with the seat, and their hands in their laps. While the mechanical impedance curves in the standard were based on the responses of 65 subjects (50 male, 15 female) measured with excitation magnitudes between 0.5 and 2.0 ms^{-2} r.m.s., the apparent mass curves were based on a more limited dataset. The five apparent mass studies used a total of only 25 male subjects, with excitation magnitudes varying between 1.0 and 3.0 ms^{-2} r.m.s.

The values are said to be applicable to broadband or sinusoidal excitations over the frequency range 0.5 Hz to 20 Hz at amplitudes less than, or equal to, 5 ms^{-2} r.m.s. Single datasets are defined for each impedance function and, as such, the values do not take into account variability known to arise from factors such as posture, input magnitude and subject characteristics. Suitable revision of the standard could take into account the effects of some of these factors; however these revisions would require knowledge of the relative importance of these factors and their effects over ranges of representative conditions.

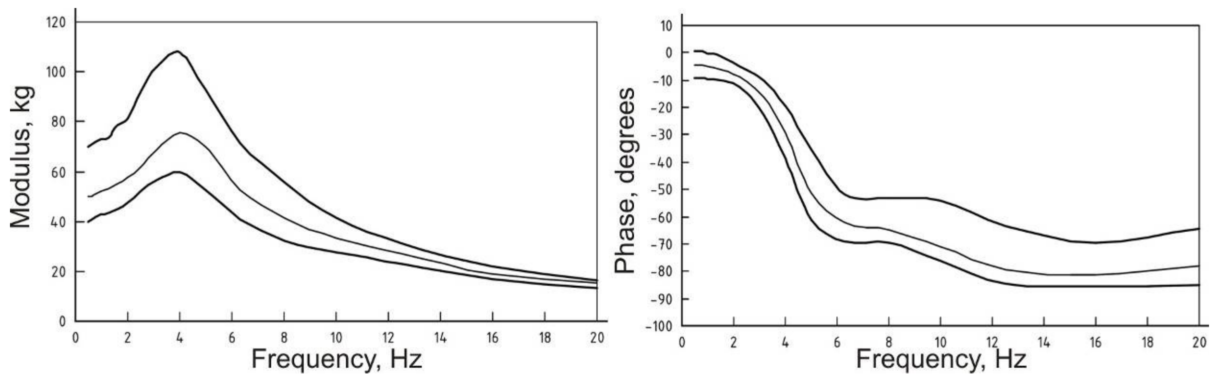

Figure 2.21 Mean (target) and range of idealized values for the apparent mass of the seated body under vertical vibration (from ISO 5982, 2001).

2.3 FACTORS AFFECTING SEAT TRANSMISSIBILITY

2.3.1 Introduction

Seats can be broadly divided into two main categories: conventional foam cushions seats and suspension seats. Conventional seats are typically constructed using a foam cushion on either a rigid or sprung seat pan. Most conventional seats have resonances in the regions of 3 to 4 Hz (e.g. see Figure 2.22). Generally, at frequencies up to around √2 times the resonance frequency (i.e. ≈5 to 6 Hz) the seat amplifies the vibration; at higher frequencies the vibration is attenuated.

In many vehicles there is significant energy in the region of 4 Hz where conventional seats will amplify vibration. Suspension seats have reduced seat stiffness and hence a lower resonance frequency. As such they are able to reduce the vibration transmitted to the occupant at low frequencies compared to conventional foam cushion seat. The response of a typical suspension seat is compared to a sprung cushion foam seat in Figure 2.22. It can be seen that the vibration transmitted between 4 and 8 Hz, where people are most sensitive to vibration, was considerably lower with the suspension seat.

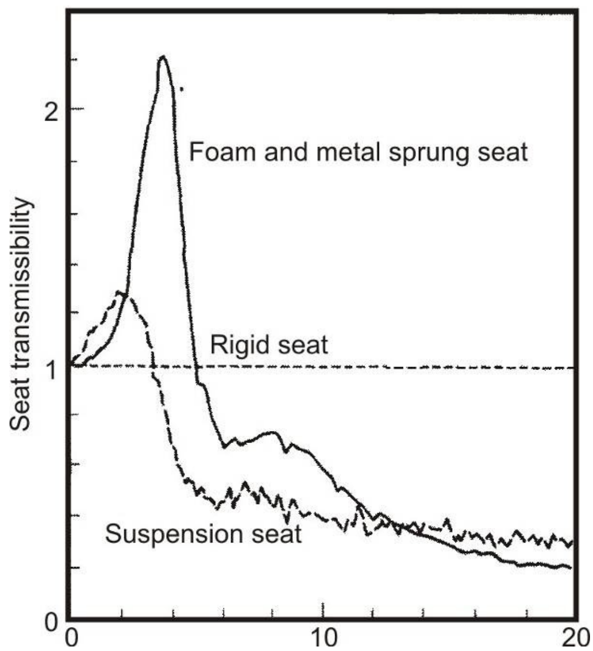

Figure 2.22 Transmissibility of a conventional foam and metal sprung seat compared to a suspension seat and a rigid seat (from Griffin, 1990).

The suspension mechanics generally consists of a spring and damper mounted beneath a relatively firm seat cushion. The low stiffness of these seats can result in substantial deflection of the mechanism under low frequency motions. The vertical travel of suspension seats depends on their application and can vary from 50mm (e.g. some fork lift truck seats) to 200 mm (e.g. for some high-speed marine craft seats). Rubber end-stops are used to minimize the severity of impacts where a seat exceeds its working travel. In some circumstances impacts with these rubber end-stops can cause more discomfort than the vibration itself (Wu, 1994).

Suspension seats tend to be highly non-linear with seats producing substantially different responses for different input magnitudes (e.g. Wu and Griffin, 1996). Sources of non-linearity include those common to conventional seats (i.e. foam non-linearity, non-linearity in the body response) in addition to those specific to suspension seats (i.e. friction in the suspension mechanism, non-linear damper characteristics, and end-stop impacts). Consequently, the effects of varying the input magnitude or input spectra between two seat types may differ considerably.

Due to the low stiffness of suspension seats, increasing the mass of the person supported on a suspension seat affects the ride height of the seat. In order to ensure the seat is operating around the mid-point it is necessary to adjust the preload of the seat to compensate for the weight of the person. Subject weight has also been shown to affect the dynamics of suspension seats with heavier subjects resulting in lower seat transmissibility resonance frequencies (Stayner, 1972); this effect may primarily be due to changes in the seat suspension systems rather than the changes in the seat cushion or the dynamics of the body.

Clearly, the influence of factors affecting the transmission of vibration through conventional seats will be different to those affecting the transmission of vibration through suspension seats (e.g. input magnitude, subject weight). Only the influences of factors affecting the transmissibility of conventional foam cushion seats are considered in the sections below.

2.3.2 Seat properties

The composition and construction of the seat cushion affects the dynamic properties of seats (e.g. see Figure 2.23). Although few studies have systematically investigated the influence of seat cushion properties on seat transmissibility, some studies have shown that some elements of the seat construction can affect the dynamics of the seat.

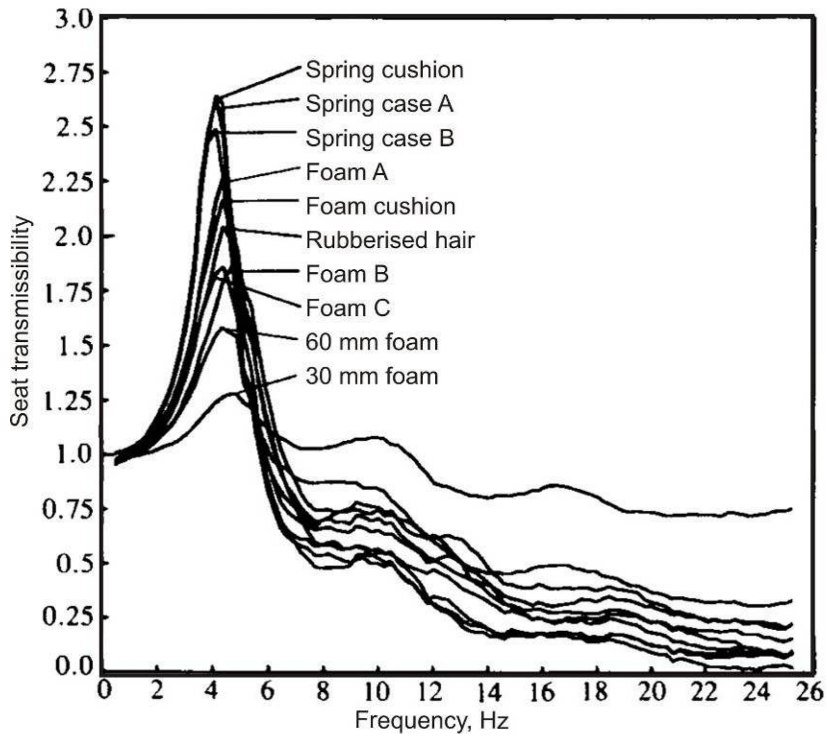

Figure 2.23 Comparison of the vertical transmissibilities of 10 alternative cushions for passenger railway seats with 0.6 ms^{-2} r.m.s. random vibration (from Corbridge *et al.*, 1989).

2.3.2.1 Foam properties

Of seat cushion properties, changing the thickness of foam has generally been found to have the largest and most predictable effects on seat transmissibility. This can be seen in Figure 2.23: comparing the seat transmissibility of railway seats fitted with 30 mm and 60 mm foam cushions (Corbridge *et al.*, 1989). The 60-mm foam yielded a higher peak transmissibility but a lower transmissibility in the frequency range above 6 Hz. The effects of varying foam thickness on seat transmissibility were systematically investigated by Ebe (1998) (Figure 2.24 – bottom right subplot). Increasing the thickness of a foam squab (from 50 to 120 mm) on a flat rigid seat pan resulted in significant increases in the peak transmissibility and significant decreases in the resonance frequency as the foam thickness was increased. If the seat-person system is simplified to a simple single-degree-of-freedom model with the body represented as a mass and the seat as a spring and a damper, the effects observed by Ebe are broadly consistent with a decrease in the spring stiffness.

Ebe (1998) compared the effects of changing foam thickness with those of changing other foam properties (i.e. composition and density). Although the effects were small, there were some significant differences in both resonance frequency and peak transmissibility when varying the composition of foams with the same density (Figure 2.24; top left subplot) or same hardness (Figure 2.24; top right subplot). Changing the foam density (and, by association, hardness) had little effect of the seat transmissibility (Figure 2.24; bottom left subplot). Ebe concluded that changing the foam thickness influenced the vibration transmission more markedly than changing the composition, density, or hardness.

Ebe and Griffin (1994) investigated the transmissibility of an automotive seat fitted with four different foam cushions varying in density from 45 to 65 kgm^{-3} but having the same dimensions and hardness. While only small differences were observed in the transmissibilities measured with the two seats, there were significant differences in subjects' comfort judgements. These differences in comfort judgements may be attributed to differences in the vibration transmitted as well as differences in the 'static' comfort of the seats.

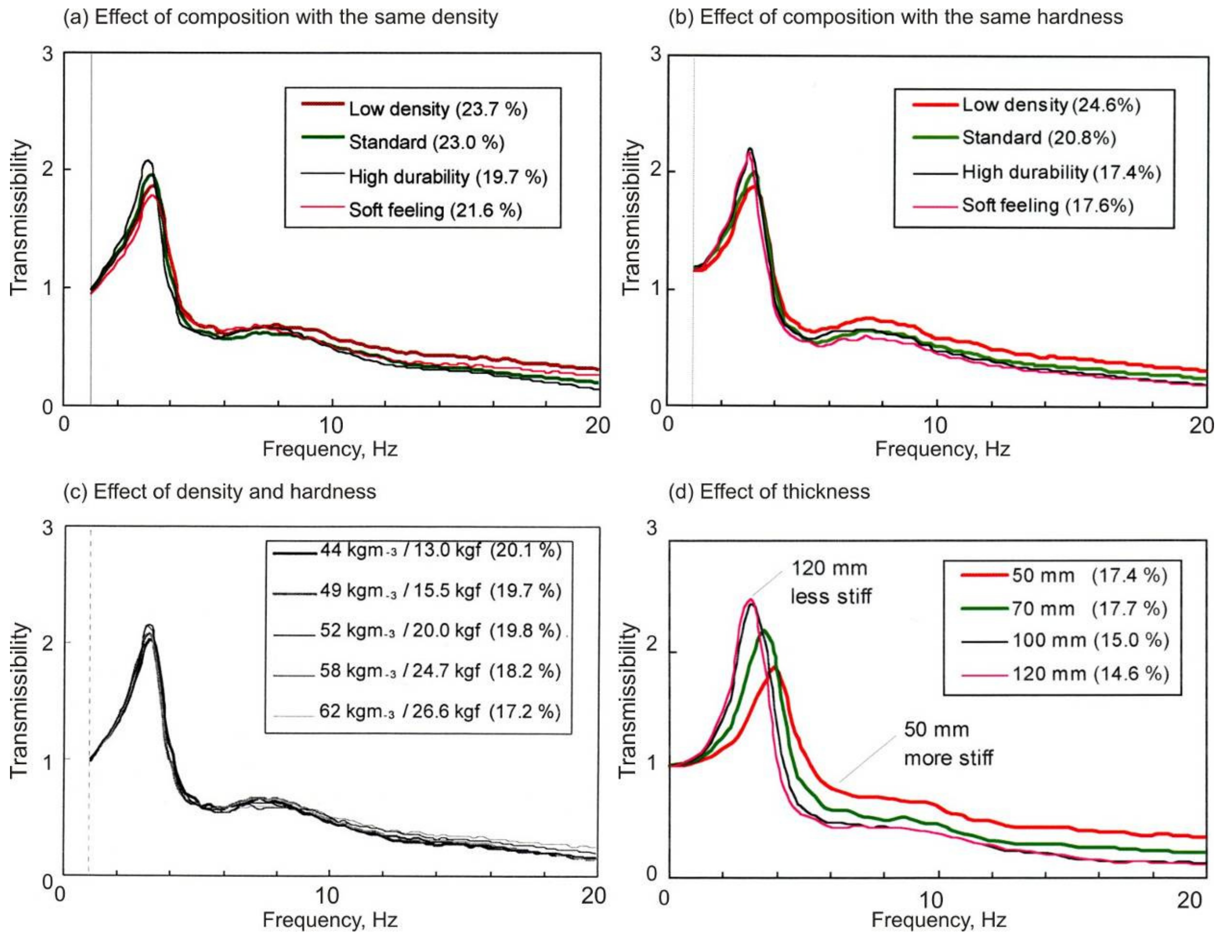

Figure 2.24 Comparison of the effects of foam composition, density (i.e. hardness) and thickness on the vibration transmissibility. Medians of 8 subjects (plots a, b, c) or 12

subjects (plot d) with 1.0 ms^{-2} r.m.s. random vibration. Numbers in parentheses indicate hysteresis loss (adapted from Ebe, 1998).

2.3.2.2 Seat cover

Corbridge and Griffin (1989) found no significant differences in the transmissibility of a train seat measured with and without a calico seat cover. Calico is a woven textile that allows the flow of air. It is possible that less porous fabrics such as leather and PVC may provide greater resistance to airflow and have a greater influence on the dynamics but the influence of these cover materials has not been reported.

2.3.2.3 Seat construction

Corbridge and Griffin (1989) investigated the influence of seat construction on seat transmissibility. They found large differences in the transmissibility measured with 10 constructions of train seat cushions: three were constructed from spring cases, four from foams block, two from foam moulded on a solid wood base, and one from a rubberized hair material. While the resonance frequency was generally around 4 Hz for all seats, the transmissibilities varied considerably: seats that had the higher transmissibilities at resonance (e.g. spring cushion seats) tended to have lower transmissibilities at frequencies greater than 6 Hz, characteristic of a more damped response. In this experiment differences in seat cushion constructions are likely to have influenced numerous seat properties (e.g. density, thickness, composition), and therefore while it is likely that seat construction influences the seat transmissibility, systematic studies are required to investigate the influence of varying the mechanical construction.

2.3.3 Backrest

How much vibration is transmitted through a seat pad cushion depends on the presence and the dynamics of the backrest. Making contact with an upright backrest increases the transmissibility at resonance and the resonance frequency compared to a ‘no backrest condition’ (Corbridge and Griffin, 1989 (Figure 2.25); Fairley, 1986). While decoupling the backrest from the seat structure so that it is able to move freely in the vertical direction reduces the seat transmissibility resonance frequency slightly (from 4.50 to 4.25 Hz) compared to a condition in which the backrest is fixed (Lewis and Griffin, 1996).

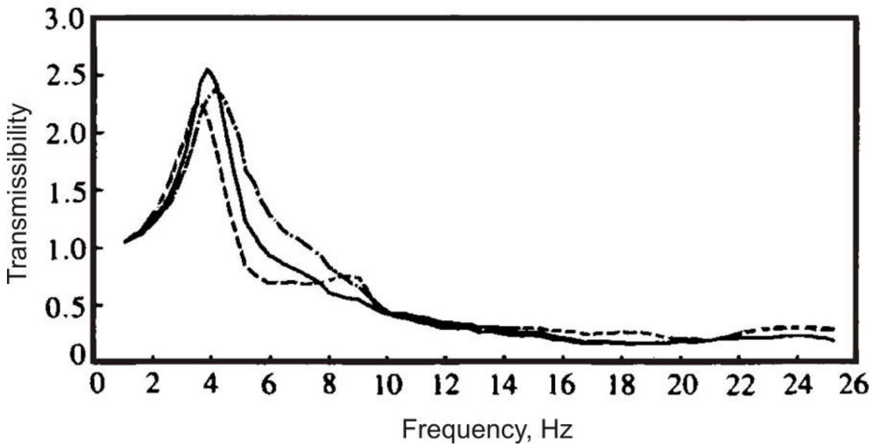

Figure 2.25 Effect of posture on the transmission of vibration through a train seat. Mean of 30 subjects (15 male, 15 female) with 0.6 ms^{-2} r.m.s. random vibration: ——— , normal (with backrest, hands in lap); –· –· –·, arms on armrests (with backrest); and - - - -, back-off (hands in lap) (from Corbridge *et al.*, 1989).

The resonance frequency and transmissibility at resonance systematically increase when reclining a car backrest (Houghton, 2003). In this study Houghton incrementally reclined the backrest of a car seat from 0 to 30 degrees in five degree increments. Houghton claimed that the increase in resonance frequency and increase in peak transmissibility was consistent with a reduction in mass supported on the seat cushion as the backrest was reclined, analogous to decreasing the mass of a single degree-of-freedom lumped parameter model. However, while reducing the moving mass in such a model would lead to an increase in resonance frequency there would be an associated decrease in peak response, contrary to the increase in the peak response seen in the study. A change in the backrest angle in a car seat produces both a change in the posture of the occupant and an alteration in the mechanical properties of the seat itself. It has been shown that the resonance frequency in the apparent mass of the body increases as a rigid backrest is reclined, and that the dynamic stiffness of a seat cushion is affected by the loading and contact area at the seat interface (Wei, 2000). Consequently, it is likely that the changes found in seat transmissibility with backrest inclination were caused not simply by a decrease in mass on the seat surface but by a combination of changes in the dynamic response of the body and changes in the dynamic stiffness of the seat.

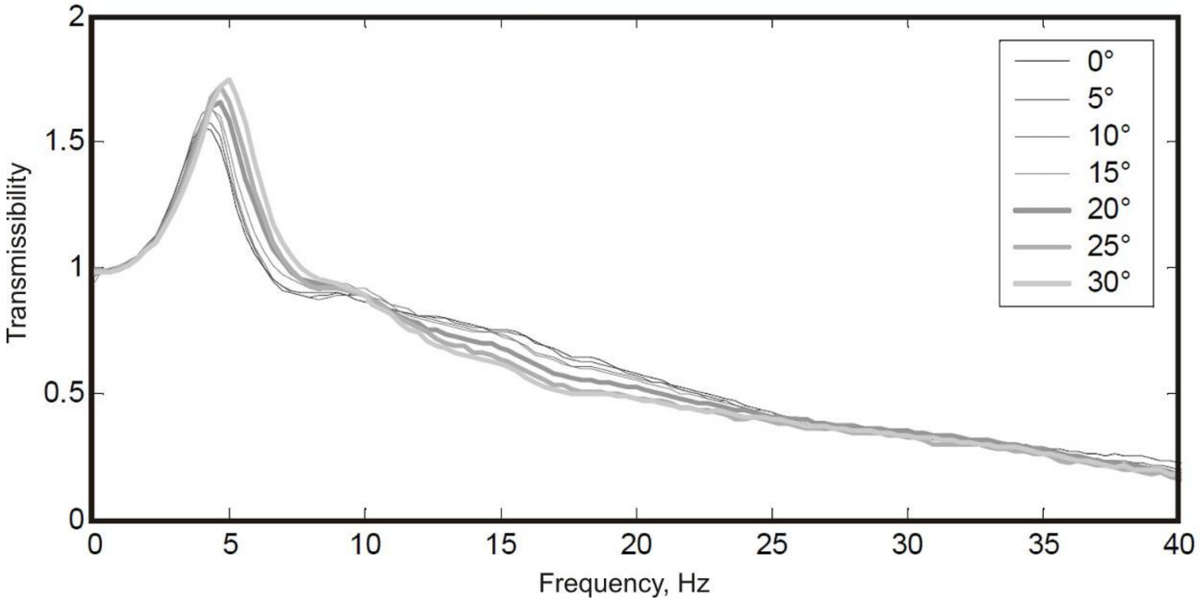

Figure 2.26 Effect of backrest inclination on seat transmissibility, medians of 12 subjects at 1.0 ms^{-2} r.m.s. (from Houghton, 2003).

2.3.4 Foot position

The effect of the height of a stationary footrest on the transmissibility of a seat occupied by a single subject, sitting with no backrest support, was examined by Fairley (1986). The transmissibility at frequencies greater than the resonance frequency, particularly between 6 and 12 Hz, increased as the feet were lowered 0.32 m in 0.04-m steps from the highest position, where there was minimal thigh contact with the seat (Figure 2.27). The author speculated that this effect was due to increased contact between the person's thighs and the seat cushion influencing the dynamic response of the body. The contact area and loading on the seat will have been influenced by the footrest height; these factors influence the dynamic stiffness and damping of the seat (e.g. Wei, 2000), and therefore changes in the dynamics of the seat as well as changes in the dynamics of the person may have affected the seat transmissibility.

There was little effect on the transmissibility of a train seat when subjects moved their feet horizontally from a position in line with the front of a seat to a position where their legs were extended: transmission of vibration at resonance increased slightly and there was an associated decrease in the transmissibility between 5 and 15 Hz (Corbridge and Griffin, 1989). Moving the feet further from the body would likely have increased the contact of the thighs with the seat. The slight decrease in seat transmissibility with increasing leg extension between 5 and 15 Hz appears inconsistent with the findings of Fairley with decreasing footrest height (1986). The footrest in Fairley's study was stationary, while the footrest in Corbridge and Griffin's study moved with the vibrator platform; this difference may account for the contradictory findings.

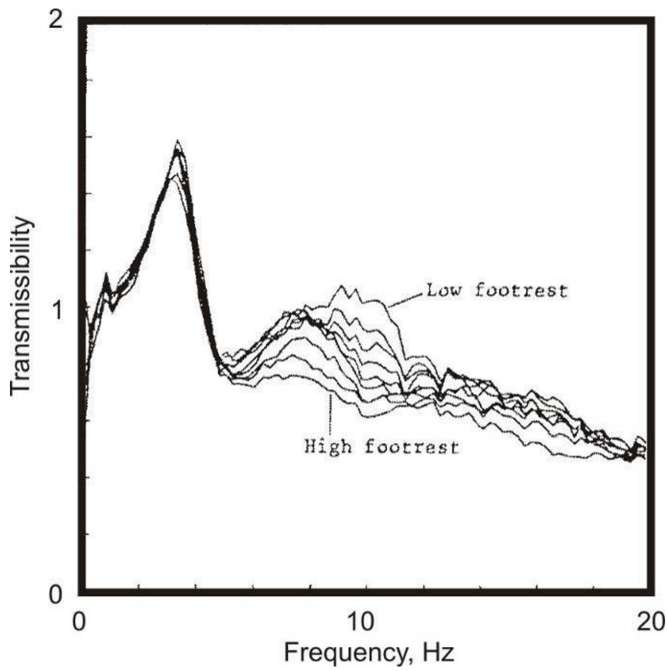

Figure 2.27 Effect of stationary footrest height on the transmissibility of a seat (from Fairley, 1986).

2.3.5 Hand position

In a study with 30 subjects, Corbridge *et al.* (1989) found that the position of a subject's hands can influence the seat transmissibility. When subjects placed their hands on the armrest the peak transmissibility was lower than when in the 'normal' hands in laps posture (Figure 2.25). Transmissibilities were also significantly higher between 4.4 and 9.5 Hz when subjects placed their arms on the armrests. The effects of holding a steering wheel on seat transmissibility have not been reported.

2.3.6 Seat pan inclination

Wei (1998) found that increasing seat inclination decreases the cushion transmissibility around resonance and increases the transmissibility at frequencies above 8 Hz, when subjects sit upright with no backrest support (Figure 2.28). This implies that increasing seat inclination will tend to improve comfort at resonance but degrade comfort at higher frequencies, assuming other aspects of comfort are unchanged (e.g. contact with the backrest). The effect of seat pan inclination with subjects supported by a backrest has not been investigated. The authors noted that the effect of seat pan inclination on seat transmissibility was greater than the influence on the apparent mass (see Section 2.2.4.4). The change of the seat transmissibility may be caused both by changes in the apparent mass and changes in the dynamics of the seat impedance as the seat inclination changes.

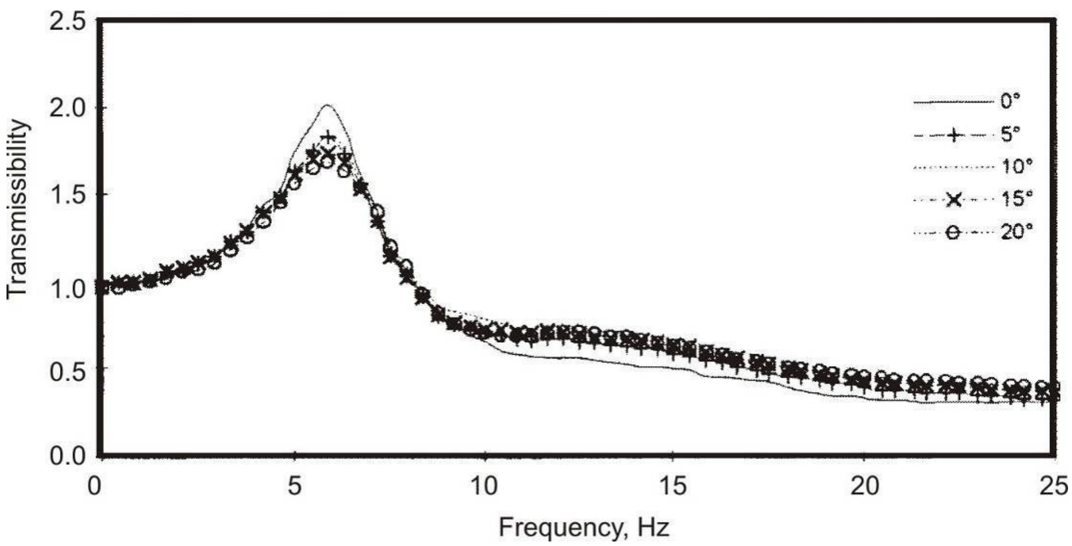

Figure 2.28 Effect of seat pan inclination on seat transmissibility (mean of 10 subjects sitting with no backrest support, 1.5 ms^{-2} r.m.s. random vibration) (from Wei, 1998).

2.3.7 Inter-subject variability

As with the impedance of the body there is considerable variability in seat transmissibilities measured with different subjects (e.g. Corbridge *et al.*, 1989; Figure 2.29). However, although the transmissibilities of seats are widely measured with human subjects, there have been few studies of the effect of subject characteristics on the transmission of vibration through seats.

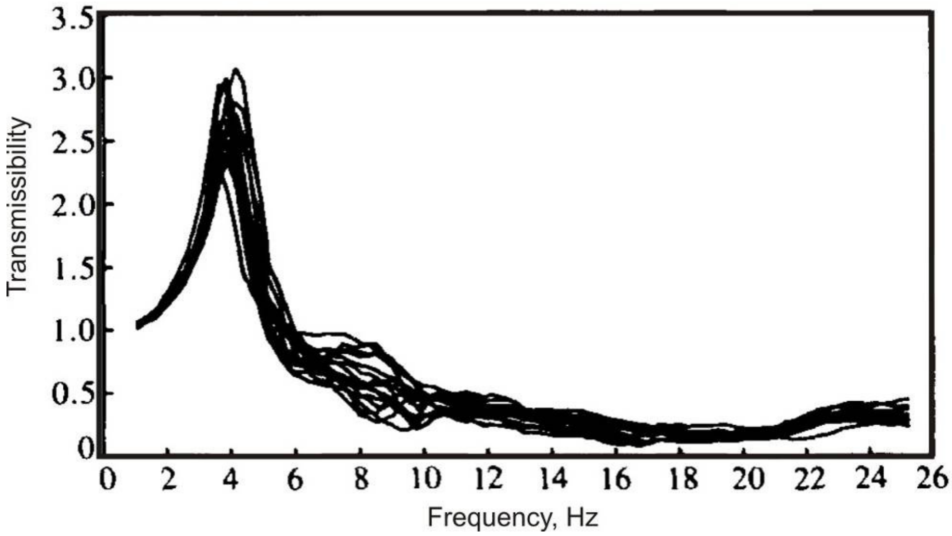

Figure 2.29 Seat transmissibility of a train seat measured with 15 male subjects (from Corbridge *et al.*, 1989).

The resonance frequency and the peak transmissibility of a car seat were claimed to be unaffected by the weight or gender of subjects despite the sitting mass varying between 31 kg and 72 kg (Varterasian and Thompson, 1977). Similarly Corbridge and Griffin (1989) concluded that 'correlations between physical characteristics and the magnitude or frequency of peak transmissibility were 'generally low, and not significant'. They measured the transmission of vertical vibration to the surface of a sprung cushion railway seat while occupied by 15 males (Figure 2.29) and 15 females. Significant positive correlations were found between the age of the female subjects and the transmissibility at resonance as well as the resonance frequency, but no significant correlations were found between the ages of the male subjects and these transmissibility features. It is of note that of the male subjects only three were aged over 35 years, whereas nine of the female subjects were aged over 35 years. The greater spread of age in the female subject group may explain the differing effects of age between gender groups, with any effects being more noticeable in the female group. There was a negative correlation between the weight of the female subjects and the frequency of peak transmissibility (this correlation was not significant for the male subjects) but the effects of other characteristics were not controlled, allowing the possibility that apparent effects of weight may have been confounded by the effects of other variables (e.g. age). No significant differences were found at any frequency between the male and female subject groups. Similar results were found when the experiment was repeated with the subjects adopting five different postures in the seat and with the seat exposed to three vibration inputs (Corbridge, 1987). The direction of the correlations of age with the features of the seat transmissibility were similar in all conditions but were not always statistically significant. The negative correlation between subject weight and resonance frequency of the female subjects was only significant in one condition (no backrest, hands on lap, feet 200 mm from front of seat). In both studies the authors found no consistent trends in the correlations between gender, stature, inside leg length, or the seat-heel distance with the seat transmissibility resonance frequency or transmissibility at resonance.

The lack of any strong correlations between subject weight and seat transfer functions may appear surprising: if a seat-person system is represented as a single degree-of-freedom system, where the resonance frequency is determined by the ratio of the stiffness to mass, an increase in mass might be expected to decrease the resonance frequency. The lack of effect might be explained by compensatory variations in the seat properties and/or the body dynamics with changing subject weight. If heavier subjects had a higher 'stiffness' this could act to counteract the effects of their increased mass on resonance frequency, however Fairley and Griffin (1989) showed that there was no effect of subject weight on the apparent mass resonance frequency. An increase in the seat stiffness in the simple model described above would also tend to increase the transmissibility resonance frequency counteracting the effects of increased mass. Using an indenter rig the dynamic stiffness and, to a lesser extent, the damping of a seat foam was found by Wei and Griffin (1998b) to increase with increasing static load with forces up to 600 N, with forces above this the stiffness and damping began to reduce. Similarly, White *et al.* (2000) measured the dynamic stiffness of a 7.6 cm cube of automotive foam under varying static compressions: the dynamic stiffness increased by a factor of three as the static compression was increased from 15 to 60° but there was no systematic effect on the damping (White *et al.*, 2000). It is likely that the weight of a person is correlated with their contact area with the seat and therefore it is likely that any changes in seat dynamics with subject weight will be caused by a combination of changes in loading and changes in the contact area.

2.3.8 Input signal

Fairley (1986) measured the transmissibility of a sprung cushion car seat with six people and six magnitudes of vibration between 0.2 and 2.5 ms^{-2} r.m.s (Figure 2.30). The mean resonance frequency decreased from 5 to 3 Hz and the transmissibility at resonance decreased from about 1.9 to 1.5 as the magnitude of vibration was increased. A second resonance was observed and was also found to decrease in frequency (from 10 to 7 Hz) as the vibration magnitude was increased. Other authors have found broadly consistent results (e.g. Leatherwood, 1975; Corbridge, 1987).

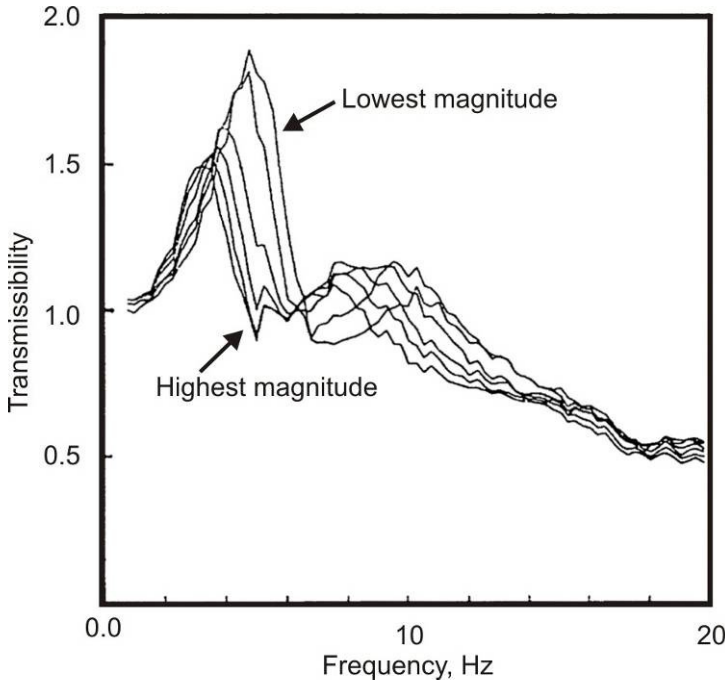

Figure 2.30 Effect of magnitude on seat transmissibility (mean of eight subjects with six different magnitudes of random vibration (0.2, 0.5, 1.0, 1.5, 2.0, 2.5 ms^{-2} r.m.s.) (from Fairley, 1986).

Non-linearity in seat transmissibility may arise from changes in the response of the seat as well as changes in the response of the person with input magnitude. The resonance frequency in the vertical apparent mass of the seated human body reduces as the magnitude of the vibration excitation increases (see Section 2.2.6.1). The dynamic properties of seat foam have also been shown to be non-linear (e.g. Wei, 2000; White *et al.*, 2000). Wei measured the dynamic properties of five different seat foams using an indenter rig with five different shaped indenter heads. A massless single degree-of-freedom model and a curve fitting technique were employed to derive the stiffness and damping of the foam. He found that with two of the foams the resonance frequency consistently decreased, with all indenter heads, when the vibration magnitude was increased from 0.25 to 2.5 ms^{-2} r.m.s. With three of the foams no large or consistent differences with increases in vibration magnitude were found. White *et al.* (2000) measured the dynamic behaviour o*f* 7.6 cm cube of foam cut from an automotive seat using a rigid mass mounted on top of the foam cube. They found that with compression levels of 30, 40 and 50% that the resonance frequency of the system decreased as the input magnitude was increased from 0.1 g to 0.25 g. The nonlinear elastic and linear viscoelastic parameters in a foam model representing the system varied with excitation amplitude, particularly the nonlinear stiffness parameters. The relative contributions of seat dynamics and body dynamics to the non-linearity in seat transmissibility have not previously been quantified.

Non-linearity in the apparent mass of the body is affected by input spectra: the magnitude of vibration at low frequencies has the greatest effects on resonance frequency (see Section 2.2.6.3), so it might be expected that a similar dependence on vibration frequency might also affect the non-linearity in seat transmissibility. Corbridge (1987) found that the transmissibility of a train seat measured with a recorded train motion at 0.33 ms^{-2} r.m.s. was more similar to the response measured with broadband motion at 0.6 ms^{-2} r.m.s. than the response measured with broadband motion at 0.3 ms^{-2} r.m.s. Inspection of the power spectra densities of the motions indicates that below 5 Hz the recorded train motion had similar input energy to the 0.6 ms^{-2} r.m.s. broadband motion, indicating that the magnitude of vibration at low frequencies has the greatest effects on seat transmissibility.

2.4 MODELLING THE SEATED BODY

2.4.1 Introduction

Most published measurements of the transmission of vibration through seats have been made with the seat occupied with a human subject. This is often unsatisfactory as there may be large variations in the results between subjects and also when using the same subject on different occasions. To control for the variability between subjects multiple subjects can be tested, however this comes with associated cost and time implications. Furthermore, there are ethical considerations in testing seats using human subjects: simulators must be safe for human exposure with mechanical and electrical safety features; and experiments should be passed by an informed safety and ethics committee. For the reasons cited above, methodologies have been proposed that do not require the use of human subjects. These approaches can be broadly classified into two general categories: (i) mechanical analogues to use on seats in place of human subjects, and (ii) mathematical models of the seat-person system. Both these approaches require knowledge of the dynamic responses of the body.

2.4.2 Response models

Fairley and Griffin (1989) showed that a one degree-of-freedom lumped parameter model (equivalent to model 1b in Figure 2.31) gave a good fit to the mean apparent mass of 60 subjects. There was evidence of a second resonance in some individuals' curves, and - a later study (Wei and Griffin, 1998a) showed that for these subjects a second degree-of-freedom (models 2a and 2b; Figure 2.31) was required to fully represent this resonance (Figure 2.32). Fairley and Griffin argued that as the frequency and prominence of the second resonance varied considerably between subjects, its effects were small in the average data and a single degree-of-freedom model may be sufficient for many applications.

Wei and Griffin (1998a) demonstrated that a one degree-of-freedom model with a rigid frame mass (model 1b, Figure 2.31) gave a better fit to the apparent masses measured by Fairley and Griffin (1989) than the model with no support structure (model 1a). However, when fitting to the individual data, Wei and Griffin found that a two degree-of-freedom model with two masses suspended from a common support frame (model 2b) was able to give a better fit to the phase and a better fit near resonance than either of the one degree-of-freedom models (Figure 2.32).

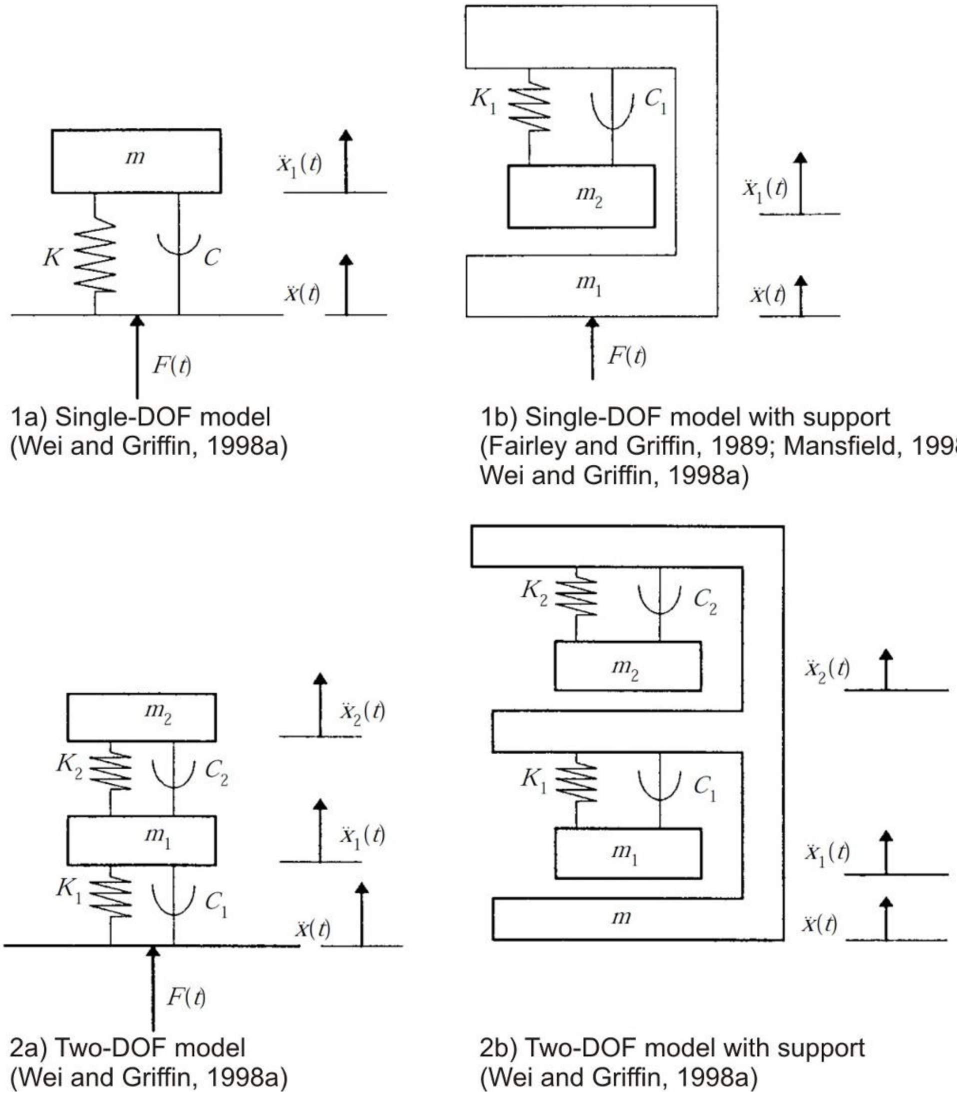

Figure 2.31 Lumped parameter models used by Fairley and Griffin (1989), Mansfield (1998), and Wei and Griffin (1998a). All figures taken from Wei and Griffin (1998a).

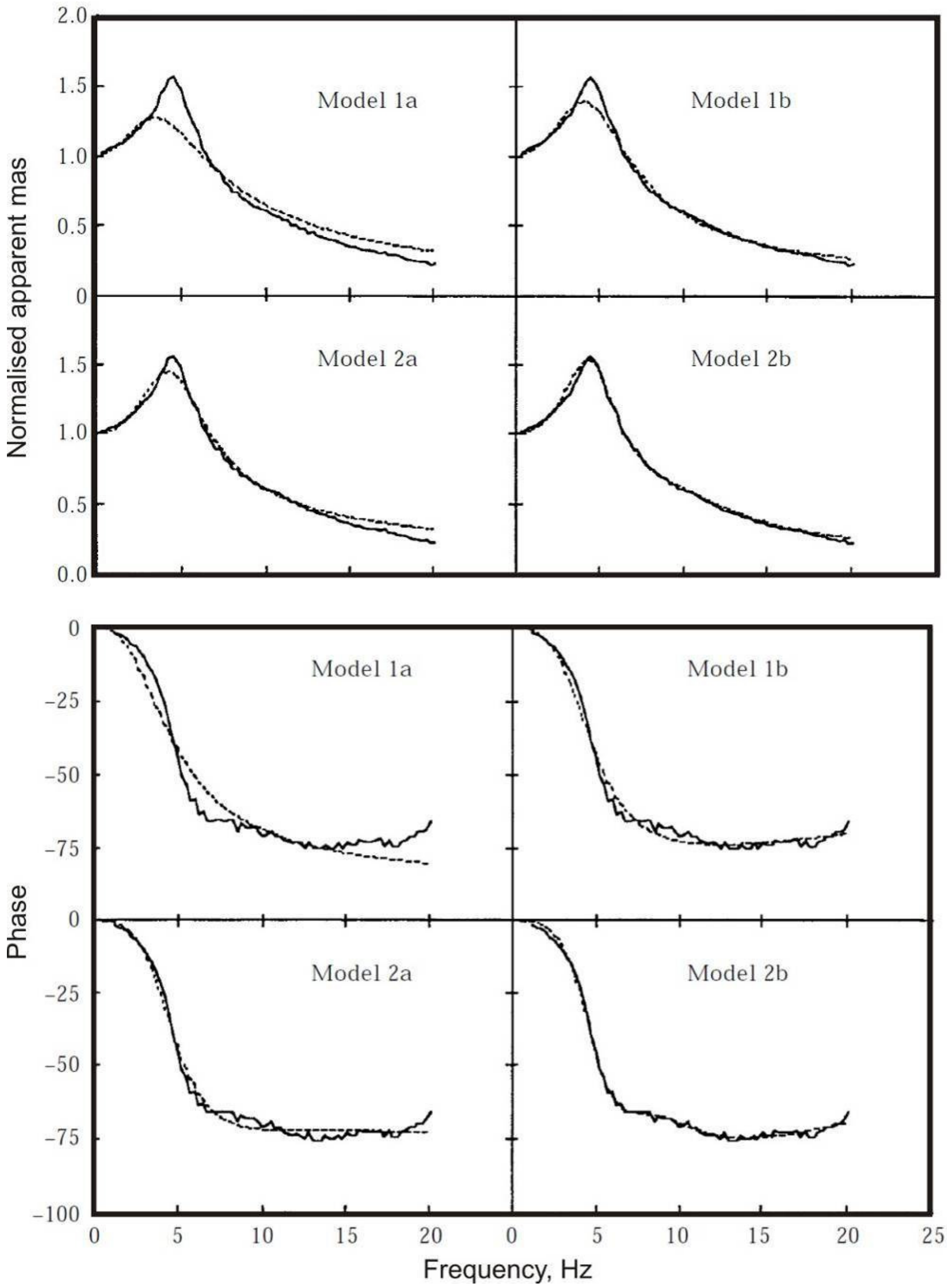

Figure 2.32 Fitted model responses of models 1a, 1b, 2a and 2b (see Figure 2.31). Models fitted to the mean apparent mass of 60 subjects by minimizing the errors in the phase: —— , experimental data; - - - -, fitted curves (from Wei and Griffin, 1998a).

More complex lumped parameter models of the body have been proposed with three or more degrees-of-freedom. Often these models were conceived to represent several responses of the body. For instance, a five degree-of-freedom model with masses to represent the legs, buttocks, abdominal components, chest, and head was developed by Mertens and Vogt (1978). The parameters of this model were determined from anatomical data and optimised using measurements of the mechanical impedance and transmissibility to the head of subjects from a previous experiment (Mertens, 1978). Similarly, Smith (1994, 2000) devised a five degree-of-freedom model which she modified to fit the 'major resonances' in the mechanical impedance and transmissibility to the chest spine and thigh of two subjects. A three degree-of-freedom lumped parameter model is defined in ISO 5982 (2001). The model is intended to have a similar apparent mass/point impedance and seat-to-head transmissibility as the idealized values defined in the standard (see Section 2.2.7).

While the multi-degree of freedom models described above generally produced reasonable fits to the impedance responses of the body in addition to other responses (e.g. transfer functions to various body locations), the fits to the point impedance responses were no better than the simpler one degree-of-freedom or two degree-of-freedom models proposed by Wei and Griffin (1998a). When representing the apparent mass of the body there appears little justification in using a more complex model, particularly in the context of the large variability between individuals.

2.4.3 Mechanistic models

In addition to models used to represent responses of the body, biodynamic models have also been developed to represent understanding of how the body moves (i.e. mechanistic models).

Two-dimensional finite-element models to represent the mode shapes of the body in the mid-sagittal plane were developed by Kitazaki (1994). The initial material properties in the models were based on data from cadavers; the models were then optimised using point impedance measurements and experimental modal analysis. Acceleration transfer functions were calculated from the vertical seat motion to the spine, pelvis, and viscera; the mode shapes and natural frequencies were then extracted by the analysis. The principal resonance in the apparent mass of the body was concluded to be caused by deformation of the tissue beneath the pelvis in phase with vertical motion of the viscera. This mode shape was broadly confirmed by Matsumoto (1999) who used lumped parameter models with masses representing the legs, pelvis, upper-body, viscera and head to represent the biodynamic responses around the principal resonance. The second mode occurring at around 10 Hz was found to be primarily caused by a rotational mode of the pelvis (Kitazaki, 1994).

While mechanistic models may provide useful understanding of the motions of the body they are not yet of an appropriate complexity to represent known variability in the apparent mass of the body (e.g. effects of posture, seating and input spectra).

2.4.4 Modelling variability in apparent mass

One approach to modelling variability in apparent mass is to use lumped parameter models with parameters that depend on the seating environment (e.g. input spectra, posture, subject physical characteristics). Several authors have used this approach to represent the 'nonlinear' behaviour of the body, using non-linear geometric arrangements of the dynamic system (e.g. an inverted pendulum; Mansfield, 1998) or using non-linear components (e.g. cubic springs and dampers; Markolf and Steidel, 1970). In general these models have been developed in order to provide some understanding of the movement of the body as opposed to developing models for predicting seat transmissibility, including the development of anthropodynamic dummies.

Mansfield (1998) investigated the use of quasi-static parameters on the response of a single degree-of-freedom model (equivalent to model 1b in Figure 2.31) to represent changes in apparent mass with input magnitude. He investigated varying the stiffness, damping, and the masses in turn, as well as allowing all parameters to vary simultaneously. Models where the masses and stiffness varied according to the magnitude of the motion resulted in better fits than linear models or models where only the damping was optimized with changes in input magnitude - allowing all the parameters to be optimized further improved the fits. In the case where all parameters were allowed to vary, the stiffness and the moving mass, 'Mass 2', consistently decreased with each increase in input magnitude (Table 2.4). The damping also tended to decrease with increased input magnitude, however between 1.5 and 2.0 ms^{-2} r.m.s. there was a slight increase. This increase of damping at 1.5 ms^{-2} r.m.s. coincided with the base mass, 'Mass 1', increasing to 0.6 kg (at all other magnitudes 'Mass 1' was 0 kg). It might be possible to predict the responses for an unmeasured magnitude by using trends in parameters such as those identified by Mansfield. Reducing the complexity of the model (i.e. fixing the base mass, 'Mass 1') may have resulted in more consistent trends in parameters. A similar approach to that used by Mansfield might be used to identify trends in apparent mass with other variables (e.g. backrest contact, backrest angle, foot position, hand position, posture, and physical characteristics).

2.4.5 Dummies

Mechanical and electro-mechanical devices have been developed to present the seat with the same dynamic loading as human subjects. These devices sometimes referred to as 'anthropodynamic dummies' have generally been based on lumped parameter models representing the apparent mass of the body.

Table 2.4 Optimised single degree-of-freedom model (all parameters allowed to vary) (from Mansfield, 1998).

Magnitude, ms^{-2} r.m.s.	Stiffness, Nm^{-1}	Damping, Nsm^{-1}	Mass 1, kg	Mass 2, kg	$\sum$ error, kg
0.25	57142	1137	0.0	48.0	1.99
0.5	46769	1048	0.0	47.9	1.86
1.0	40877	976	0.0	47.6	1.72
1.5	35542	792	0.6	46.4	1.84
2.0	34514	809	0.0	47.0	1.75
2.5	33272	751	0.0	46.7	1.84

2.4.5.1 Testing with rigid masses

Rigid masses are an obvious alternative to human occupants when testing the dynamics of conventional seats. However, many researchers have shown that measuring the transmissibility of a conventional seat loaded with a rigid mass yields a higher peak transmissibility and a higher resonance frequency compared to testing the seat with a human subject of the same seated weight (e.g. Appendix A; Figure 2.33). To measure a relevant seat transfer function on conventional seats, a load is required with a mechanical impedance representative of a subject.

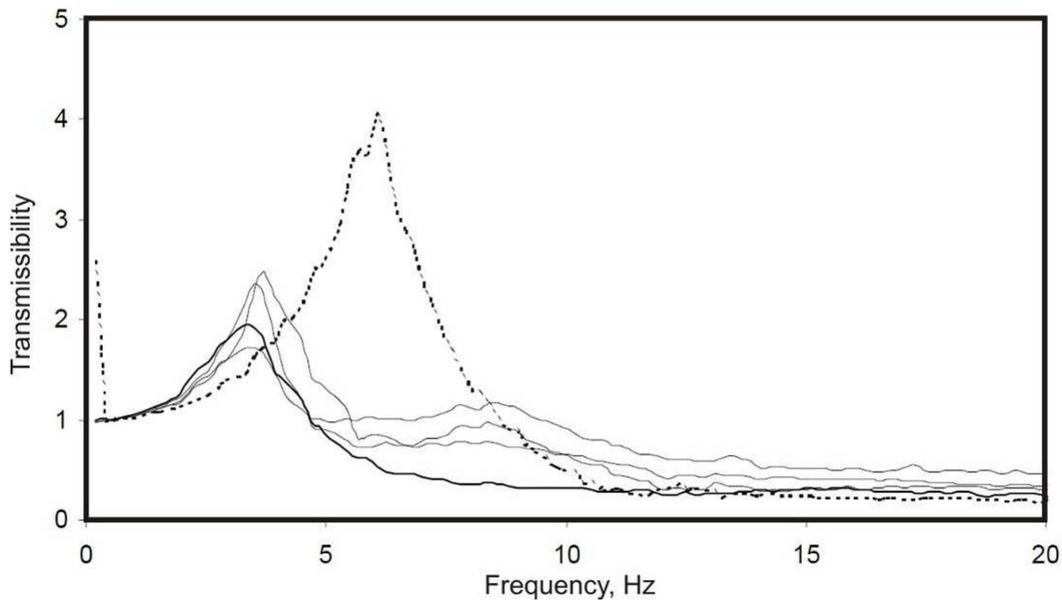

Figure 2.33 Transmissibilities of a foam-cushion car seat measured with: —— ,three subjects; ——, anthropodynamic dummy; and - - - - rigid mass (from Appendix A).

2.4.5.2 *Passive dummies*

A number of dummies have been constructed using passive components (e.g. Mathews, 1967; Suggs *et al.*, 1969; Gu, 1998; Lewis, 1998; Appendix A). These dummies have been reported to give good agreement with the apparent mass or impedance of human subjects over a limited range of conditions but have not been demonstrated to reflect factors that are known to alter the dynamic response of the body (e.g. the dynamic non-linearity of the body and the effects of body posture).

Early dummies were primarily designed to measure the transmissibilities of suspension seats and used conventional oil-filled dampers (e.g. Mathews, 1967; Suggs *et al.*, 1969). Lewis (1998) investigated the effect of increasing the excitation magnitude of broadband vibration (from 0.35 to 2.0 ms^{-2} r.m.s.) on a dummy with a conventional oil-filled damper. At lower magnitudes of vibration the response was increasingly influenced by friction, resulting in lower apparent masses in the region of the resonance frequency and higher apparent masses at frequencies greater than about 6 Hz (Figure 2.34). Clearly, such a device would be unsuitable for most seat environments where the vibration is likely to be of the same order as the lower magnitude stimuli used in the above measurements. The response of a dummy using an alternative viscous dashpot damper, in which an open tube moved in and out of an open bath of viscous fluid, was investigated by Lewis (1998). He found that the dummy gave a similar apparent mass with all magnitudes between 0.25 and 1.25 ms^{-2} r.m.s. A dummy using this damper was later found to give similar seat transmissibilities to human subjects when testing a conventional seat (Figure 2.33) and two suspension seats, using representative test inputs (Appendix A).

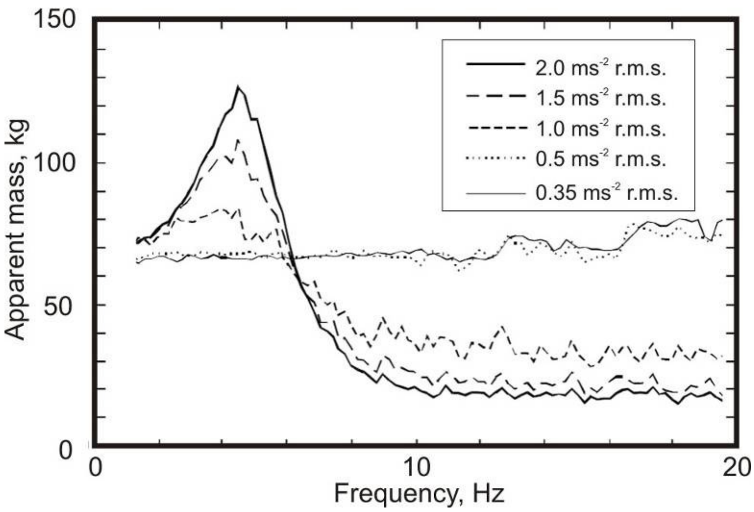

Figure 2.34 Effect of input magnitude on prototype dummy with conventional oil filled damper (from Lewis, 1998).

While it is conceivable that a passive dummy could reflect some variability in the apparent mass of human subjects with input magnitude and other factors (e.g. posture, subject characteristics) by suitable adjustments to the components, in practice this would not be easily achievable.

2.4.5.3 Active dummies

An alternative to using only passive components in a dummy is to use an electrodynamic actuator to generate damping forces and spring forces, controlled by feedback from transducers (e.g. Lewis and Griffin, 2002; Mozaffarin *et al.*, 2008). An advantage of these 'active dummies' is that it is easy to change the response of the dummy by adjustment of feedback parameters and the masses to reflect variations in the apparent mass of subjects. An additional feature of an active dummy is that it is possible to generate an apparent mass characteristic that departs from that of a single degree-of-freedom system without the complexity of adding more moving parts, making it possible to reproduce the second resonance seen in some subjects. Active dummies are now commercially available. A dummy developed by the Wölfel group (Figure 2.35; Wölfel, 2008) is designed to replicate the apparent mass of three mass percentiles (5^{th} percentile female, 50^{th} percentile male, 95^{th} percentile male) at three magnitudes of vibration (0.3, 0.7, 1.4 ms^{-2} r.m.s.). The response of the dummy is varied by changes to the moving mass on the dummy as well as changes to the feedback parameters.

While there is little evidence that gender and weight of subjects affects the transmission of the vibration through conventional foam cushion seats, other variables known to affect seat transmissibility (e.g. backrest angle, foot position, subject age) are not currently reproduced in commercially available dummies.

(1) Seat surface interface

(2) Feedback transducers

(3) Electrodynamic actuator

(4) Moving mass

(5) Passive springs

(6) Backrest interface

Figure 2.35 MEMOSIK active anthropodynamic dummy (from Wölfel group, 2008).

2.5 MODELLING THE SEAT-PERSON SYSTEM

2.5.1 Mechanical impedance method

A mechanical impedance method for predicting seat transmissibility was reported by Fairley and Griffin (1986). They demonstrated that the seat transmissibility could be predicted from independent measurements of the seat dynamic stiffness and the apparent mass of the body.

The seat dynamic stiffness was measured using an indenter rig (Figure 2.36). A seat was mounted on an electrodynamic simulator beneath a rigid test stand. An indenter shaped like a SIT-BAR (Whitham and Griffin, 1977) was fixed to the stand. By screwing the indenter head down onto the seat a preload was applied representing the static weight of a subject.

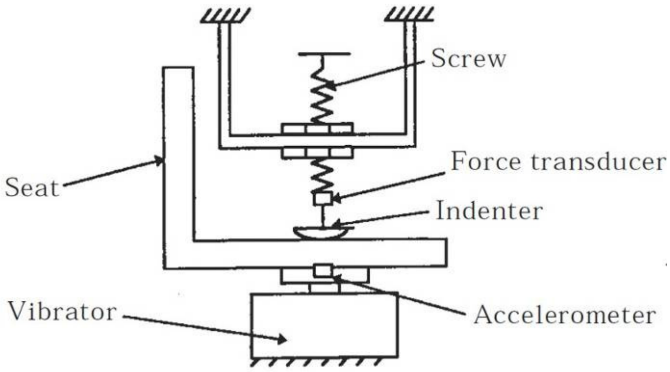

Figure 2.36 Indenter rig (left) and foam model used by Fairley and Griffin (1986), and Wei and Griffin (1998b). Figure from Wei and Griffin (1998b).

The seat dynamic stiffness, $S(\omega)$, was derived from measurements of the force at the indenter head, $F(\omega)$, and the acceleration at the base of the seat, $A(\omega)$, while the seat was vibrated:

$$S(\omega) = \frac{F(\omega)}{-\omega^2 A(\omega)} \qquad \textbf{2.10}$$

The seat transmissibility, $T(\omega)$, was then calculated from the seat dynamic stiffness and the apparent mass of a subject or groups of subjects, $M(\omega)$, by using:

$$T(\omega) = \frac{\omega^2 S(\omega)}{\omega^2 S(\omega) - (M(\omega) + m_2)} \qquad \textbf{2.11}$$

Where m_2 is the mass of the seat that is assumed to move relative to the base. Fairley and Griffin (1986) showed that for conventional seats it was possible to assume that the moving mass was negligible (i.e. $m_2 = 0$).

The method was shown to give reasonable predictions to the measured transmissibilities of eight different subjects on a single seat (Figure 2.37-A) as well as of one subject sitting in eight different seats (Figure 2.37-B). The resonance frequency was accurately predicted but the predicted response at this frequency was lower than observed with the subjects. Above around 6 Hz, the predicted transmissibilities were greater than the measured transmissibilities.

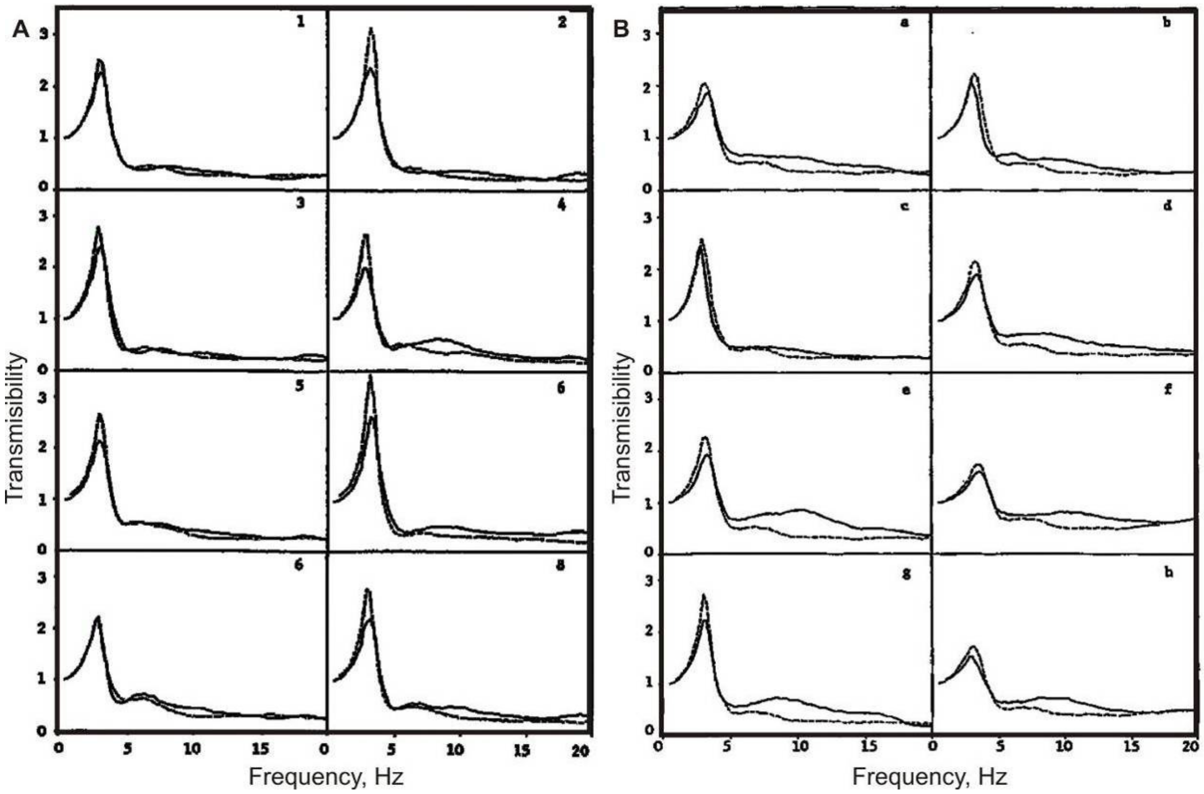

Figure 2.37 Comparison of measured (——) and predicted (- - - -) transmissibilities for: (A) one seat with eight different people; and (B) eight different seats with the same subject (from Fairley and Griffin, 1986).

2.5.2 Lumped parameter models

A variation of the seat transmissibility prediction method described by Fairley and Griffin (1986) is to fit lumped parameter models to both the measured dynamic stiffness of the seat and the apparent mass, and use the two models to predict the transmission of vibration through the seat; this approach was demonstrated by Wei and Griffin (1998b). First, the complex dynamic stiffness of the seat was measured using an indenter rig, with the stiffness and damping (k and c respectively in Figure 2.38) determined using a curve fitting approach. Then, by using the fitted stiffness and damping in combination with a previously determined apparent mass model, the seat transmissibility was predicted. The authors predicted the transmissibilities of a seat and a foam squab using seat transmissibility models based on two alternative models of the body (a one degree-of-freedom model and a two degree-of-freedom model). Both models yielded good fits to the modulus of the transmissibility but the authors observed that the two degree-of-freedom model was able to better predict the response around the second resonance (Figure 2.39). At low frequencies the measured and predicted phase responses were in good agreement but above around 7 Hz the models predicted less phase lag than was measured.

An attraction of the lumped parameter model prediction approach is that it allows the dynamic characteristics of seats to be simply expressed in terms of dynamic stiffness and damping.

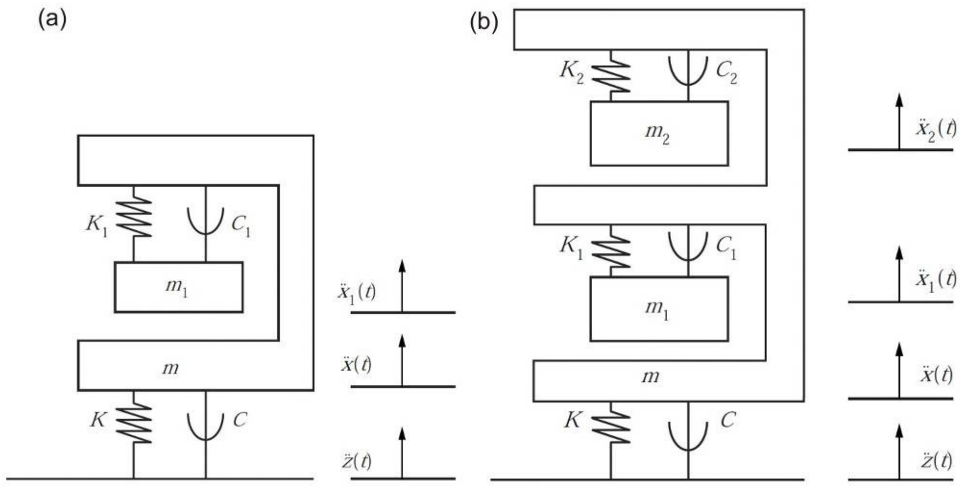

Figure 2.38 Seat transmissibility models (based on apparent mass models 1b and 2b in Figure 2.31) (from Wei and Griffin, 1998b).

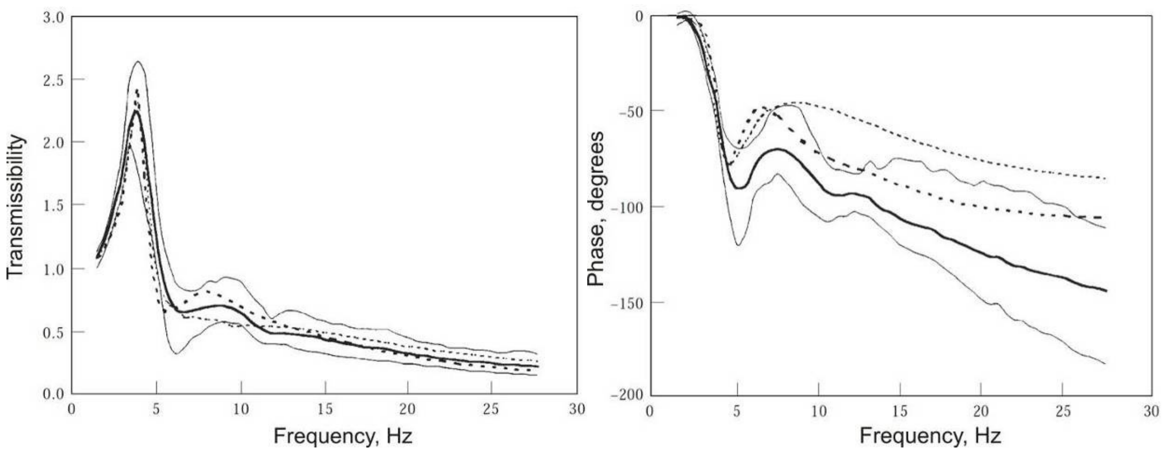

Figure 2.39 Comparison of measured and predicted seat transmissibility. ——— ,mean of eight subjects; ———, range of subject data; **- - - -**, single degree-of-freedom model; and - - - -, two degree-of-freedom model (models (a) and (b) respectively in Figure 2.38) (from Wei and Griffin, 1998b).

2.5.3 Seat interface

The dynamic properties of seats and foams measured with an indenter rig vary according to the dimensions of the indenter head and the preload applied to the seat (Wei, 2000). Large variations were observed between dynamic properties derived with five differently shaped indenter heads, including three different diameter disks, a SIT-bar shaped indenter and a buttock-shaped indenter. However the dynamic properties did not vary systematically with changes in the contact area of the indenter, even between indenters of the same nominal shape (i.e. 150, 200, and 250-mm diameter disks). This suggests that the seat properties were not only affected by contact area but may also have been affected by the contouring of the indenter head. Wei and Griffin (1998b) also investigated the effect of increasing the preload applied to five different indenters from 300 to 700 N. They found that the dynamic stiffness and the damping increased as the pre-load on the seat was increased, both for a car seat and a foam squab (Table 2.5).

Table 2.5 Effect of pre-load on the derived damping and stiffness of a car seat and foam squab measured using an indenter rig with a SIT-bar shaped indenter (from Wei and Griffin, 1998b).

Pre-load, N	Seat		Foam	
	K, N/m	*C*, Ns/m	*K*, N/m	*C*, Ns/m
300	42 300	260	21167	354
400	44 121	270	23904	457
500	50 210	276	25082	515
600	59 300	280	34903	570
700	68 000	285	42340	740
800	73 000	293	54363	831

Ideally, when measuring the dynamic stiffness of a seat using an indenter rig, the contact conditions should match those with a person sitting on the seat. While it is conceivable that a ‘typical’ indenter and preload could be found to represent the average contact conditions of a population, it may be unfeasible to represent the contact condition for all individuals. One solution to this would be to make corrections to the typical values to account for differences between an individual and the ‘typical’ conditions. This approach requires knowledge on the effect of the physical characteristics of people on the seat properties.

2.5.4 Finite element models

Finite element (FE) models with varying degrees of complexity have been developed to represent the dynamic characteristics of the seated human body. Using the FE approach the body is divided into a number of interconnecting discrete elements with defined material properties. Finite element models of the body can provide useful insights into the dynamic responses of the body that cannot be directly measured. For instance, Kitazaki (1994) and Kitazaki and Griffin (1997) developed models of the seated body so as to provide understanding of the motions of the body at the major resonance (see Section 2.4.3); while Pankoke *et al.* (2001) proposed a model to predict spinal loads under vibration. Finite element models have also been used to represent bulk responses of the body such as the apparent mass or the transmission of vibration to the head.

A FE approach to predict the transmissibility of seats was presented by Siefert *et al.* (2008). This approach combined a FE model of the seat with a 'CASIMIR' FE human body model (Figure 2.40). The CASIMIR model was presented in more detail in an earlier paper (Pankoke, 2003). The material properties of the seat structure elements were taken from the literature. The dynamic properties of the seat foam were measured using an indenter rig at frequencies between 1 and 30 Hz under various static deflections; the foam properties were assumed to be linear with respect to input magnitude.

The dynamic properties of the body tissues in the CASIMIR models were initially defined using anatomical data, where available, and then optimised against the gross dynamic responses of the body. The accuracy of finite element models is determined by the availability of reliable information on the in-vivo characteristics of body tissues. However, there is comparatively little data available on the dynamic characteristics of body tissues under realistic conditions (i.e. live tissue under representative excitations). Consequently there is often considerable uncertainty in the material properties defined in these models. The magnitude and effect of these errors on the target responses for the CASIMIR model is not disclosed, although such information is required to assess the applicability of FE models.

The model was shown to provide a good representation of transmissibilities measured with a single subject: both for the transmission of vertical vibration at the seat base to vertical vibration on the seat surface (Figure 2.41), and vertical vibration at the seat base to fore-and-aft vibration on the backrest.

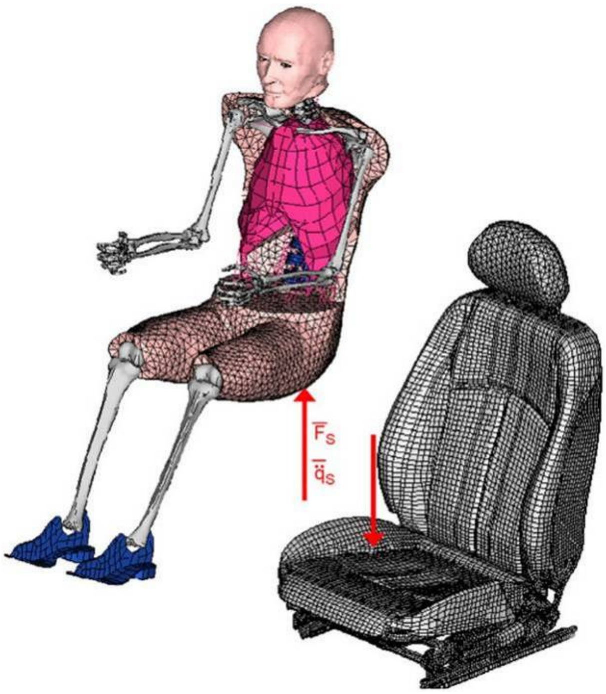

Figure 2.40 Finite element models of seat and person used to predict seat transmissibility (from Siefert *et al.*, 2008).

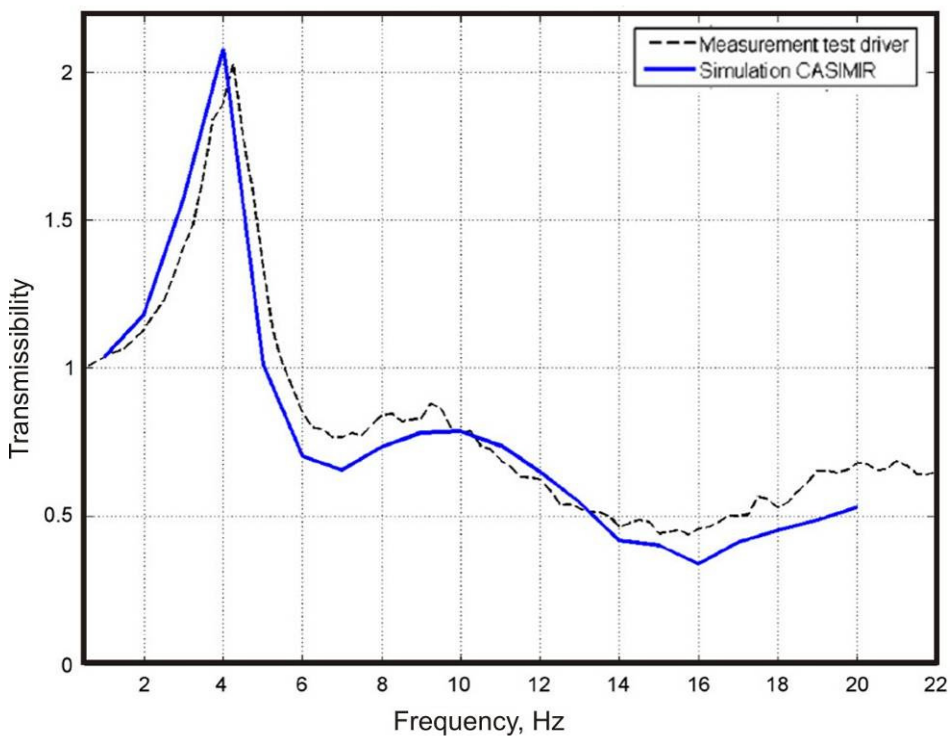

Figure 2.41 Transmissibility of a car seat determined using CASIMIR model compared to the transmissibility measured with a human subject (model response in bold) (from Siefert *et al.*, 2008).

The dynamic characteristics of the body vary with posture and input spectra. It might be envisaged that a FE model might represent some of these variations with suitable changes to model parameters (e.g. changes in model geometry to reflect postural changes; non-linear material properties to represent the effects of changes in input magnitude). While the effect of some postural variations on the responses of an FE model of the body have been claimed (e.g. effects of backrest inclination; changes to the curvature of the spine; Siefert *et al.*, 2008) these responses have not be validated against representative measurements of the responses of the body.

It is concluded that while FE models may develop to provide useful insights into the dynamic behaviour of the body, their complexity is not yet appropriate for representing the responses (e.g. the apparent mass of the body) needed to predict seat transmissibility.

2.6 CONCLUSIONS

Measurements of the apparent mass of the body in the vertical direction show that the main resonance of most people sitting upright with no backrest support occurs around 5 Hz. However, there is considerable inter-subject variability in the magnitude of apparent mass at all frequencies. The causes of this variability are not fully understood. Subject mass appears to account for a large proportion of the variability in apparent masses between subjects. Other physical characteristics of the body may also contribute to inter-subject variability, but there are few data showing their influence.

While some studies have reported an influence of changes in muscle tension and posture on the apparent mass, the effects have generally been small and inconsistent. Furthermore these studies have compared relatively extreme postures, unlikely to be adopted by subjects in most situations; the proportion of inter-subject variability accounted for by postural differences in ‘normal’ sitting postures is not known.

The seating environment (i.e. backrest, foot-position, hand position, and input stimulus) can influence the apparent mass of the body. Few studies have systematically investigated the influence of these seating factors. Idealized biodynamic responses are presented in ISO 5982 (2001) but these values do not take into account the influence of the seating environment or inter-subject variability. Further understanding of the causes and nature of the variability in apparent mass is required to assist a revision of this standard.

Transmissibility resonance frequencies of most conventional foam cushion seats occur between 3 and 4 Hz. The seat and person form a coupled system so factors affecting the properties of the seat as well as factors affecting the apparent mass of the person may be expected to influence seat transmissibility. The dynamic properties of seats vary with compression, input magnitude, and contact area. The influence of these factors on seat transmissibility and the relative contributions of changes in apparent mass and changes in seat dynamics to changes in seat transmissibility are not known.

Finite element models and multi-body models may provide useful insights into the dynamics of the body, but at present they mostly fail to reflect factors that are known to affect the dynamic responses of the body and that can be expected also to alter seat transmissibility (e.g. the dynamic non-linearity of the body and the effects of body posture). For many applications a simple one-degree-of-freedom lumped parameter model may sufficiently represent the apparent mass of the body, particularly in the context of the large variability that occurs between subjects. It is possible that variations in apparent mass between subjects, variations due to posture and due to changes in vibration stimuli may be represented by suitable adjustments to the parameters of such a model.

It is desirable for reasons of cost, repeatability, and safety to determine seat transmissibilities without using human subjects. Models of the apparent mass of the body have been used in the development of anthropodynamic dummies and in combination with measurements of the dynamic stiffness of seats to predict seat transmissibility. These methods are not yet in widespread use, partly due to their inability to reflect changes in transmissibility with variations in the seating environment.

This literature review has identified areas where further research is required to improve understanding of the seated apparent mass of the body and the vibration transmitted through seats. There is evidence that the vertical apparent mass of the body can be influenced by the seating environment (e.g. backrest, steering wheel, footrest, vibration spectra), although there has been little systematic study. Experimental studies are required to measure the influence of the seating environment on apparent mass, advance understanding of the biodynamic mechanisms involved, and assist the development of dynamic models of the body. The apparent mass of the human body has been shown to vary considerably between people but further study is also required to improve understanding of the influence of subject physical characteristics on apparent mass.

Although models of the apparent mass of the body have been proposed, they do not take into account the variability associated with the seating environment and inter-subject variability. It seems appropriate to investigate whether previously proposed simple lumped parameter apparent mass models can be developed to represent the influence of these factors.

Little is known about how the apparent mass of the body, and factors that influence the apparent mass of the body, affect the transmission of vibration through foam cushion seats. It would be helpful to understand how the seat environment and subject physical characteristics influence seat transmissibility, and whether this influence can be represented by simple lumped parameter seat-body models.

CHAPTER 3: EQUIPMENT AND METHODS

3.1 INTRODUCTION

All experiments were carried out in the laboratories of the Human Factors Research Unit, the Institute of Sound and Vibration Research, University of Southampton. The principal apparatus used in these experiments is detailed below. Further details relating to some apparatus and analysis techniques specific to each experiment are described in the relevant experimental chapter.

3.2 VIBRATOR

A Servotest electro-hydraulic vibrator was used to produce vibration in the vertical direction (Figure 3.1; Corbridge *et al.*, 1990). The vibrator table was constructed from cast aluminium, the weight of the platform and other moving parts was approximately 200 kg. A 16-mm thick aluminium top-plate, with dimensions of 1.50 by 0.90 m, was attached to the surface of the table via 100 mm steel spacers. The experimental apparatus was attached to this top-plate.

Figure 3.1 Hydraulic simulator and test seats.

3.2.1 Performance

The vibrator had an operating stroke of 1 metre and was capable of achieving accelerations up to ±10 ms^{-2}. Cross-axis coupling were specified at less than 5% of the target motion over the frequency range 0.1 Hz to 50 Hz. Over this frequency range, the peak of the cross-axis motion occurred at around 13 Hz and was about 5% of the vertical motion.

The piston of the vibrator moved on hydrostatic bearings, with no oil seals, to minimize friction and resulting distortion. Corbridge *et al.* (1990) measured the waveform distortion of the system using three magnitudes (0.3, 0.6 and 0.9 ms^{-2} r.m.s.) of sinusoidal vibration at 1.0, 2.0, 4.0, 8.0, 16 and 32 Hz. At all frequencies between 1 and 32 Hz, the distortion was less than 15% for the 0.3 ms^{-2} r.m.s. stimuli, and less than 6% for the 0.6 and 0.9 ms^{-2} r.m.s stimuli.

Without any motion, but with the simulator hydraulics pressurised and the simulator 'ramped', the background vibration measured on the vibrator table had a magnitude of 0.017 ms^{-2} r.m.s. The vibrator had a capability of generating a dynamic force up to 10 kN and a static force up to 8.8 kN.

The response of the system was previously shown to change as the hydraulic oil temperature increased (Corbridge *et al.*, 1990). In the first 20 minutes of the system being operated, the response of the system fell by up to 10% over the frequency range 2.5 to 50 Hz. However, in the period between 20 and 60 minutes there was only a 5% change in the modulus part of the transfer function (Corbridge *et al.,* 1990). To reduce this influence of oil temperature, a minimum 'warm-up' period of 30 minutes was used prior to each experimental session. During this period the system was operated with a 0.5-Hz sinusoidal motion with a peak-to-peak displacement of approximately 0.5 m.

3.2.2 Safety features

The vibrator's performance was in accordance with BSI 7085: 'Guide to safety aspects of experiments in which people are exposed to mechanical vibration and shock'. The system incorporated mechanical, hydraulic, and electrical safety features to minimise risk of excessive exposure to vibration. In addition, both the experimenter and the subject had access to emergency stop buttons at all times, and the subject was restrained using a loose fitting lap belt.

Mechanical safety features:

- 100-mm hydraulic snubbers at the ends of the actuator stroke – giving average decelerations less than ± 50 ms^{-2}.

- Rubber end-stop buffers to prevent metal-to-metal contact.
- Pressure switch to disable the system if snubber pressure dropped below operating limits.
- Pressure relief valves to limit hydraulic fluid pressure.

Hydraulic safety features:

- Electrical interlocks to disable the pump in case of high oil temperature, low oil level, low system pressure, or dirty oil filter.

Electronic safety feature which would cause the simulator to come to safe stop in the event of the:

- Table acceleration exceeding pre-set limits (± 5 ms^{-2}).
- Table displacement exceeding pre-set limits (± 0.35 m).
- Operation of user or subject emergency stop buttons.
- Hydraulic system power failing.

3.2.3 Equalisation

An equalisation routine was used to adjust the input signals so as to obtain the desired output signals, allowing for the response of the vibrator. A random motion, with a similar frequency content and magnitude to the desired signal, was output from a computer to the vibrator and the 'platform' motion acquired using an accelerometer. In the case of the rigid seat, the 'platform' accelerometer was attached to the surface of the force platform to minimize the influence of the seat. The transfer function between the output signal and the acquired acceleration was used to define the transfer function of the system. The inverse of this transfer function was then applied to the desired signal to produce a compensated output signal. The test stimuli were equalised after a simulator 'warm-up' period of 30 minutes (see Section 3.2.1).

3.3 SEATS

3.3.1 Rigid seat

Measurements of apparent mass were made with subjects sitting on a rigid seat with an adjustable backrest (Figure 3.2). The seat was constructed using 18-mm thick plywood, reinforced with aluminium L-sections. Spacers were attached to the backrest in some conditions to ensure consistency of posture between conditions (e.g. see Figure 3.2). A Kistler force platform was bolted to the surface of the seat. The seat was shimmed under the corners of the force platform so that the platform was level and evenly supported.

To check the rigidly of the seat, transmissibilities were measured between the vibrator platform and the surface of the force platform, and between the surface of the force platform and the backrest. During these measurements a 71-kg male subject sat on the seat, the seat backrest was adjusted to the vertical position, and the seat was excited using 1.0 ms^{-2} r.m.s broadband vibration. In-line vertical transmissibilities between the platform and the seat, and between the seat and the backrest, deviated by less than 5% over the frequency range 1.0 to 20 Hz. The cross-axis transmissibility between vertical vibration on the seat surface and fore-and-aft vibration on the backrest, which ideally would have been zero, was less than 0.05 at frequencies between 1.0 and 20 Hz, except at around 13 Hz where the cross-axis motion was approximately 8% of the vertical motion. The response at 13 Hz reflected a previously observed pitching mode of the simulator (see Section 3.2.1).

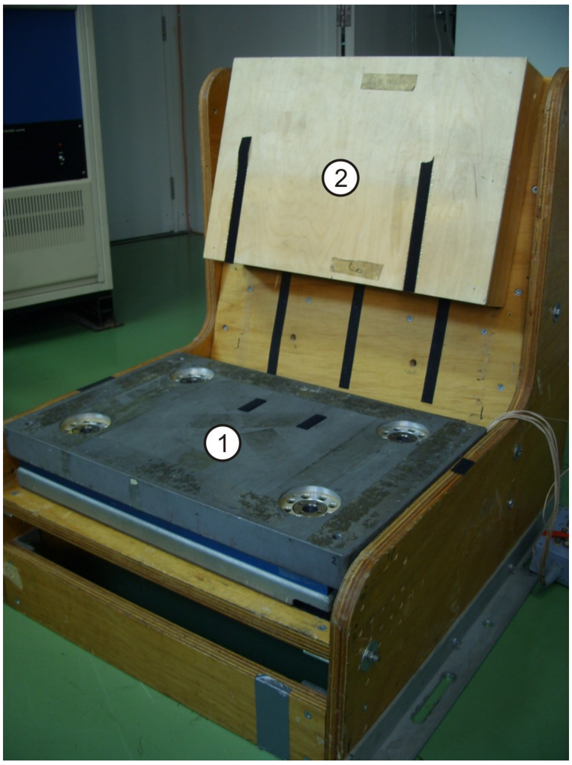

Figure 3.2 Rigid seat with force platform, '1'; and backrest attachment '2'.

Figure 3.3 Car seat.

3.3.2 Car seat

The transmissibility of a passenger seat originating from a Ford Mondeo was measured. The car seat cushion was of full-foam construction, with a foam squab attached to a pressed-steel seat pan. The backrest of the seat consisted of a steel sprung support mat with a thin foam covering. The seat had an adjustable lumbar support, which was set to the minimum, fully-in, position. The seat backrest was inclined by 15 degrees from the vertical and the seat cushion was at 12° to the horizontal, as measured using an *H*-point manikin (ISO 20176, 2006). The uncompressed leading edge of the seat surface was 0.44 m above the vibrator platform on which subjects rested their feet.

3.4 ACCELEROMETERS

The vertical motion on the vibrator platform was measured using Entran EGCS-DO-10 piezo-resistive accelerometers (Figure 3.4). The specifications of these are given in Table 3.1.

Table 3.1 Manufacture specifications of Entran EGCS-DO-10 accelerometers.

Parameter	Specification
Range	± 10 g
Sensitivity	≈ 13 mv/g
Frequency response	0-200 Hz
Non-linearity	± 1% FSO
Cross-axis sensitivity	± 2% (maximum)
Thermal sensitivity shift, (for 50° change in temperature)	± 2.5% (for 50° change in temperature)
Damping coefficient	0.58

Measurements of vibration perpendicular to the seat surface were made using an *HVLab* SIT-pad meeting the specification set out in ISO 10326-1 (1994), see Figure 3.5. The device consisted of a semi-rigid disk with a central cavity containing an Entran EGCSDO-10 piezo-resistive accelerometer. The flexible rubber pad was designed to conform to the contours of the seat and not influence the posture of a seated person or adversely affect contact conditions with the seat surface. Subjects were asked to sit on the pad so that their ischial tuberosities were either side of the bulge on the upper surface. The SIT-pad was used to measure the vibration on the surface of both the car seat and also on the force platform.

The accelerometers were calibrated before each experiment using a 'roll over' procedure - to give a zero reading when placed on a horizontal surface and a reading of -2g when inverted (ISO 5347-5, 1993). These calibrations were performed before each experiment and checked during and after the experiment. To check the dynamic calibration of the accelerometer and SIT-pad, the transmissibility between them was measured when they were placed side-by-side on the vibrator platform. Ideally, the transmissibility between the transducers would give a value of unity at all frequencies. At frequencies between 1.0 and 20 Hz the transmissibility was found to be in the range 1.0 ± 3%.

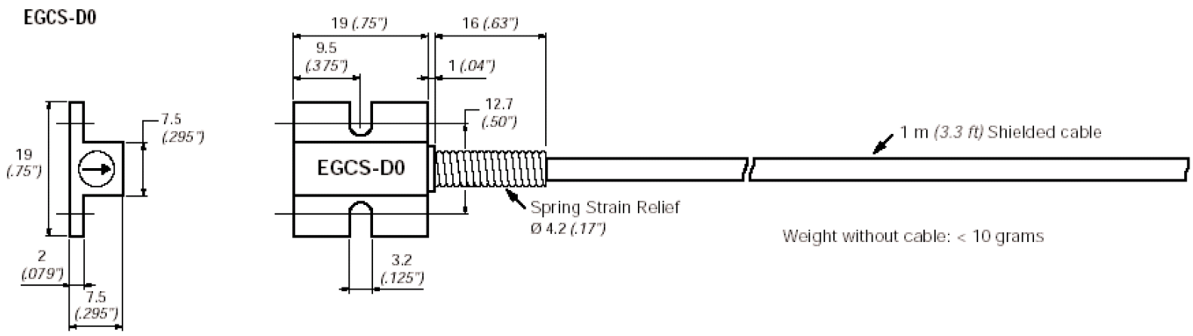

Figure 3.4 Entran EGCS-DO- accelerometer. From http://www.strainsense.co.uk.

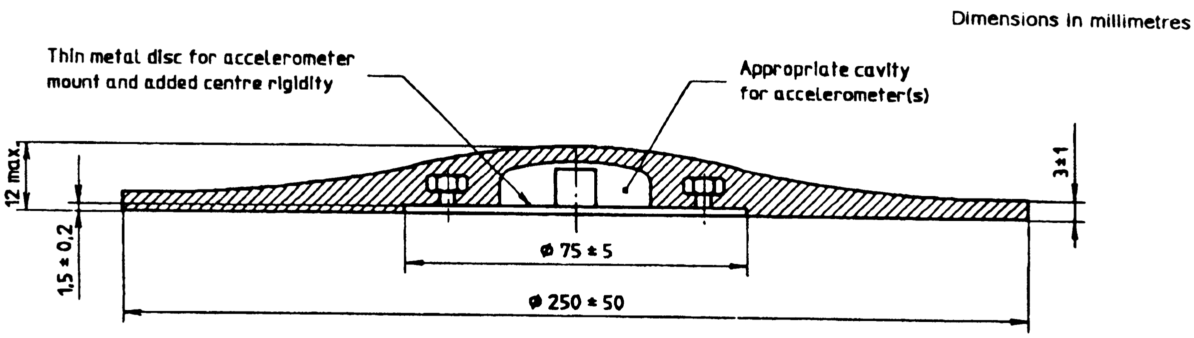

Figure 3.5 SIT-pad used to measure vibration on the seat surface. ISO 10326-1 (1992).

3.5 FORCE PLATFORM

The driving force at the seat surface was measured using a Kistler 9281B force platform (Table 3.2). This consisted of four matched piezo-electric tri-axial force cells, located at the four corners of a rigid support frame. An aluminium alloy plate of dimensions 0.6 x 0.4 x 0.047 m, weighing 29.5 kg, was bolted rigidly on top of the force transducers. The platform was capable of measuring forces in the three orthogonal dimensions simultaneously, however only vertical force measurements are reported. The signals from each vertical force cell were summed to provide a single signal which was amplified using either a Kistler 5001 or 5007 charge amplifier.

Table 3.2 Manufacture specifications of Kistler 9281B force platform.

Parameter (*z*-axis)	Specification
Range	- 10 / + 20 kN
Sensitivity	≈ -3.8 pC/N
Resonance frequency	≈ 850 Hz
Non-linearity	± 0.5% FSO
Cross-axis sensitivity, x, $y \rightarrow z$	±2% (maximum)
Thermal sensitivity shift,	± 2.5% (for 50°C change in temperature)

The force platform was calibrated first statically and then dynamically. Static calibration was carried out by adding and removing 20 kg and 40 kg weights from the surface of the platform and adjusting the charge amplifier gain as appropriate. The charge amplifier time constant was set to 'long' during this process.

Dynamic calibration was carried out by measuring the apparent mass of the platform under three load conditions (no load, 20 kg, and 40 kg). The platform was vibrated with broadband random vibration at 1.0 ms^{-2} r.m.s. between 1.0 and 20 Hz r.m.s. In each load case, the error in the modulus of the apparent mass was less than 4% of the total mass above the load cells. The error in the phase of the apparent mass was less than 0.04 radians at frequencies below 20 Hz. The apparent mass in the 'no load' condition indicated that the combined mass of the top plate and force transducers above the sensing elements was 33.0 kg.

3.6 DATA ACQUISITION AND ANALYSIS

Input signals were generated using *HVLab* software (version 3.81). When generating the broadband random stimuli there were some variations in the input energy across the frequency range. These variations caused ‘ripple’ artefacts in the transfer functions due to resulting variations in the coherency. To minimize the influence of these variations, different random signals were generated for each subject, so that their effect was averaged across subjects.

A 16-channel *HVLab* data acquisition system was used to output signals to the simulator and record transducer signals. The system used an *Advantech PClabs PCL-818* 12-bit acquisition card and a *Techfilter TF-16* anti-aliasing card. Signals output to the simulator were monitored using an oscilloscope. Input signals from the accelerometers were amplified using pre-amplifiers; signals from the force plate were amplified using a charge amplifier. With the exception of the study on the effect of input spectra on apparent mass (see Chapter 6), the measured acceleration and force signals were acquired at 400 samples per second via anti-aliasing filters set to 133 Hz; during the input spectra experiment, signals were acquired at 510 samples per second with anti-aliasing filters set to 170 Hz.

Initial analysis of the acquired time-domain signals was carried out using *HVLab* software (version 3.81). Signals were first normalised to remove any DC offset and low-pass filtered. The influence of the mass of the force plate from the force measurements was removed by mass cancelation using the time domain method (see Section 2.1.2, Equation 2.7). Then, relevant transfer and coherency functions were calculated using the cross-spectral density method (see Section 2.1.1). A frequency resolution of 0.25 Hz was used during the input spectra experiment (see Chapter 6), for all other experiments a resolution of 0.195 Hz was used. Subsequent analysis of the frequency domain transfer functions was carried out using MATLAB (versions 7.01 and 7.5.0).

3.7 LUMPED PARAMETER MODELS

Lumped parameter models were used to represent the seated apparent mass of the body and seat transmissibility (see Chapters 7 and 9).

The apparent mass models consisted of either one or two masses, $m_{1,2}$, suspended from a common frame, m_0, via springs, $k_{1,2}$, and dampers, $c_{1,2}$. Models representing seat transmissibility had an additional spring, k, and damper, c, beneath the frame, representing the dynamic stiffness of the foam. Derivations of the responses of these models are described in the subsections below.

3.7.1 One degree-of-freedom apparent mass model

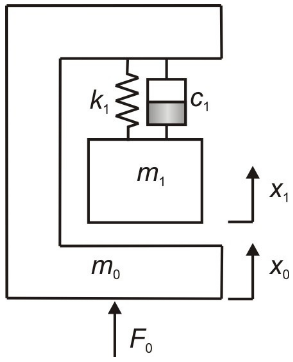

Figure 3.6 One degree-of-freedom apparent mass model

The equations of motion are:

$$F_0 = m_0\ddot{x}_0 + c_1\dot{x}_0 + k_1 x_0 - c_1\dot{x}_1 - k_1 x_1 \quad \textbf{3.1}$$

$$0 = m_1\ddot{x}_1 + c_1(\dot{x}_1 - \dot{x}_0) + k_1(x_1 - x_0) \quad \textbf{3.2}$$

Using the Laplace Transform ($x \rightarrow X$, $\dot{x} \rightarrow sX$, $\ddot{x} \rightarrow s^2 X$) the equations of motions can be expressed as:

$$F_0(s) = A_1 X_0 - A_2 X_1 \quad \textbf{3.3}$$

$$0 = A_3 X_1 - A_2 X_0 \quad \textbf{3.4}$$

where:

$$A_1 = m_0 s^2 + c_1 s + k_1 \quad \textbf{3.5}$$

$$A_2 = c_1 s + k_1 \quad \textbf{3.6}$$

$$A_3 = m_1 s^2 + c_1 s + k_1 \quad \textbf{3.7}$$

By substitution, X_1 can be expressed in terms of X_0:

$$X_1 = \frac{A_2 X_0}{A_3} \quad \textbf{3.8}$$

Substituting eq. 3.8 into eq. 3.3 the force acting at the base, $F_0(s)$, can be expressed as:

$$F_0(s) = X_0\left(A_1 - \frac{A_2^2}{A_3}\right) \quad \textbf{3.9}$$

By Newton's Second Law, the apparent mass, *M(s)*, is given by:

$$M(s) = \frac{F_0}{X_0 s^2} = \left(A_1 - \frac{A_2^2}{A_3}\right)\left(\frac{1}{s^2}\right) \quad \textbf{3.10}$$

The modulus (i.e. $|M|$) and the phase (i.e. arctan^{-1}(M)) of the apparent mass can then be calculated by replacing the Laplace Transform operator s with angular frequency ω ($s = \omega i$, where i is the imaginary operator).

3.7.2 Two degree-of-freedom apparent mass model

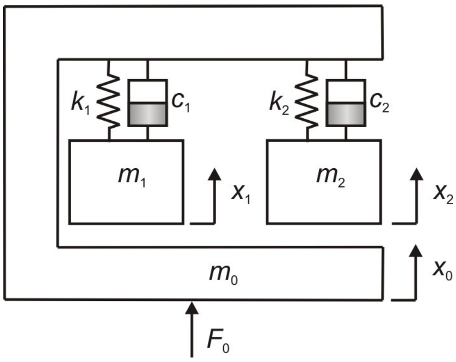

Figure 3.7 Two degree-of-freedom apparent mass model

The equations of motion are:

$$F_0 = m_0\ddot{x}_0 + (c_1 + c_2)\dot{x}_0 + (k_1 + k_2)x_0 - c_1\dot{x}_1 - k_1x_1 - c_2\dot{x}_2 - k_2x_2 \quad \textbf{3.11}$$

$$0 = m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - c_1\dot{x}_0 - k_1x_0 \quad \textbf{3.12}$$

$$0 = m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2x_2 - c_2\dot{x}_0 - k_2x_0 \quad \textbf{3.13}$$

Using the Laplace Transform ($x \to X$, $\dot{x} \to sX$, $\ddot{x} \to s^2X$) the equations of motions can be expressed as:

$$F_0(s) = A_1X_0 - A_2X_1 - A_3X_2 \quad \textbf{3.14}$$

$$0 = A_5X_1 - A_2X_0 \quad \textbf{3.15}$$

$$0 = A_4X_1 - A_3X_0 \quad \textbf{3.16}$$

where:

$$A_1 = m_0s^2 + (c_1 + c_2)s + k_1 + k_2 \quad \textbf{3.17}$$

$$A_2 = c_1s + k_1 \quad \textbf{3.18}$$

$$A_3 = c_2s + k_2 \quad \textbf{3.19}$$

$$A_4 = m_1s^2 + c_1s + k_1 \quad \textbf{3.20}$$

$$A_4 = m_2s^2 + c_2s + k_2 \quad \textbf{3.21}$$

By substitution, X_1 and X_2 can be expressed in terms of X_0:

$$X_1 = \frac{A_2X_0}{A_4} \text{ and } X_2 = \frac{A_3X_0}{A_5} \quad \textbf{3.22, 3.23}$$

Substituting eq. 3.22 and 3.23 into eq. 3.14 the force acting at the base, $F_0(s)$, can be expressed as:

$$F_0(s) = A_1X_0 - \frac{A_2^2X_0}{A_4} - \frac{A_3^2X_0}{A_5} \quad \textbf{3.24}$$

By Newton's Second Law, the apparent mass, $M(s)$, is given by:

$$M(s) = \frac{F_0}{X_0s^2} = \left(A_1 - \frac{A_2^2}{A_4} - \frac{A_3^2}{A_5}\right)\left(\frac{1}{s^2}\right) \quad \textbf{3.25}$$

The modulus (i.e. $|M|$) and the phase (i.e. arctan^{-1}(M)) of the apparent mass can then be calculated by replacing the Laplace Transform operator s with angular frequency ω ($s = \omega i$, where i is the imaginary operator).

3.7.3 Two degree-of-freedom seat transmissibility model

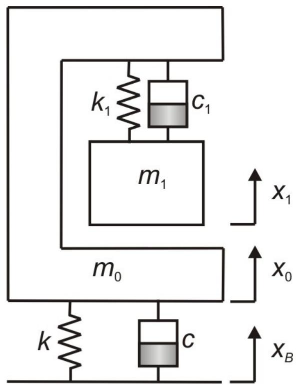

Figure 3.8 Two degree=of-freedom seat transmissibility model

The equations of motion are:

$$0 = m_0\ddot{x}_0 + (c + c_1)\dot{x}_0 + (k + k_1)x_0 - c.\dot{x}_B - k.x_B - c_1\dot{x}_1 - k_1x_1 \qquad \textbf{3.26}$$

$$0 = m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - c_1\dot{x}_0 - k_1x_0 \qquad \textbf{3.27}$$

Using the Laplace Transform ($x \to X$, $\dot{x} \to sX$, $\ddot{x} \to s^2X$) the equations of motions can be expressed as:

$$0 = A_1X_0 - A_2X_B - A_3X_1 \qquad \textbf{3.28}$$

$$0 = A_4X_1 - A_3X_0 \qquad \textbf{3.29}$$

where:

$$A_1 = m_0s^2 + (c + c_1)s + k + k_1$$

$$A_2 = c.s + k \qquad \textbf{3.30}$$

$$A_3 = c_1s + k_1 \qquad \textbf{3.31}$$

$$A_4 = m_1s^2 + c_1s + k_1 \qquad \textbf{3.32}$$

By substitution, X_1 can be expressed in terms of X_0:

$$X_1 = \frac{A_3X_0}{A_4} \qquad \textbf{3.33}$$

Substituting eq. 3.33 into eq. 3.28:

$$0 = A_1X_0 - A_2X_B - \frac{A_3^2X_0}{A_4} \qquad \textbf{3.34}$$

By rearranging the seat transmissibility, *T(s)*, is given by:

$$T(s) = \frac{X_0}{X_B} = \frac{A_2}{\left(A_1 - \frac{A_3^2}{A_4}\right)} \qquad \textbf{3.35}$$

The modulus (i.e. $|T|$) and the phase (i.e. $\arctan^{-1}(T)$) of the seat transmissibility can then be calculated by replacing the Laplace Transform operator *s* with angular frequency ω ($s = \omega i$, where *i* is the imaginary operator).

3.7.4 Three degree-of-freedom seat transmissibility model

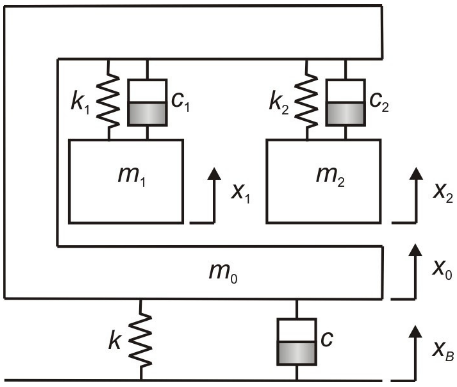

Figure 3.9 Three degree-of-freedom seat transmissibility model

The equations of motion are:

$$0 = m_0\ddot{x}_0 + (c + c_1 + c_2)\dot{x}_0 + (k + k_1 + k_2)x_0 - c.\dot{x}_B - k.x_B - c_1\dot{x}_1 - k_1x_1 - c_2\dot{x}_2 - k_2x_2 \qquad \textbf{3.36}$$

$$0 = m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - c_1\dot{x}_0 - k_1x_0 \qquad \textbf{3.37}$$

$$0 = m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2x_2 - c_2\dot{x}_0 - k_2x_0 \qquad \textbf{3.38}$$

Using the Laplace Transform ($x \to X$, $\dot{x} \to sX$, $\ddot{x} \to s^2X$) the equations of motions can be expressed as:

$$0 = A_1X_0 - A_2X_B - A_3X_1 - A_4X_2 \qquad \textbf{3.39}$$

$$0 = A_5X_1 - A_3X_0 \qquad \textbf{3.40}$$

$$0 = A_6X_1 - A_3X_0 \qquad \textbf{3.41}$$

where:

$$A_1 = m_0s^2 + (c + c_1 + c_2)s + k + k_1 + k_2$$

$$A_2 = c.s + k \qquad \textbf{3.42}$$

$$A_3 = c_1s + k_1 \qquad \textbf{3.43}$$

$$A_4 = c_2s + k_2 \qquad \textbf{3.44}$$

$$A_5 = m_1s^2 + c_1s + k_1 \qquad \textbf{3.45}$$

$$A_6 = m_2s^2 + c_2s + k_2 \qquad \textbf{3.46}$$

By substitution, X_1 and X_2 can be expressed in terms of X_0:

$$X_1 = \frac{A_3X_0}{A_5} \text{ and } X_2 = \frac{A_4X_0}{A_6} \qquad \textbf{3.47, 3.48}$$

Substituting eq. 3.47 and 3.48 into eq. 3.39:

$$0 = A_1X_0 - A_2X_B - \frac{A_3^2X_0}{A_5} - \frac{A_4^2X_0}{A_6} \qquad \textbf{3.49}$$

By rearranging the seat transmissibility, *T(s)*, is given by:

$$T(s) = \frac{X_0}{X_B} = \frac{A_2}{\left(A_1 - \frac{A_3^2}{A_5} - \frac{A_4^2}{A_6}\right)} \qquad \textbf{3.50}$$

The modulus (i.e. $|T|$) and the phase (i.e. $\arctan^{-1}(T)$) of the seat transmissibility can then be calculated by replacing the Laplace Transform operator *s* with angular frequency ω ($s = \omega i$, where *i* is the imaginary operator).

CHAPTER 4: EFFECT OF SEAT BACKREST ON APPARENT MASS

4.1 INTRODUCTION

The apparent mass of the human body has often been measured with subjects sitting on a flat rigid seat with no back support (e.g. Fairley and Griffin, 1989; Holmlund *et al.*, 2000). Sitting in a car seat involves contact with a backrest, with the backrest varying greatly from one car to another and presenting different contact conditions from those in most laboratory studies of apparent mass.

Some of the mass of a seated body can be supported by a backrest, so even with a rigid vertical backrest the apparent mass at low frequencies can be reduced by a backrest (Nawayseh and Griffin, 2004). Some studies have found that the resonance frequency and the apparent mass between 5 and 18 Hz tend to be increased by a backrest (Nawayseh and Griffin, 2004; Wang *et al.*, 2004). When a backrest is reclined, a greater proportion of the body mass is supported by the backrest (approximately 30% with a backrest reclined to 24° (Rakheja *et al.*, 2006). Compared with an upright backrest, the resonance frequency, and the apparent mass at frequencies greater than the resonance frequency, have been reported to increase when subjects are supported by a rigid backrest inclined to 12° (Wang *et al.*, 2004). With the upper-body supported by a rigid backrest inclined by 24°, the apparent mass normal to the backrest has been reported to have peaks with a magnitude similar to those measured at the seat surface (Rakheja *et al.*, 2002). The apparent masses of subjects supported in an 'automotive posture' (rigid backrest inclined by 24°, seat pan inclined by 13°) showed peaks between 6.5 and 8.6 Hz, compared to 4.5 to 5.5 Hz in studies where the back was unsupported or supported by an upright backrest (Rakheja *et al.*, 2006). With subjects fully reclined to the supine position, the dominant resonance frequency in the apparent mass has been reported to reduce from 10.4 to 7.3 Hz as the vibration magnitude increased from 0.125 to 1.0 ms^{-2} r.m.s. (Huang and Griffin, 2008).

Reduced seat transmissibility has been reported at resonance when the back is supported by a foam backrest than when it is supported by a rigid backrest, with the transmissibility at resonance decreasing less when reclining a foam backrest than when reclining a rigid backrest (Appendix B). It seems likely that some of the reported variations in seat transmissibility can be explained by the dynamic properties of seat cushions and variations in the biodynamic responses of the body. The thickness of foam used in a seat has a systematic effect on seat transmissibility and the frequency of the primary seat resonance, consistent with increased hysteretic damping with increased foam thickness (Ebe and Griffin, 2000). The effect of foam at a backrest on the vertical apparent mass of the body measured at the seat surface has not previously been reported.

The objectives of this study were to investigate the effects of backrest contact, backrest inclination, and backrest foam thickness on the vertical apparent mass measured at the seat surface. It was anticipated that reclining the backrest would reduce the mass supported on the seat surface and, with increased support for the upper-body, the frequency of the primary resonance would increase. It was further hypothesised that the addition of foam to the backrest would reduce the magnitude of the primary resonance in the apparent mass measured at the seat surface, and that the apparent mass at resonance would decrease further with increasing inclination of the backrest as a greater proportion of the mass of the body was supported by the backrest.

4.2 METHODS AND PROCEDURES

4.2.1 Apparatus

The vertical apparent mass of the human body was measured on the surface of a rigid seat with an adjustable backrest. The seat was mounted to a 1-m stroke electro-hydraulic vertical vibrator. Foam squabs of uniform thickness were attached to the backrest of the seat and adjustments made so that with 50-mm, 100-mm and 150-mm thick foam backrests and a rigid backrest the subject posture remained unchanged. The dynamic properties of the 100-mm foam had been previously measured using a SIT-bar shaped indenter with a 100-N preload. Over the range of frequencies studied here, the foam stiffness was found to be approximately 21 kN/m and the damping approximately 109 Ns/m. Subjects sat with their feet supported on a footrest inclined at 35 degrees to the horizontal. The angle of the footrest and its vertical position relative to the seat were chosen to create a posture representative of a car driver. Subjects were instructed to adjust the fore-and-aft position of the footrest to obtain a posture similar to their normal driving posture. A loose lap strap was fastened around the subjects for safety purposes. The general arrangement of the apparatus is illustrated in Figure 4.1.

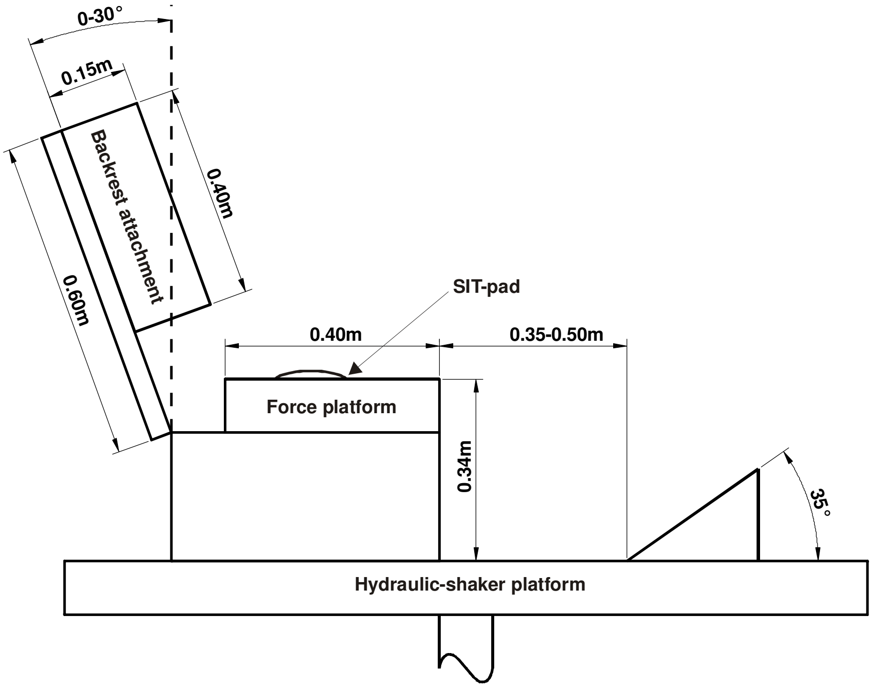

Figure 4.1 General arrangement of the seat, footrest, and transducers on the vibrator platform.

The vertical force on the seat surface was measured using a Kistler 9821B force platform consisting of four single-axis piezo-electric force cells located beneath each corner of a top plate. The charge output from the four force cells was summed and conditioned using a Kistler 5001 charge amplifier. An *HVLab* SIT-pad containing an Entran EGCSDO-10 piezo-resistive accelerometer was used to measure the vertical acceleration on the seat surface.

4.2.2 Backrest conditions

The vertical apparent masses of seated subjects were measured with different backrest conditions to investigate the effects of: (i) an upright rigid backrest and three thicknesses of upright foam backrest (50 mm, 100 mm and 150 mm); (ii) the angle of inclination with rigid and 100-mm thick foam backrests (from 0 to 30 degrees in 5-degree increments); (iii) the angle of inclination with 50 mm and 150 mm foam backrests (from 0 to 30 degrees in 10-degree increments). Additionally, the vertical apparent mass of each subject was measured in an upright posture with no backrest contact. In all conditions, the subjects were asked to maintain a relaxed posture without slouching. They placed their hands in their laps and looked straight ahead.

Subjects were exposed to the 23 conditions in a single session lasting approximately 1 hour. The conditions were presented to subjects in independent random orders to minimize the influence of order effects.

4.2.3 Vibration

The platform was excited using 60-s periods of Gaussian random vibration at 1.0 ms^{-2} r.m.s. band-limited by 8-pole Butterworth filters between 0.125 and 40 Hz. Over this frequency range the constant bandwidth acceleration spectrum was approximately flat. Signals were generated and analysed using an *HVLab* data acquisition and analysis system (version 3.81). Different random signals were generated for each subject and equalized for the response of the vibrator. Signals from the force platform and the accelerometer were sampled at 400 samples per second via 133 Hz anti-aliasing filters.

4.2.4 Subjects

Twelve healthy male subjects (aged 21 to 48 years mean 28.1 years) participated in the study. Their statures ranged between 1.69 and 1.86 m (mean 1.81 m) and their weights between 64 and 93 kg (mean 74.4 kg).

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.

4.2.5 Analysis

Mass cancellation was performed to remove the influence of the mass of the top-plate of the force platform (33.0 kg) from the measured force. Mass cancellation was performed in the time domain: the acceleration time-history on the seat surface was multiplied by the mass of the force platform, and then subtracted from the measured force response.

Transfer functions were calculated between the vertical seat acceleration and the vertical force at the seat surface after mass cancellation, to give the apparent masses of the subjects. The apparent mass, $H_{io}(f)$, was calculated from the cross spectral density between the acceleration and the force at the seat, $G_{io}(f)$, and the power spectral density of the acceleration at the seat, $G_{ii}(f)$, using a resolution of 0.195 Hz:

$$H_{io}(f) = \frac{G_{io}(f)}{G_{ii}(f)}. \quad \textbf{4.1}$$

The coherency between the force and acceleration was calculated after mass cancellation in the time domain and found to be greater than 0.9 over the frequency range 0.4 to 30 Hz; above 30 Hz the coherency tended to decrease slightly but was still generally over 0.8.

The medians of the primary resonance frequencies and the apparent masses at resonance for the 12 subjects were calculated for each condition. The apparent mass at the primary resonance frequency was assumed to be the greatest apparent mass over the measurement range. The primary resonance frequency was defined as the frequency at which the apparent mass was greatest.

Data analysis was performed using non-parametric statistical methods using SPSS (version 14). Non-parametric tests (Friedman test for *k*-related samples and the Wilcoxon matched-pairs signed ranks test for two-related samples) were employed in the statistical analysis. Non-parametric statistics were used to avoid assuming a normal distribution in the data.

4.3 RESULTS

4.3.1 Effect of backrest contact

The vertical apparent masses of the 12 subjects with no-backrest, with a rigid vertical backrest, and with a vertical 100-mm foam backrest are compared in Figure 4.2. With all three backrest conditions, the apparent mass increased to a peak around 5 Hz and decreased at higher frequencies. Some subjects exhibited a second resonance, with the frequency varying between subjects over the range 7 to 14 Hz. At frequencies between 15 and 40 Hz there was no evidence of major resonances of the body. The phase lag between the vertical acceleration and the vertical force increased to 1.5 radians around the resonance and then remained approximately constant to higher frequencies. For some subjects the phase response decreased or increased slightly from 15 to 40 Hz. The phase can be very much influenced by imperfect mass cancellation – the response at 40 Hz may have been influenced by small errors in the mass cancellation for some subjects. The median apparent masses for these three conditions are shown in Figure 4.3.

The medians of the resonance frequencies of the 12 subjects with each of the 23 backrest conditions are given in Table 4.1 and the medians of the individual apparent masses at each subject's resonance frequency are shown in Table 4.2. There was no significant difference between no-backrest, a vertical rigid backrest, and a vertical 100-mm foam backrest in either the frequency of the primary resonance or the apparent mass at resonance ($p = 0.12$ and $p = 0.17$, respectively; Friedman).

Further statistical analysis was conducted to investigate whether backrest contact affected the proportion of the subject mass supported on the seat surface. At very low frequencies the measured apparent mass of a subject is approximately equal to the static mass supported on the seat surface, because the body is almost rigid. Significant differences in apparent mass were found between the three backrest conditions (no-backrest, a vertical rigid backrest, and a vertical 100-mm foam backrest) at 0.4 Hz (Friedman, $p = 0.01$). The apparent mass at 0.4 Hz reduced by approximately 10 kg with a rigid and a foam backrest compared to no-backrest ($p < 0.01$; Wilcoxon). There was no significant difference in the mass supported on the seat surface with the rigid and the foam backrests ($p = 0.35$).

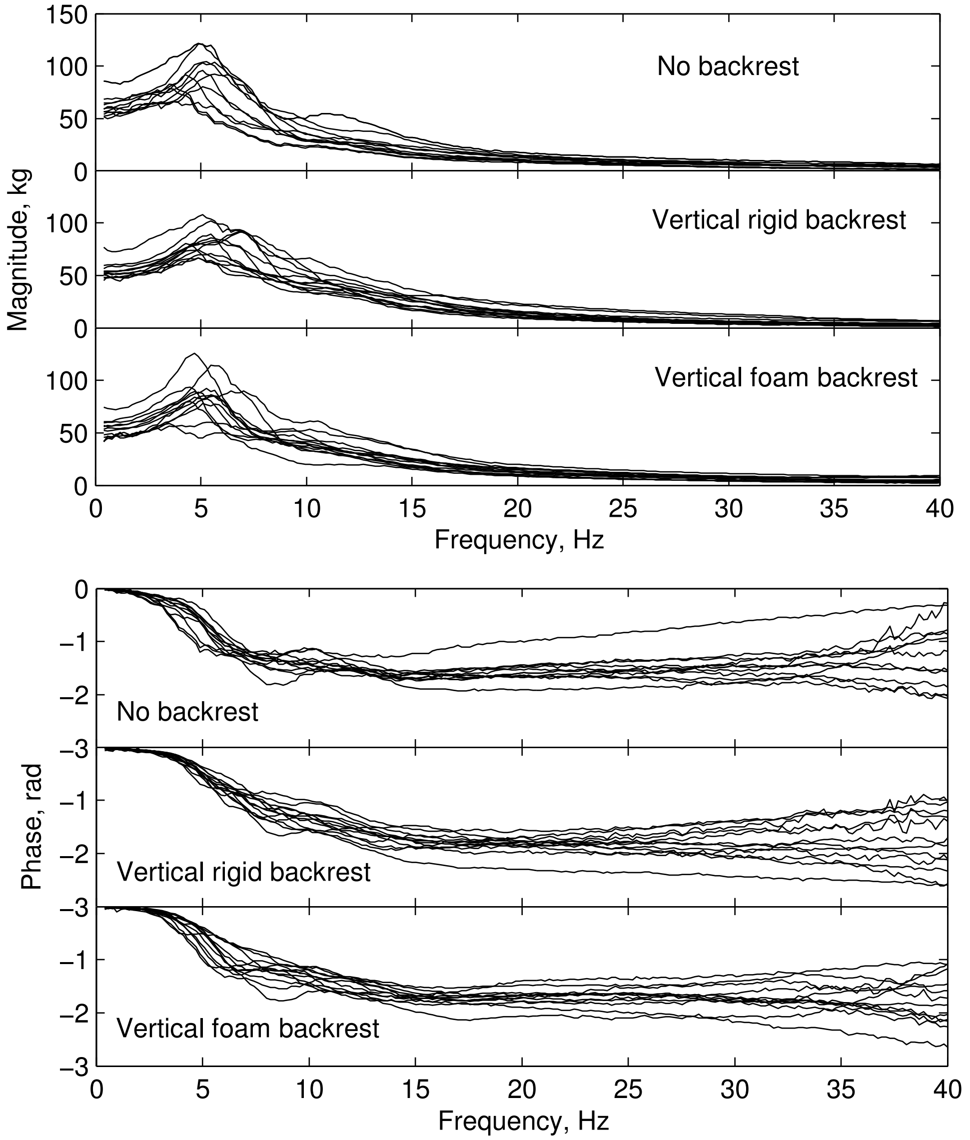

Figure 4.2 Moduli and phases of the vertical apparent masses of the 12 subjects with no backrest, a vertical rigid backrest, and a vertical foam (100 mm) backrest.

At frequencies between 7 and 15 Hz, the apparent mass in the three conditions was influenced by the backrest (Friedman, $p < 0.01$). The apparent mass increased when there was contact with the rigid backrest compared to no-backrest (at 12 Hz, $p = 0.02$; Wilcoxon), and between the foam backrest and the no-backrest conditions ($p = 0.01$; Wilcoxon). There was no significant difference in apparent mass between the no-backrest and the foam backrest conditions ($p = 0.27$).

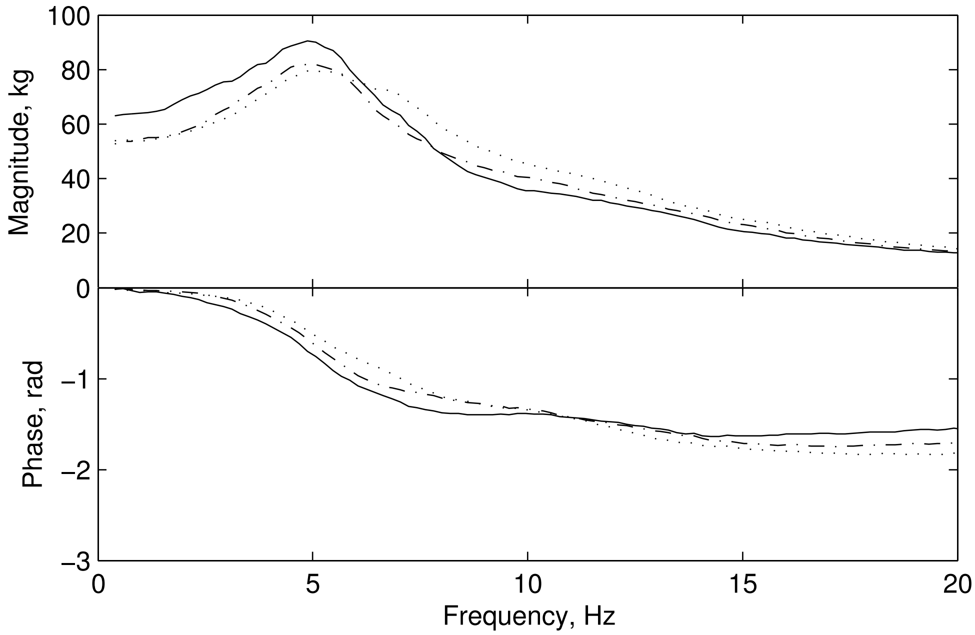

Figure 4.3 Effect of backrest contact and backrest type on the modulus and phase of the median apparent mass (median vertical apparent mass of 12 subjects measured on the seat): ——— , no backrest; · · · · · · , rigid backrest at 0°; · - · - · - ,100-mm foam backrest at 0°.

A comparison of apparent masses at 40 Hz produced significant differences between pairs of conditions similar to those at 12 Hz. The influences of other backrest variables (angle, foam thickness) on apparent mass were also statistically significant at 40 Hz if they were significant at 12 Hz. Consequently, subsequent figures and analysis are only presented for frequencies less than 20 Hz.

Table 4.1 Median resonance frequencies and interquartile values (25%, 75%) in the apparent mass moduli for the 23 backrest conditions.

Angle	Frequency (Hz)				
	No backrest	Rigid backrest	50-mm foam backrest	100-mm foam backrest	150-mm foam backrest
0°	**5.0** (4.1,5.2)	**5.5** (4.9,5.6)	**5.6** (5.1,5.8)	**5.2** (4.7,5.5)	**5.3** (5.1,5.8)
5°		**5.5** (5.5,6.4)		**5.4** (4.9,5.7)	
10°		**5.6** (5.3,6.4)	**4.9** (4.7,5.6)	**5.0** (4.8,5.6)	**4.9** (4.6,5.5)
15°		**6.3** (5.6,6.5)		**4.9** (4.6,5.3)	
20°		**6.3** (5.6,6.6)	**4.8** (4.5,5.3)	**4.7** (4.6,5.1)	**4.6** (4.4,5.0)
25°		**5.8** (5.3,6.3)		**4.6** (4.2,4.8)	
30°		**6.4** (6.1,6.9)	**4.9** (4.9,5.3)	**4.5** (4.1,4.7)	**4.2** (3.7,4.8)

Table 4.2 Median apparent masses and interquartile values (25%, 75%) at the primary resonances for the 23 backrest conditions.

Angle	Apparent mass (kg)				
	No backrest	Rigid backrest	50-mm foam backrest	100-mm foam backrest	150-mm foam backrest
0°	**94.1** (81.5,103.8)	**83.7** (72.4,90.2)	**86.1** (76.7,89.3)	**87.3** (78.8,91.1)	**83.6** (74.1,91.6)
5°		**82.0** (77.7,88.2)		**85.5** (74.9,92.4)	
10°		**78.4** (71.8,86.3)	**89.0** (76.6,91.6)	**87.2** (73.8,94.3)	**88.1** (70.1,93.8)
15°		**76.3** (71.7,84.1)		**89.5** (79.5,97.0)	
20°		**75.1** (69.0,81.9)	**86.4** (78.9,94.5)	**85.8** (76.4,96.0)	**90.8** (79.3,92.1)
25°		**73.2** (66.4,75.8)		**84.7** (71.0,89.0)	
30°		**70.3** (62.4,75.3)	**75.8** (72.3,86.1)	**79.3** (67.2,83.5)	**76.3** (69.0,82.0)

4.3.2 Effect of inclination of the rigid backrest

The median apparent masses of the 12 subjects measured with each inclination of the rigid backrest are shown in Figure 4.4. The frequency of the primary resonance tended to increase as the backrest was reclined from 0° to 25°, although only when the backrest was reclined to 15° and 20° was the resonance frequency significantly greater than with the upright backrest ($p < 0.05$). The resonance frequency with the backrest inclined to 30° was significantly greater than when the backrest was inclined to 0, 5, 10 and 25° ($p < 0.05$) but was not significantly greater than with 15° and 20° inclination ($p > 0.05$, Table 4.3).

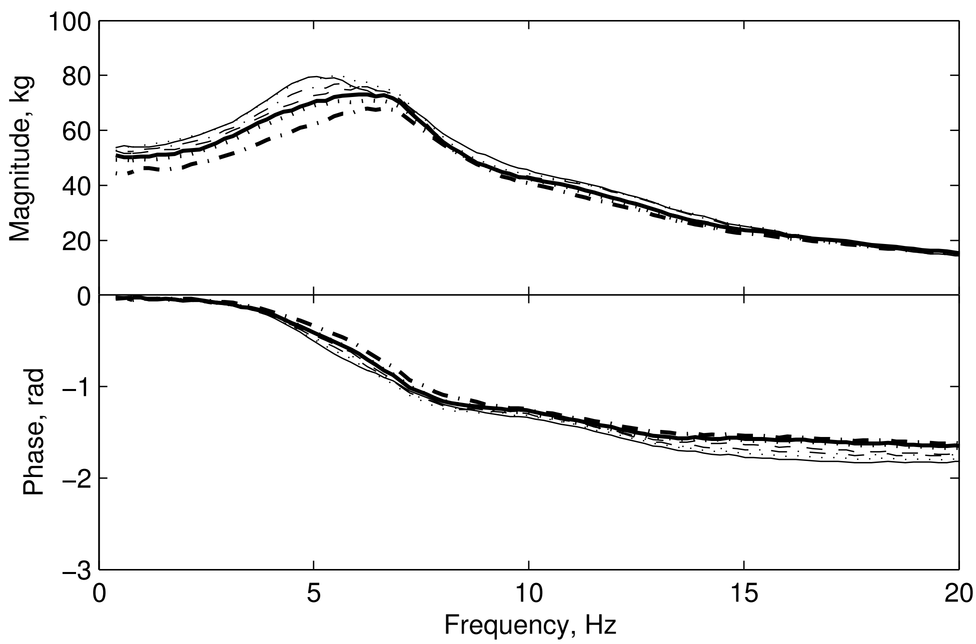

Figure 4.4 Effect of inclination of a rigid backrest on the median vertical apparent masses of 12 subjects measured on the seat: ———, 0°; · · · · · ·, 5°; · - · - · - 10°; - - - - - ,15°; ━━━ ,20°; ▪ ▪ ▪ ▪ ▪ ,25°; · ━ · ━ · ,30°.

Table 4.3 Effect of inclination of the rigid backrest: results of Wilcoxon matched-pairs signed-ranks tests and directions of change for differences in the apparent mass resonance frequency and apparent mass at resonance, at 0.4 Hz, and at 12 Hz.

Backrest inclination, degrees	5	10	15	20	25	30
(a) Resonance frequency						
0	ns –	ns ↑	* ↑	* ↑	ns ↑	** ↑
5		ns ↑	ns ↑	ns ↑	ns ↑	* ↑
10			ns ↑	ns ↑	ns ↑	* ↑
15				ns ↑	ns ↑	ns ↑
20					ns ↑	ns ↑
25						* ↑
(b) Apparent mass at resonance						
0	ns ↓	ns ↓	ns ↓	* ↓	* ↓	** ↓
5		* ↓	** ↓	** ↓	** ↓	** ↓
10			ns ↓	* ↓	* ↓	** ↓
15				ns ↓	ns ↓	** ↓
20					ns ↓	** ↓
25						* ↓
(c) Apparent mass at 0.4 Hz						
0	ns ↑	ns ↓	ns ↑	** ↓	** ↓	** ↓
5		ns ↑	* ↓	* ↓	* ↓	** ↓
10			ns ↑	* ↓	** ↓	** ↓
15				** ↓	** ↓	** ↓
20					** ↓	** ↓
25						** ↓
(d) Apparent mass at 12 Hz						
0	ns ↑	ns ↓	ns ↓	ns ↓	* ↓	** ↓
5		ns ↓	ns ↓	ns ↓	* ↓	** ↓
10			ns ↓	ns ↓	** ↓	** ↓
15				ns ↑	ns ↓	* ↓
20					ns ↓	* ↓
25						ns ↓

ns = not significant, $p > 0.05$; *$p < 0.05$; **$p < 0.01$.
↑ median higher with greater backrest angle, ↓ median lower with greater backrest angle,
– median same with both backrest angles.

At frequencies less than 8 Hz, the apparent mass tended to reduce as the backrest was reclined. A similar but lesser effect is seen in the apparent mass between 10 and 15 Hz. At frequencies greater than 15 Hz, the apparent mass was unaffected by backrest inclination. The apparent mass at the primary resonance tended to decrease with increasing backrest inclination, with significant differences between 14 of the 21 pairs of backrest inclinations ($p < 0.05$; Table 4.3).

The median 'static mass' supported on the platform (i.e. the apparent mass at 0.4 Hz) decreased from 51.7 kg to 43.9 kg as the backrest was reclined from 0° to 30°. The apparent mass at 0.4 Hz was unaffected by variations in backrest inclinations up to 15°, but was significantly reduced with the backrest inclined at 20, 25, and 30° ($p < 0.05$; Table 4.3).

4.3.3 Effect of inclination of the 100-mm foam backrest

Figure 4.5 shows the effect of reclining the 100-mm foam backrest on the median apparent mass; statistical analysis is given in Table 4.4. With inclinations greater than 5°, the resonance frequency tended to decrease with increasing backrest angle. This differs from the effect of reclining the rigid backrest where the resonance frequency tended to increase with increasing backrest inclination. There were significant differences between the resonance frequencies with 14 of the 21 backrest pairs (p < 0.05). However, the resonance frequencies with the backrest reclined to 5, 10, and 15° (p > 0.05) did not differ from that with the upright backrest.

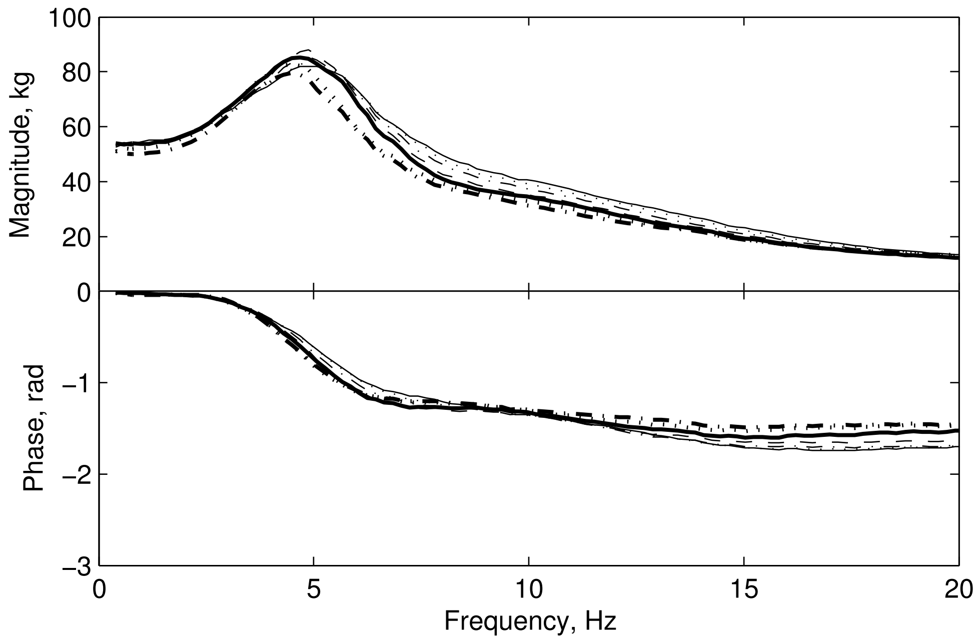

Figure 4.5 Effect of inclination of a 100-mm foam backrest on the median vertical apparent masses of 12 subjects measured on the seat: ——— , 0°; · · · · · · , 5°; · - · - · - 10°; - - - - - ,15°; ▬▬▬ ,20°; ▪ ▪ ▪ ▪ ▪ ,25°; · ▬ · ▬ · ,30°.

The static mass supported on the seat surface (the apparent mass at 0.4 Hz) was unaffected by inclinations of the 100-mm foam backrest up to 25° (p > 0.05; Friedman). As the inclination increased from 25° to 30°, the apparent mass reduced from 51.7 kg to 48.8 kg. There were statistically significant differences in the apparent mass at 0.4 Hz between 5° and 30°, between 15° and 30°, and between 20° and 30° (p < 0.05). Similarly, the apparent mass at resonance was broadly unchanged with backrest angles up to 25° but decreased at 30°. The apparent mass between 8 and 20 Hz tended to decrease with increasing backrest inclination, with significant differences between 15 of the 21 pairs of backrest inclinations for the response at 12 Hz (p < 0.05).

Table 4.4 Effect of inclination of the 100-mm foam backrest: results of Wilcoxon matched-pairs signed-ranks test and directions of change for differences in the apparent mass resonance frequency and apparent mass at resonance, at 0.4 Hz and at 12 Hz.

Backrest inclination, degrees	5	10	15	20	25	30
(a) Resonance frequency						
0	ns ↑	ns ↓	ns ↓	ns ↓	* ↓	* ↓
5		* ↓	* ↓	** ↓	** ↓	** ↓
10			ns	* ↓	** ↓	** ↓
15				ns ↓	* ↓	* ↓
20					* ↓	* ↓
25						ns
(b) Apparent mass at resonance						
0	ns ↓	ns ↓	ns ↑	ns ↓	ns ↓	ns ↓
5		ns ↑	ns ↑	ns ↑	ns ↓	ns ↓
10			ns ↑	ns ↓	ns ↓	* ↓
15				ns ↓	** ↓	** ↓
20					* ↓	** ↓
25						ns ↓
(c) Apparent mass at 0.4 Hz						
0	ns ↓	ns –	ns ↓	ns ↓	ns ↓	ns ↓
5		ns ↑	ns ↓	ns ↓	ns ↑	* ↓
10			ns ↓	ns ↓	ns ↓	ns ↓
15				ns ↑	ns ↑	* ↓
20					ns ↑	** ↓
25						ns ↓
(d) Apparent mass at 12 Hz						
0	ns –	ns ↓	* ↓	* ↓	** ↓	** ↓
5		ns ↓	* ↓	* ↓	** ↓	** ↓
10			ns ↓	* ↓	** ↓	** ↓
15				ns ↓	* ↓	* ↓
20					* ↓	** ↓
25						ns ↓

ns = not significant, $p > 0.05$; *$p < 0.05$; **$p < 0.01$.
↑ median higher with greater backrest angle, ↓ median lower with greater backrest angle, – median same with both backrest angles.

4.3.4 Effect of backrest foam thickness at different backrest inclinations

The effect on apparent mass of increasing the thickness of the foam on the backrest at different angles of backrest inclination is shown in Figure 4.6. With the upright backrest, the apparent masses with the three foam thicknesses were similar at frequencies less than 8 Hz, with no significant differences in either the apparent mass at 0.4 Hz or the apparent mass at resonance ($p > 0.1$, Friedman). At frequencies between 8 and 20 Hz, the rigid backrest resulted in slightly greater apparent mass compared to the foam backrests. There were significant differences in apparent mass between the rigid backrest and the three thicknesses of foam backrest at 12 Hz, but no significant difference in apparent mass between the three foam backrests at this frequency.

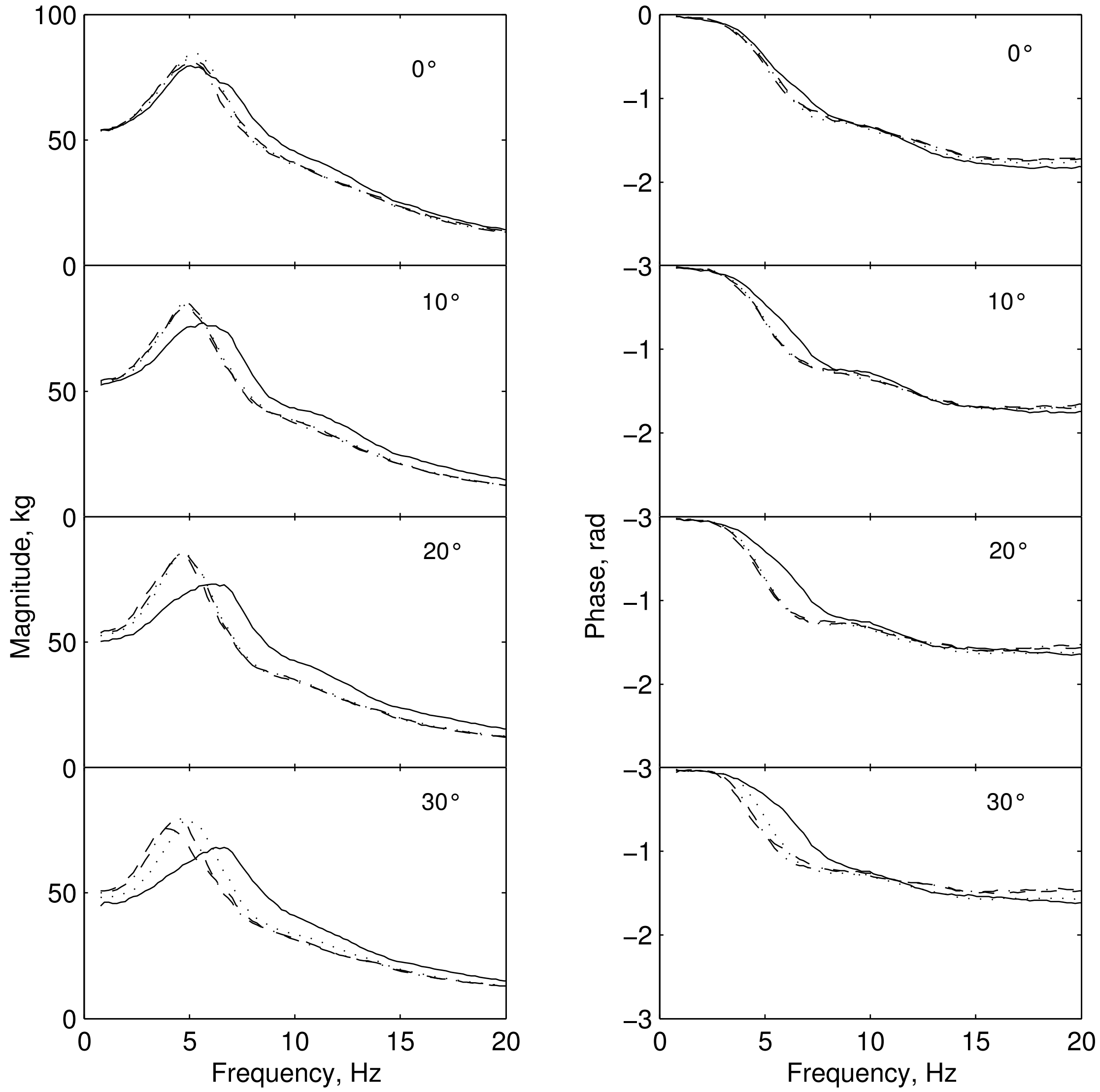

Figure 4.6 Effect of backrest foam thickness at different backrest inclinations on the median vertical apparent masses of 12 subjects measured on the seat: ——— , rigid backrest; · · · · · · , 50-mm foam; · - · - · - 100-mm foam; - - - - - , 150-mm foam.

With the backrest inclined to 10 degrees, the apparent mass was unaffected by the thickness of the three foam backrests, but the apparent mass was greater with the rigid backrest at frequencies between 7 and 30 Hz ($p < 0.05$ at 12 Hz).

With the backrest inclined to 20°, a difference between the rigid backrest and the three thicknesses of foam backrest was more evident. With the rigid backrest, the apparent mass was reduced at frequencies less than 8 Hz but increased at higher frequencies than with the three foam backrests. There were significant differences in the apparent mass between the rigid backrest and all three thicknesses of foam backrest at resonance and at 12 Hz. At 0.4 Hz there were significant differences in the apparent mass between the rigid and the two thicker foam backrests ($p < 0.05$) and also between the 50 mm foam backrest and the other two foam backrests ($p < 0.05$). The resonance frequency of the apparent mass was significantly higher with the rigid backrest than with each of the three thickness of foam backrest ($p < 0.05$).

Table 4.5 Statistically significant different (i.e. p<0.05) pairs of backrest foam thicknesses with different backrest inclinations. 0: rigid backrest; 50: 50-mm foam backrest; 100: 100-mm foam backrest; 150: 150-mm foam backrest.

	Resonance frequency	Apparent mass at resonance	Apparent mass at 0.4 Hz	Apparent mass at 12 Hz	Total out of 24 possible combinations
Backrest at 0°				0/50 ↓ 0/100 ↓ 0/150 ↓	3
Backrest at 10°				0/50 ↓ 0/100 ↓ 0/150 ↓	3
Backrest at 20°	0/50 ↓ 0/100 ↓ 0/150 ↓ 100/150 ↓	0/50 ↑ 0/100 ↑ 0/150 ↑	0/100 ↑ 0/150 ↑ 50/100 ↑ 50/150 ↑	0/50 ↓ 0/100 ↓ 0/150 ↓	14
Backrest at 30°	0/50 ↓ 0/100 ↓ 0/150 ↓ 50/100 ↓ 50/150 ↓	0/50 ↑ 0/100 ↑ 0/150 ↑	0/50 ↑ 0/100 ↑ 0/150 ↑ 50/100 ↑ 50/150 ↑	0/50 ↓ 0/100 ↓ 0/150 ↓ 50/100 ↓ 50/150 ↓	18

Comparisons shown where p < 0.05; Wilcoxon matched-pairs signed ranks test.
↑ median higher with greater foam thickness, ↓ median lower with greater foam thickness.

With the backrest inclined to 30°, the apparent mass with the 50-mm foam backrest was lower at 0.4 Hz and higher at 12 Hz compared to the apparent mass with the 100-mm and 150-mm foam backrests ($p < 0.05$). The apparent mass resonance frequency with the rigid backrest, was 6.4 Hz, and significantly higher than with the 150-mm foam backrest, at 4.2 Hz ($p < 0.01$). The resonance frequency was also higher with the 50-mm foam backrest than with the other two thicker backrests ($p < 0.05$; Table 4.1).

4.3.5 Effect of backrest angle with different thicknesses of foam backrest

The effect of backrest angle on apparent mass with the rigid backrest and the three thicknesses of foam backrest is shown in Figure 4.7. At low frequencies (i.e., < 1 Hz) and at resonance there is a small but consistent reduction in the apparent mass as the backrest angle increases with the rigid backrest, but this is less noticeable with the foam backrests. This was borne out in the statistical analysis which showed that, at 0.4 Hz and at resonance, the number of significant differences between apparent masses at pairs of backrest angles was less for each of the foam backrests than the rigid backrest (Table 4.6). From 8 to 20 Hz, the variation in apparent mass with backrest inclination tended to increase with increasing foam thickness, with the apparent mass generally decreasing as the backrest was reclined. At 12 Hz, the differences in apparent mass were significant between five of the six backrest angle pairs for both the 100-mm and the 150-mm foam backrests compared to only three of the six for the rigid backrest.

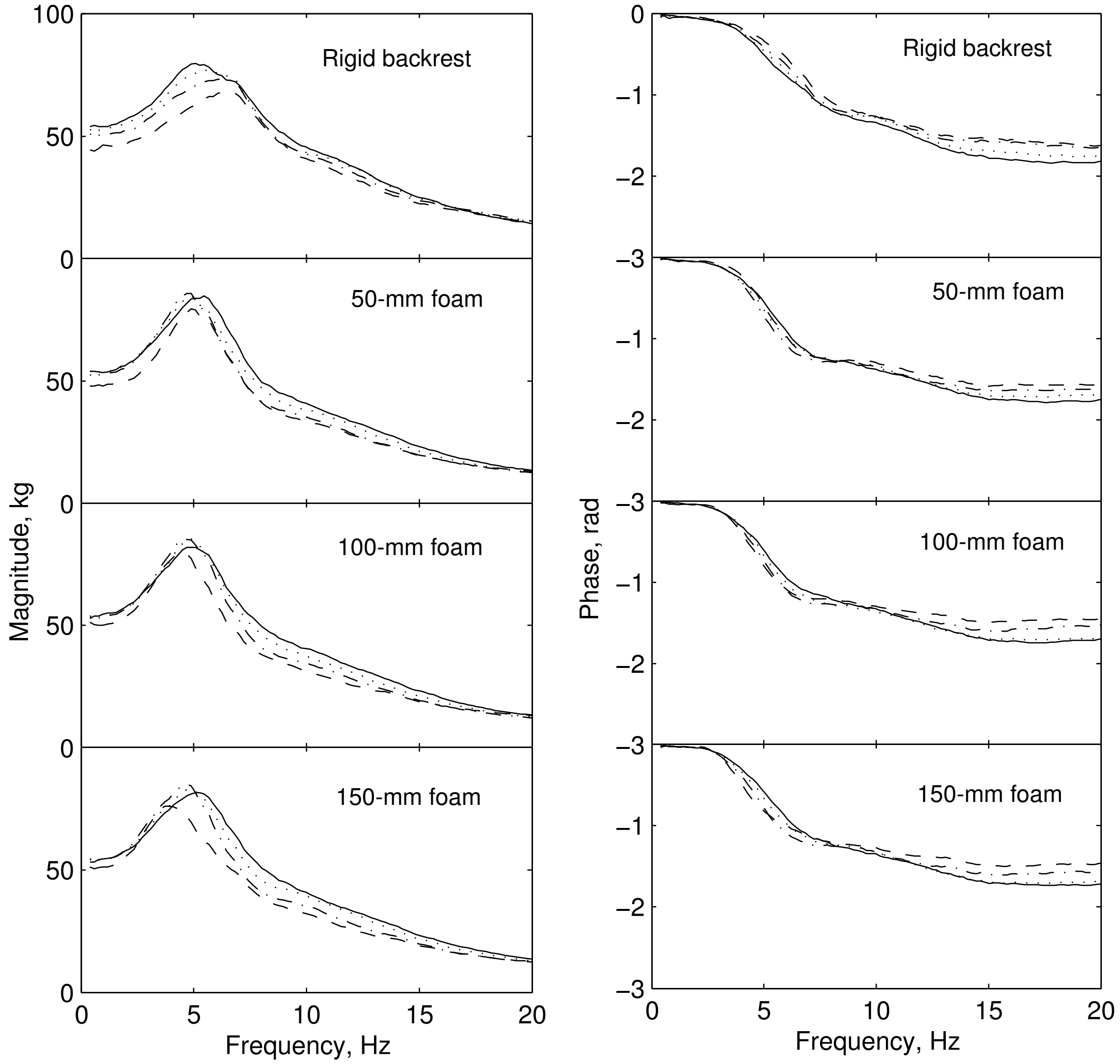

Figure 4.7 Effect of backrest inclination with different thicknesses of foam backrest on the median vertical apparent masses of 12 subjects measured on the seat: ——— , 0°; · · · · · · , 10°; - · - · - 20°; - - - - - ,30°.

With the rigid backrest, as the backrest angle increased the frequency of the first resonance increased. With the foam backrests, the resonance frequency tended to decrease as the backrest angle increased. Statistical analysis shows that this effect was more pronounced with greater thickness of foam (Table 4.5).

With the 50-mm foam backrest, the greatest apparent mass at resonance occurred when the backrest was reclined to 10° and the lowest apparent mass at resonance occurred when the backrest was reclined to 30° (Table 4.2). A similar trend occurred with the 100-

mm and 150-mm foam backrests, except that the greatest apparent mass at resonance occurred when the seat was reclined to 15° and 20°, respectively.

Table 4.6 Statistically significant different (i.e. $p < 0.05$) pairs of backrest inclinations with different thickness of foam backrest. 0: upright backrest; 10: backrest reclined to 10°; 20: backrest reclined to 20°; 30: backrest reclined to 30°.

	Resonance frequency	Apparent mass at resonance	Apparent mass at 0.4 Hz	Apparent mass at 12 Hz	Total out of 24 possible combinations
Rigid backrest	0/20 ↑ 0/30 ↑ 10/30 ↑	0/20 ↓ 0/30 ↓ 10/20 ↓ 10/30 ↓ 20/30 ↓	0/20 ↓ 0/30 ↓ 10/20 ↓ 10/30 ↓ 20/30 ↓	0/30 ↓ 10/30 ↓ 20/30 ↓	16
50 mm foam	0/20 ↓	0/30 ↓ 10/30 ↓ 20/30 ↓	0/30 ↓ 10/20 ↓ 10/30 ↓ 20/30 ↓	0/20 ↓ 0/30 ↓ 10/20 ↓ 10/30 ↓	12
100 mm foam	0/30 ↓ 10/20 ↓ 10/30 ↓ 20/30 ↓	10/30 ↓ 20/30 ↓	20/30 ↓	0/20 ↓ 0/30 ↓ 10/20 ↓ 10/30 ↓ 20/30 ↓	12
150 mm foam	0/10 ↓ 0/20 ↓ 0/30 ↓ 10/30 ↓ 20/30 ↓	10/30 ↓ 20/30 ↓	0/30 ↓ 10/30 ↓ 20/30 ↓	0/20 ↓ 0/30 ↓ 10/20 ↓ 10/30 ↓ 20/30 ↓	15

Comparisons shown where p < 0.05; Wilcoxon matched-pairs signed ranks test.
↑ median higher with greater backrest angle, ↓ median lower with greater backrest angle.

4.4 DISCUSSION

4.4.1 Effect of backrest contact

The moduli and phases of the vertical apparent masses of the subjects with no backrest contact were similar to those previously reported (e.g. Fairley and Griffin, 1989; Mansfield and Griffin, 2000; Nawayseh and Griffin, 2003). Subjects showed a principal resonance in the 5-Hz region and some subjects showed a second resonance in the 7 to 14 Hz range.

Contact with the rigid vertical backrest generally decreased the apparent mass at frequencies less than the resonance frequency and increased the apparent mass in the frequency range 7 to 14 Hz, consistent with the findings of Fairley and Griffin (1989) and Nawayseh and Griffin (2005). Although Wang *et al.* (2004) found a similar increase in the apparent mass at frequencies greater than the primary resonance with an upright backrest, they found the apparent mass at frequencies less than the resonance frequency was largely unaffected by backrest contact, contrary to the findings of this study. Although the seat heights differed between the studies (0.34 m above the foot support in this study and 0.46 m in the previous study), this is unlikely to explain the difference: Nawayseh and Griffin (2004) found that backrest contact decreased the apparent mass at frequencies less than the resonance frequency irrespective of the height of the feet relative to the seat surface. The increase in the apparent mass between 7 and 14 Hz with backrest contact is consistent with an increase in damping of the primary resonance.

There was a small but statistically significant increase in the resonance frequency when subjects were supported by a rigid backrest compared to no backrest. This is consistent with Nawayseh and Griffin (2004) but contrary to Nawayseh and Griffin (2005) and the findings of Wang *et al.* (2004) in which there were no significant effects of a rigid backrest on the resonance frequency. The difference might be explained by the backrest employed: in this study and the earlier study by Nawayseh and Griffin (2004) the lumbar spine and pelvis were not in contact with the backrest whereas in the later study by Nawayseh and Griffin (2005) and the study by Wang *et al.* (2004) there was contact with the full length of the back. Previous studies (e.g. Fairley and Griffin, 1989) have found that when subjects vary between an ‘erect’ and ‘tensed’ posture there is a corresponding change in their apparent mass resonance frequency. Where the lumbar region was not supported, the subjects may have exerted greater muscle tension or maintained a more upright posture than with no backrest or a full backrest support, resulting in an increased resonance frequency.

In this study the apparent mass at 0.4 Hz decreased by approximately 10 kg when there was contact with a rigid flat vertical backrest. This indicates that either this was supported by the backrest or the feet supported a greater proportion of the body weight when this backrest was present. Nawayseh and Griffin (2004) measured the vertical apparent mass at both the seat and the backrest and found that when subjects were in contact with an upright backrest the apparent mass at the seat was reduced at low frequencies, consistent with the findings of this study. They also found that the vertical forces on a seat with no backrest were the same as the vector addition of the vertical forces at the seat surface and the backrest. This indicates that a proportion of subject body weight was supported by shear forces at the backrest.

With the 100-mm foam backrest, the apparent mass at frequencies less than the resonance frequency was similar to that with the rigid backrest, indicating that at low frequencies a similar proportion of subject mass was supported in shear by the 100-mm foam backrest and the rigid backrest. At frequencies between 7 Hz and 15 Hz, the apparent mass was lower with the foam backrest than with no backrest, possibly due to the second resonance being less evident in some subjects when there was no backrest.

The origin of the second resonance is not certain, but a biodynamic model developed by Matsumoto and Griffin (2001) indicated that the resonance could be caused by a rotational mode of the pelvis and the lower upper-body. This mode may have been more damped by the foam backrest than the rigid backrest.

4.4.2 Effect of backrest inclination

The resonance frequency in the vertical apparent mass at the seat surface increased from 5.5 Hz with a vertical rigid backrest to 6.4 Hz when this backrest was reclined to 30°. Rakheja *et al.* (2002) measured the vertical apparent mass on the surface of a seat with a backrest reclined to 24° and found the mean resonance of the subjects at 7.8 Hz. The present study used an input magnitude of 1.0 ms^{-2} r.m.s. whereas Rakheja *et al.* (2002) used 0.5 ms^{-2} r.m.s over a similar frequency range (0.5 to 40 Hz). It is has been widely reported that the response of the body is non-linear with input magnitude: the resonance frequency decreasing with increasing vibration magnitude (e.g. Matsumoto and Griffin, 2002b). The differences in resonance frequency between the two studies may be a result of the different excitation magnitudes. There were also postural differences between the two studies: in this experiment a flat rigid seat pan was used but Rakheja *et al.* (2002) employed a seat pan inclined to 13°. However, both Nawayseh and Griffin (2005) and Wang *et al.* (2004) have found that the inclination of a seat pan had a negligible effect on the vertical apparent mass. The resonance frequency of the apparent mass of the body (not legs) of supine subjects measured with an input magnitude of 1.0 ms^{-2} r.m.s., as in this study, has been reported as 7.3 Hz (e.g. Huang and Griffin, 2008). This is higher than the resonance frequencies measured in this study and consistent with increased resonance frequency with increased inclination. The findings of these studies suggest that the changes in the apparent mass of the body caused by contact with an inclined rigid backrest may be reflected by increasing the stiffness in an apparent mass model, although the actual changes in the body will be more complex. This increase in stiffness could be a result of the rigid backrest constraining the motions of the upper body. At higher backrest inclinations, more mass of the body is supported on the backrest this may further constrain the motions of the upper body.

With no backrest, excitation of the body occurs primarily through the supporting seat surface. When subjects are also supported by a backrest, there is an additional source of excitation, which is in the *z*-axis of the back when the backrest is vertical but increasingly in the *x*-axis of the back as the backrest is reclined. The two inputs will be in-phase with a rigid seat but there will be phase differences between the inputs when either the backrest or the seat surface are not rigid. Clearly, the dynamic response of the body under these circumstances is not simple, although it may be possible to provide simple representations of the apparent mass of the body that are sufficient to assist the optimisation of the dynamic responses of seats.

The apparent mass resonance frequency and also the response between 5 and 15 Hz tended to decrease as the foam backrests were reclined; this is consistent with a decrease in the ‘stiffness’ of the combined response of the body and the backrest. This decrease in stiffness might be explained by the foam being more compliant when there was more of the subject’s weight supported normal to the backrest and consequently greater compression forces acting on the foam. That this decrease became more pronounced as the thickness of foam increased, is consistent with the compressive stiffness of the foam decreasing as the thickness was increased.

The apparent mass reduced at low frequencies as the rigid backrest and the 50-mm foam backrest were reclined, indicating that a reduced proportion of the subject body mass was supported on the seat surface. With the 100-mm and 150-mm foam backrests, the static mass supported on the seat surface increased as the backrest was reclined from 0° to 10° but then decreased as the backrest was reclined from 10° to 30°. At 30°, the static mass on the seat surface with the rigid backrest was 43.9 kg, while the median static mass at this inclination with the foam backrests varied between 47.0 and 48.7 kg. The difference in static mass supported on the seat surface between the reclined rigid and reclined foam backrests might be explained by postural differences. With the reclined rigid backrest, subjects were likely to maintain a straight back whereas with the foam backrests subjects may have adopted a kyphotic posture in which the centre of gravity was brought forward, reducing the mass supported on the backrest.

4.4.3 Effect of the thickness of foam on the backrest

The thickness of foam on the backrest had the greatest effect on the measured apparent mass when the backrest was inclined to 30°, with the resonance frequency decreasing with increasing thickness of foam, consistent with a lowering of the stiffness of the body-backrest system.

There was evidence of increased damping of the primary resonance in the apparent mass (a broadening of the resonance peak with increased apparent mass at frequencies greater than the resonance frequency) with the foam backrest compared to the rigid backrest. However, there was no evidence in the apparent mass of further increases in damping with increasing foam thickness. The mass supported on the seat surface increased with increasing thickness of foam, consistent with the thicker foam being more compliant and supporting less of the subject weight on the backrest.

4.4.4 Implications for seat testing and biodynamic models

This study shows that contact with a backrest, and the inclination and compliance of a backrest, influence the vertical apparent mass of the human body measured at a seat surface. As the vibration transmitted through a seat is dependent on the apparent mass of the body, contact with a backrest and the inclination and compliance of a backrest will also affect seat transmissibility (e.g. Appendix B). When measuring seat transmissibility it therefore seems advisable to use an appropriate backrest set to an angle appropriate for the vehicle, or to measure seat transmissibility with a range of backrest inclinations.

Biodynamic models of the dynamic responses of the body have not generally been developed to consider interactions with a backrest (e.g. Matsumoto and Griffin, 2001; Wei and Griffin, 1998a). Wei and Griffin (1998a) showed that a simple two-degree of freedom model could accurately reflect the apparent mass of subject sitting upright with no backrest contact. This model was combined with measurements of the dynamic stiffness and damping of foam to provide useful predictions of seat transmissibility for subjects sitting with no backrest (Wei and Griffin, 1998b). The principal effect of contact with a backrest in the current study was a shifting of the resonances in the apparent mass as opposed to the addition of new resonances. This suggests it may be appropriate for the effect of backrest contact on the apparent mass at the seat surface to be approximated by adjustments to the parameters of a two degree-of-freedom model (e.g. Wei and Griffin, 1998a). Different types and inclinations of backrest might be represented by different values for the variables within the model. An alternative to this approach is to include backrest interaction within a mechanistic model. The vertical transmissibility of a car seat with subjects supported by a backrest reclined to 20° can be represented by a four degree-of-freedom lumped parameter model with vertical stiffness and damping elements representing the total compliance of the back and the backrest (Wei *et al.*, 2000). This model did not attempt to separate out the compliance of the backrest or reflect the effects of backrest inclination. To represent these factors, a mechanistic model requires rotational or cross-axis components. It has been found that a three degree-of-freedom model with vertical, fore-and-aft and rotational (i.e., pitch) degrees-of-freedom can be optimised to represent the vertical apparent mass and the fore-and-aft cross-axis apparent mass of the human body with no backrest support (Nawayseh and Griffin, 2009). The dynamic properties of a reclined compliant backrest has been taken into account in a nine degree-of-freedom model representing the transmission of vertical vibration to the hip and head and also the fore-aft transmissibility to the back, with the human body represented by three rigid bodies connected by rotational spring and damper elements (Cho and Yoon, 2001). A similar model could represent the dynamic response of the body and the backrests in the conditions investigated in this study.

4.5 CONCLUSIONS

Contact with an upright rigid backrest or upright foam backrests reduces the body mass supported on the seat surface, indicating backrests support a proportion of the body mass in shear. Reclining a backrest reduces the proportion of subject mass supported on the seat surface, although the reduction is less apparent when compliance of foam in a backrest reduces the proportion of the body mass supported by the backrest.

The apparent mass resonance frequency is little affected by contact with either a vertical flat rigid backrest or a vertical foam backrest. Whereas reclining a rigid backrest increases the resonance frequency, reclining a foam backrest decreases the resonance frequency: with a backrest inclined to 30°, the resonance frequency was 6.4 Hz with a rigid backrest compared to 4.5 Hz with a 100-mm foam backrest.

The thickness of foam on the backrest had the greatest effect on the vertical apparent mass measured at the seat when the backrest was maximally inclined to 30 degrees, with the resonance frequency and the apparent mass between 5 and 15 Hz greater, and the mass supported on the seat less, with 50-mm foam than with 100-mm and 150-mm foam.

CHAPTER 5: EFFECT OF FOOTREST AND STEERING WHEEL ON APPARENT MASS

5.1 INTRODUCTION

In vehicles, drivers and passengers are supported by reclined compliant backrests, seat pans are inclined, and the legs may be extended forward. The operation of steering wheels and pedals results in drivers having different postures from passengers. The influence of such variations in the positions of the hands and the feet on the apparent mass of the body has received little attention.

Changes in the apparent mass of the body due to changes in posture may be expected due to variations in either the geometry of the body or the tension in muscles that support the body. Decreases in the frequency and magnitude of the principal vertical resonance around 5 Hz have been reported when subjects adopt slouched as opposed to erect postures (e.g. Fairley and Griffin, 1989; Miwa, 1975). Increases in the frequency of the principal resonance have been reported when subjects tense muscles in the upper-body during vibration (Fairley and Griffin, 1989). The apparent mass of the body is non-linear with vibration magnitude, with the resonance frequency decreasing with increasing magnitude (Mansfield and Griffin, 2002). Matsumoto and Griffin (2002a) showed that this non-linearity depended on muscle tension in the abdomen and, particularly, the buttocks, with non-linear characteristics less clear in tensed postures.

Factors influencing the apparent mass of a seated person include seat height (Nawayseh and Griffin, 2004), foot position (Rakheja *et al.*, 2002) and, to a lesser extent, seat pan inclination (Wang *et al.*, 2004). A seat backrest can alter body posture and the distribution of the forces supporting the body mass over seat surfaces. Supporting the back by an upright backrest decreases the apparent mass at resonance and the proportion of the body mass supported on the seat surface, but increases the resonance frequency (see Chapter 4). Inclining a rigid backrest decreases the apparent mass at resonance and also the static mass supported on the seat surface, but increases the resonance frequency, although inclining a compliant backrest reduces the resonance frequency of the apparent mass(see Chapter 4). Raising the height of a seat pan relative to the feet increases the apparent mass at resonance, due to more mass being supported on the seat surface (Wang *et al.*, 2004; Nawayseh and Griffin, 2003). A slight increase in the apparent mass at resonance has been observed if the feet are moved forward, possibly as a result of more mass being supported on the seat surface, however only a small range of foot movement (150 mm) has been investigated (Rakheja *et al.*, 2002).

Rakheja *et al.* (2002) found apparent mass resonances between 6.5 and 8.6 Hz for subjects in car driving postures, compared to 4.5 to 5.0 Hz in previous studies with subjects sitting upright with no backrest support (e.g. Fairley and Griffin, 1989). When subjects moved their hands from their laps to a steering wheel, both the apparent mass at resonance and the resonance frequency decreased and a second resonance became more pronounced in some subjects. Similarly, the resonance frequency and the apparent mass measured in a direction normal to a reclined backrest reduced when subjects exposed to vertical vibration held a steering wheel (Rakheja *et al.*, 2006).

In studies of the transmission of vibration from a rigid seat to points on the body, the fore-and-aft position of the seat relative to controls, and therefore the arm and leg angles, affected the movement of the upper-arm, lower-arm, shin and thigh (Nishiyama *et al.*, 2000). The transmissibility at resonance to the upper-arm increased as the elbow angle increased from 90° to 180°, while the resonance frequency in the transmissibility to the thigh increased as either arm or leg angles increased. If arm and leg position affect the transmission of vibration to the body, they will also affect the apparent mass of the body. However, there are no known studies of the effect of the position of a steering wheel or a wide range of positions of the feet on the apparent mass of the body.

The objective of this study was to determine the effects of steering wheel location and foot position on the vertical apparent mass measured at the seat surface. It was hypothesized that holding a steering wheel would restrain the motions of the upper body, increasing the damping and therefore decreasing the magnitude of the primary resonance in the apparent mass. Increasing the distance of the feet from the leading edge of a seat was expected to increase the mass supported on the seat surface and consequently increase the apparent mass at resonance.

5.2 METHODS AND PROCEDURES

5.2.1 Apparatus

The study was conducted using a 1-metre stroke vertical electro-hydraulic vibrator in the laboratory of the Human Factors Research Unit. A flat rigid seat with a rigid flat vertical backrest was attached to the vibrator platform. An adjustable footrest and an adjustable ‘steering wheel’ were also fixed to the platform (Figure 5.1). The horizontal position and angle of inclination of the footrest, and the horizontal and vertical positions of the steering wheel, were adjustable. The force applied by the subjects to the footrest was measured by a set of digital scales (CPW-35 load cell scales; Adam Equipment, Danbury, USA) having a maximum rated load of 35 kg and ± 0.02 kg linearity) attached to the footrest. The force applied to the steering wheel was measured indirectly using the same digital scales attached to the backrest.

Measurements of the dynamic vertical force at the seat surface were made using a force plate (model 9281 B, Kistler, Hook, UK). The signal from the force plate was amplified using a charge amplifier (Kistler 5007). Vibration on the platform was monitored using a piezo-resistive accelerometer (EGCSY-240D-10; Entran, Potterspury, UK) attached to the underside of the force platform.

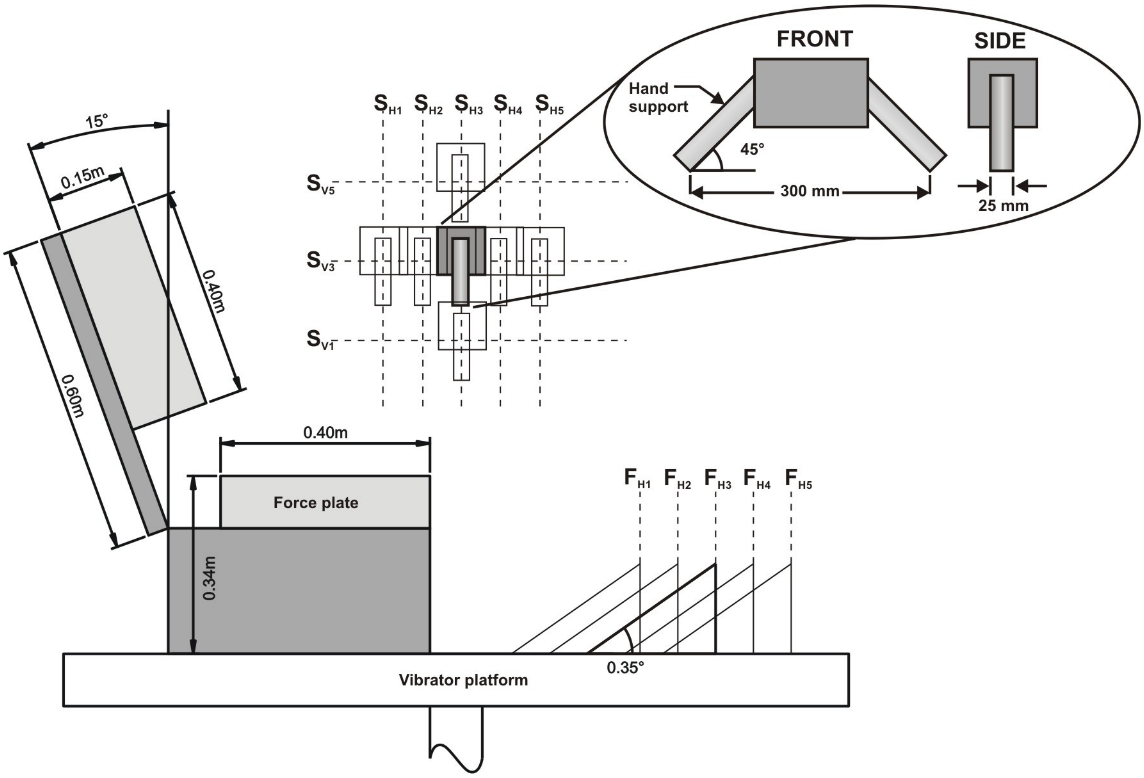

Figure 5.1 Experimental apparatus.

5.2.2 Postures

The apparent mass on the seat surface was measured with subjects sitting in 21 different postures (Figure 5.1, Table 5.1). These postures allowed the study of five horizontal positions of the steering wheel, three vertical position of the steering wheel, five horizontal distances of the footrest from the leading edge of the seat, five forces on the steering wheel, five forces on the footrest, and a 'no backrest' condition.

Table 5.1 Position of the hands and feet, force applied to the steering wheel and backrest, and backrest support in each of the 21 postures. The groups of comparable conditions are highlighted.

Posture	Horizontal hand position	Vertical hand position	Foot position	Force applied to steering wheel	Force applied to footrest	Backrest
1	Lap	Lap	F_{H4}	0	0	No backrest
2	Lap	Lap	F_{H4}	0	0	15°
2*	Lap	Lap	F_{H4}	0	0	15°
3	S_{H3}	S_{V3}	F_{H4}	0	0	15°
4	S_{H1} (min)	S_{V3}	F_{H4}	0	0	15°
5	S_{H2}	S_{V3}	F_{H4}	0	0	15°
3*	S_{H3}	S_{V3}	F_{H4}	0	0	15°
6	S_{H4}	S_{V3}	F_{H4}	0	0	15°
7	S_{H5} (max)	S_{V3}	F_{H4}	0	0	15°
8	S_{H3}	S_{V1} (min)	F_{H4}	0	0	15°
3*	S_{H3}	S_{V3} (mid)	F_{H4}	0	0	15°
9	S_{H3}	S_{V5} (max)	F_{H4}	0	0	15°
10	Lap	Lap	F_{H1} (min)	0	0	15°
11	Lap	Lap	F_{H2}	0	0	15°
12	Lap	Lap	F_{H3} (mid)	0	0	15°
2*	Lap	Lap	F_{H4}	0	0	15°
13	Lap	Lap	F_{H5} (max)	0	0	15°
3*	S_{H3}	S_{V3}	F_{H4}	0 N	0	15°
14	S_{H3}	S_{V3}	F_{H4}	50 N	0	15°
15	S_{H3}	S_{V3}	F_{H4}	100 N	0	15°
16	S_{H3}	S_{V3}	F_{H4}	150 N	0	15°
17	S_{H3}	S_{V3}	F_{H4}	200 N	0	15°
2*	Lap	Lap	F_{H4}	0	0 N	15°
18	Lap	Lap	F_{H4}	0	50 N	15°
19	Lap	Lap	F_{H4}	0	100 N	15°
20	Lap	Lap	F_{H4}	0	150 N	15°
21	Lap	Lap	F_{H4}	0	200 N	15°

* The same as previous posture with this number.

At the closest footrest position (F_{H1}), the angle between the femur and fibular was 90 degrees. In the furthest position of the footrest (F_{H5}), the legs were outstretched and the femur and fibular were at 180°. The other three positions (F_{H2}, F_{H3}, and F_{H4}) were equally spaced between the maximum and minimum positions appropriate for each subject. At each position, the angle of the footrest was adjusted so that the sole of the foot was at 90 degrees to the fibular. During these measurements the hands were in the lap and the backrest was reclined to 15 degrees. Subjects were supported by the backrest and asked to maintain a relaxed upright posture and place their feet on the footrest without exerting additional force.

The mid position for both the vertical and the horizontal adjustment of the steering wheel (S_{H3}, S_{V3}) was set so that the forearm (radius) and upper arm (humerus) were at 45 degrees and the hands were vertically inline with the mid-point of the sternum. Subjects were supported by the footrest in position (F_{H4}) and by the reclined backrest. Subjects were asked not to exert additional unnecessary force to the steering wheel, backrest, or footrest.

At the closest steering wheel position (S_{H1}), the forearm (radius) and upper arm (humerus) were at 90 degrees. In the furthest position (S_{H5}) the arms were outstretched. The other three horizontal positions (S_{H2}, S_{H3} and S_{H4}) were set equidistance between the closest and furthest positions. The lowest position (S_{V1}) and the highest position (S_{V5}) of the steering wheel were set the same distance from the mid position (S_{V3}) as the extreme horizontal positions (S_{H1} and S_{H5}). Subjects were asked to maintain full contact with the backrest with all steering wheel positions.

When investigating the effect of force at the footrest, subjects were asked to exert 0, 50, 100, 150 or 200 N while sitting with their hands in their laps and their legs almost outstretched (at position F_{H4}) and the backrest reclined to 15°. Subjects monitored the force using a digital display connected to the scales.

When investigating the effect of force at the hands, subjects were asked to apply 0, 50, 100, 150, or 200 N to the steering wheel in the mid-position (S_{H3}, S_{V3}). The subjects were supported by the backrest and the footrest in position F_{H4}. The force applied to the steering wheel was measured using the digital scales attached to the backrest. The scales were zeroed with a subject supported by the backrest and holding the steering wheel before being was asked to exert force on the steering wheel.

In the 'no backrest' condition subjects were asked to sit in a relaxed upright posture without making contact with the reclined backrest. The footrest was adjusted to position F_{H4} and subjects placed their hands in their laps.

The conditions were presented to subjects in independent random orders to minimize the influence of order effects.

5.2.3 Vibration

The vibrator platform was excited using 60-s periods of 1.0 ms^{-2} r.m.s. Gaussian random vibration (band-limited from 0.13 to 40 Hz using 8-pole Butterworth filters). The approximately flat constant bandwidth acceleration spectra were generated and analysed using an *HVLab* data acquisition and analysis system (version 3.81; University of Southampton, UK). Different random input signals were generated for each subject. The measured force and acceleration were acquired at 400 samples per second via 133 Hz anti-aliasing filters.

5.2.4 Subjects

Twelve healthy male subjects aged 22 to 48 years (mean 30.7 years) participated in the experiment. The subjects ranged in stature from 1.69 to 1.89 m (mean 1.80 m) and ranged in weight between 64.5 and 100.7 kg (mean 77.1 kg). All subjects were exposed to all conditions in a single session lasting approximately 90 minutes. Subjects wore a loose fitting lap belt and had access to an emergency stop button. Subjects gave informed consent to participate in the experiment that was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

5.2.5 Analysis

Transfer functions were calculated between the vertical seat acceleration and the vertical force at the seat surface, to give the apparent masses of the subjects. Apparent mass was calculated using the cross-spectral density (CSD) technique with a resolution of 0.195 Hz. The apparent mass, $H_{io}(f)$, was calculated from the ratio of the CSD of acceleration at the seat, $G_{io}(f)$, to the power spectral density (PSD) of the acceleration at the seat, $G_{ii}(f)$:

$$H_{io}(f) = \frac{G_{io}(f)}{G_{ii}(f)}. \qquad 5.1$$

Prior to the calculation of the apparent mass, mass cancellation of the mass of the force platform top-plate (33.0 kg) was performed in the time domain to remove its influence from the measured force: the acceleration time-history on the seat surface was multiplied by the mass of the force platform, which was then subtracted from the measured force.

The medians of the primary resonance frequencies and the apparent masses at resonance for the 12 subjects were calculated for each condition. The apparent mass at the primary resonance frequency was assumed to be the greatest apparent mass over the measurement range. The primary resonance frequency was defined as the frequency at which the apparent mass was greatest.

Statistical analysis was performed using SPSS (version 14). Non-parametric tests (the Friedman test for *k*-related samples and the Wilcoxon matched-pairs signed ranks test for two-related samples) were employed. Non-parametric statistics were used to avoid assuming a normal distribution in the data.

5.3 RESULTS

5.3.1 Effect of backrest and steering wheel contact

The effects of contact with the backrest and holding the steering wheel on the median modulus and phase of the apparent masses of the 12 subjects are shown in Figure 5.2. The median resonance frequency increased from 4.8 Hz with 'no backrest contact' to 6.7 Hz when the back was supported by the backrest reclined to 15° (Table 5.2; $p < 0.01$, Wilcoxon matched-pairs signed ranks). At the lowest frequencies, the mass supported on the seat surface was reduced by 8.5 kg when supported by the backrest. The apparent mass at resonance was also significantly reduced with the backrest ($p < 0.01$).

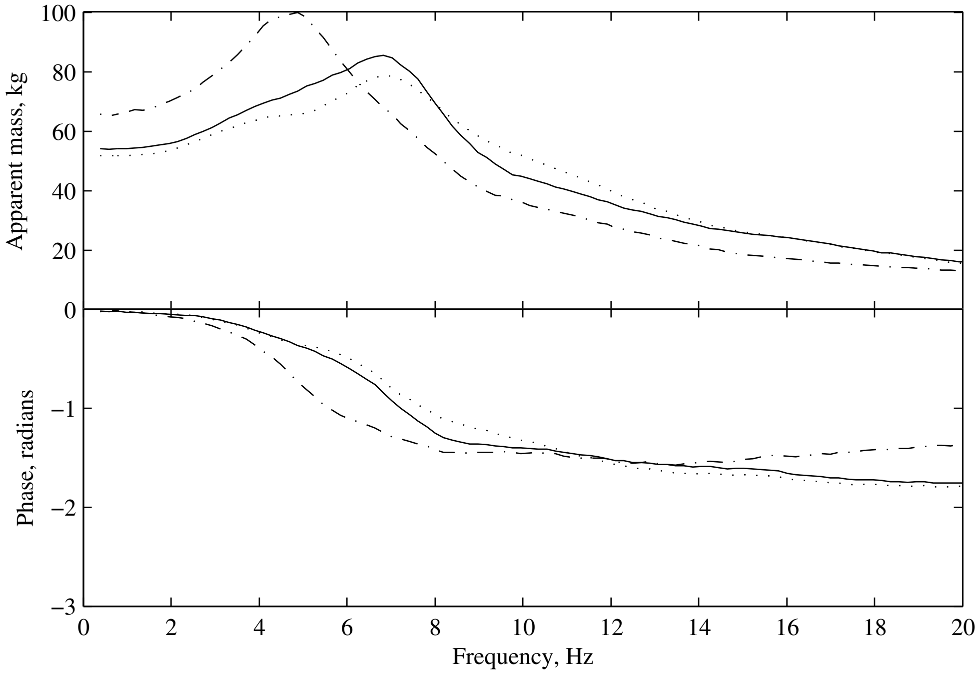

Figure 5.2 Effect of backrest and steering wheel contact on apparent mass (medians of 12 subjects with the footrest at position F_{H4}): — · — · —, No backrest contact (hands in lap); ——, Backrest at 15° (hands in lap); · · · · · , Hands on steering wheel (backrest at 15°).

The median resonance frequency was similar, irrespective of whether subjects supported by the backrest had their hands in their laps or held the steering wheel (6.7 Hz compared to 6.8 Hz; $p = 0.27$). Although holding the steering wheel did not affect the resonance frequency, it tended to decrease the apparent mass at resonance and the apparent mass at 0.4 Hz ($p < 0.01$). The decrease in the response at 0.4 Hz is consistent with the steering wheel supporting some of the mass of the arms. When subjects held the steering wheel, the response between 8 and 14 Hz tended to increase ($p < 0.01$ at 12.0 Hz) and, in some subjects, there was evidence of a further resonance occurring at around 4 Hz.

Table 5.2 Effect of posture on the primary resonance frequencies and apparent masses at resonance, at 0.4 Hz and at 12.0 Hz (medians of 12 subjects); as well as interquartile values (25%, 75%).

	Resonance frequency, Hz	Apparent mass at resonance, kg	Apparent mass at 0.4 Hz, kg	Apparent mass at 12.0 Hz, kg
Backrest and steering wheel contact				
No backrest (hands in lap, feet F_{H4})	**4.8** (4.3,5.1)	**99.6** (98.3,112.2)	**61.8** (59.1,66.9)	**30.8** (28.6,31.9)
Hand in lap (backrest at 15°, feet F_{H4})	**6.7** (6.4,7.0)	**87.2** (78.7,101.7)	**53.3** (49.9,56.0)	**36.8** (34.0,39.6)
Hands on steering wheel (backrest at 15°, feet F_{H4})	**6.8** (6.3,7.2)	**84.5** (72.0,92.7)	**51.5** (48.3,53.2)	**41.2** (40.1,44.5)
Horizontal steering wheel position (hands S_{V3}, feet F_{H4})				
S_{H1} (minimum)	**6.9** (6.5,7.5)	**84.6** (73.0,95.3)	**51.1** (47.7,52.2)	**39.6** (37.8,41.9)
S_{H2}	**6.9** (6.4,7.1)	**85.5** (74.1,95.3)	**50.8** (48.0,53.4)	**39.2** (37.7,41.9)
S_{H3}	**6.8** (6.3,7.2)	**84.5** (72.0,92.7)	**51.5** (48.3,53.2)	**41.2** (40.1,44.5)
S_{H4}	**6.8** (6.3,7.4)	**80.8** (68.9,87.1)	**51.1** (47.3,53.2)	**43.2** (40.1,45.6)
S_{H5} (maximum)	**6.6** (5.9,7.4)	**75.0** (68.7,80.8)	**50.1** (47.3,52.9)	**43.2** (40.3,46.7)
Vertical steering wheel position (hands S_{H3}, feet F_{H4})				
S_{V1} (minimum)	**6.8** (6.2,7.0)	**84.5** (70.9,89.1)	**50.8** (48.4,53.3)	**39.6** (37.0,41.6)
S_{V3} (mid)	**6.8** (5.9,7.2)	**84.5** (67.6,92.7)	**51.1** (48.3,53.2)	**42.0** (40.2,45.9)
S_{V5} (maximum)	**6.9** (6.5,7.4)	**82.8** (73.3,93.0)	**50.8** (47.0,54.4)	**41.2** (39.7,44.7)
Footrest position (hands in lap)				
F_{H1} (minimum)	**6.4** (5.7,7.1)	**75.2** (67.0,80.0)	**49.7** (47.0,52.7)	**38.9** (36.2,44.0)
F_{H2}	**6.6** (5.8,7.1)	**76.6** (68.6,83.9)	**52.3** (46.8,54.4)	**38.9** (35.6,46.8)
F_{H3} (mid)	**6.8** (5.5,7.1)	**80.0** (68.0,93.3)	**53.0** (48.2,55.6)	**39.2** (36.1,46.0)
F_{H4}	**6.7** (6.4,7.0)	**87.2** (78.7,101.7)	**53.3** (49.9,56.0)	**36.8** (34.0,39.6)
F_{H5} (maximum)	**6.1** (5.7,6.3)	**92.0** (83.0,102.2)	**54.3** (50.9,61.1)	**35.4** (33.8,39.0)
Force applied to steering wheel (hands S_{H3}, feet F_{H4})				
0 N	**6.8** (6.3,7.0)	**85.0** (77.7,93.9)	**52.4** (49.3,53.8)	**42.0** (40.2,44.8)
50 N	**6.8** (6.8,7.4)	**79.2** (70.3,89.8)	**50.8** (48.8,56.0)	**44.1** (42.2,47.9)
100 N	**7.2** (6.8,7.6)	**80.5** (72.8,88.2)	**49.7** (46.2,52.0)	**45.6** (42.9,47.3)
150 N	**7.6** (7.1,7.7)	**75.5** (69.0,86.8)	**49.6** (44.4,55.3)	**43.8** (42.3,48.0)
200 N	**6.8** (6.1,7.7)	**76.6** (67.6,83.3)	**48.2** (41.0,53.4)	**43.7** (39.3,47.8)
Force applied to footrest (hands in lap, feet F_{H4})				
0 N	**6.6** (6.3,7.0)	**89.4** (80.3,105.5)	**53.9** (52.0,56.1)	**37.0** (33.7,39.7)
50 N	**7.0** (6.4,7.4)	**90.4** (80.5,111.3)	**51.6** (47.9,52.9)	**39.0** (34.4,39.7)
100 N	**7.0** (5.9,7.3)	**89.5** (78.7,106.0)	**49.3** (45.8,58.4)	**36.1** (34.8,37.6)
150 N	**7.0** (6.4,7.2)	**86.1** (81.1,102.0)	**45.6** (44.7,52.2)	**35.4** (33.1,37.5)
200 N	**6.8** (5.5,7.0)	**80.7** (77.0,101.8)	**44.9** (37.9,52.9)	**32.2** (30.1,36.5)

5.3.2 Effect of steering wheel position

Changing the horizontal position of the steering wheel had no effect on the proportion of the subject weight supported on the seat surface ($p > 0.63$ at 0.4 Hz, Friedman). The apparent mass at frequencies greater than 10 Hz was also little affected by the horizontal position of the steering wheel. However, as the steering wheel moved from the closest position (S_{H1}) to the furthest position (S_{H5}), the median apparent mass decreased at the primary resonance from 84.6 kg to 75.0 kg (Table 5.2, Figure 5.3) and increased at the secondary resonance around 4 Hz.

The vertical position of the steering wheel had little effect of the apparent mass at any frequency (Figure 5.4, Table 5.2): there were no significant changes in the response at 0.4 Hz ($p = 0.56$), at resonance ($p = 0.56$), or at 12.0 Hz ($p = 0.56$). However, the resonance frequency increased slightly as the steering wheel was raised ($p = 0.02$).

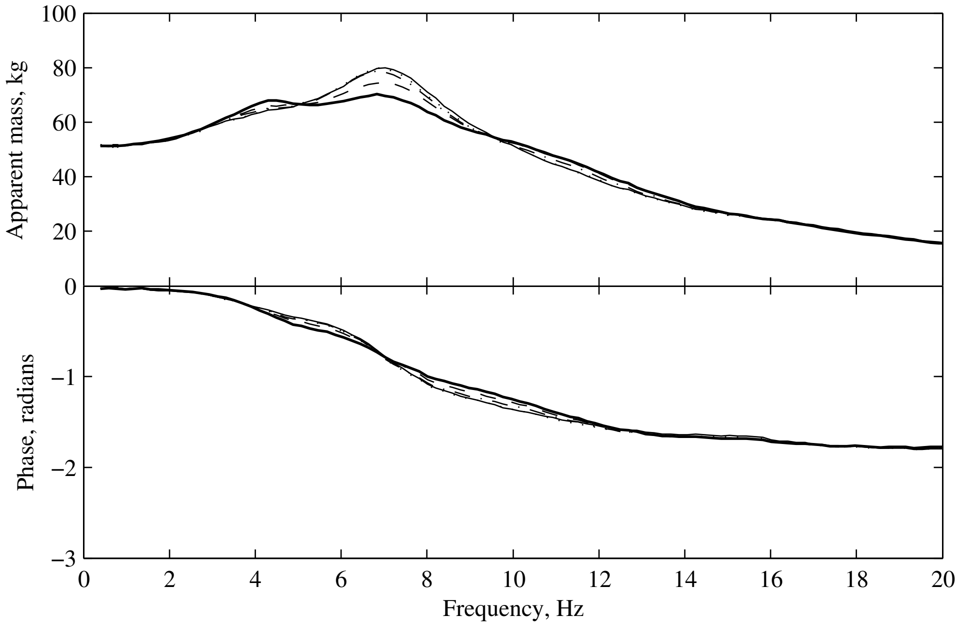

Figure 5.3 Effect of horizontal position of the steering wheel on apparent mass (medians of 12 subjects with steering wheel at vertical position S_{V3} and footrest at F_{H4}): S_{H1} (——), S_{H2} (· · · · ·), S_{H3} (— · — ·), S_{H4} (– – –) and S_{H5} (——).

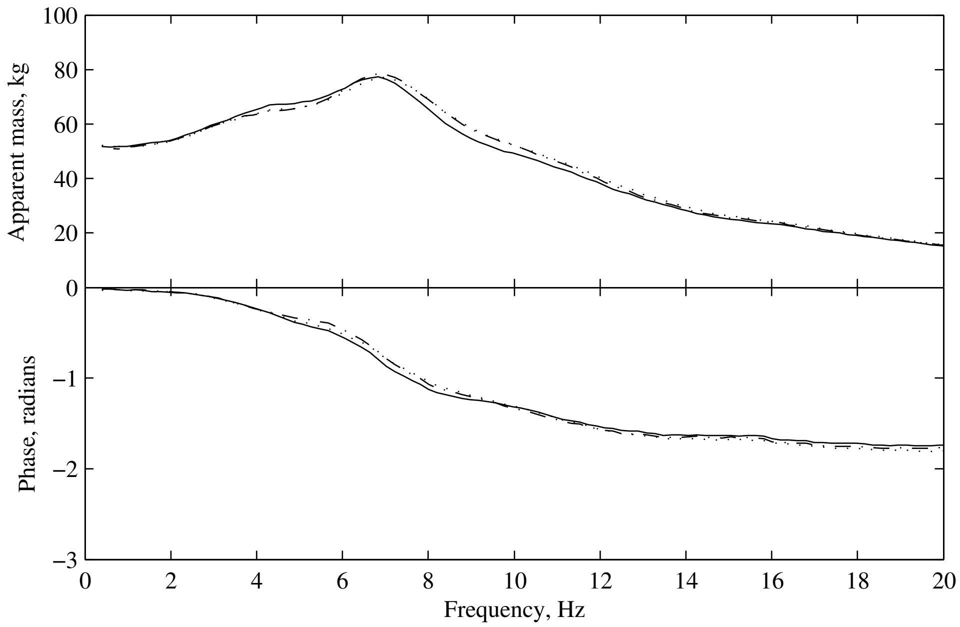

Figure 5.4 Effect of vertical position of the steering wheel on apparent mass (medians of 12 subjects with the steering wheel at horizontal position S_{H3} and footrest at F_{H4}): S_{V1} (——), S_{V3} (· · · · ·) and S_{V5} (— · — ·) at 1.0 ms^{-2} r.m.s.

5.3.3 Effect of horizontal footrest position

Increasing the distance of the footrest from the leading edge of the seat tended to increase the apparent mass at resonance (Figure 5.5, Table 5.2; $p < 0.01$, Friedman) and at low frequencies (at 0.4 Hz, $p < 0.01$, Friedman). There was a tendency for the principal peak in the apparent mass to narrow as the feet were positioned further forward, but the frequency of the primary resonance was not significantly changed ($p = 0.16$, Friedman).

5.3.4 Effect of force applied to the footrest and the steering wheel

Increasing the force applied to the steering wheel reduced the apparent mass at the principal resonance (Figure 5.6 and Table 5.2; Friedman $p < 0.01$). To a lesser extent, the apparent mass at 0.4 Hz also decreased as the force on the steering wheel increased (Friedman $p < 0.01$). The median resonance frequency increased from 6.8 Hz to 7.6 Hz as the force increased from 0 N to 150 N ($p = 0.07$) but decreased to 6.8 Hz as the force was increased further to 200 N ($p = 0.05$).

Increasing the force applied to the footrest reduced the apparent mass at the principal resonance (Figure 5.7 and Table 5.2; Friedman, $p = 0.02$), similar to the effect of force on the steering wheel, but less marked. As the force on the footrest increased, the apparent mass reduced at 0.4 Hz (Friedman, $p < 0.02$) and at 12.0 Hz (Friedman, $p = 0.01$). The resonance frequency was unaffected by footrest force (Friedman, $p = 0.43$).

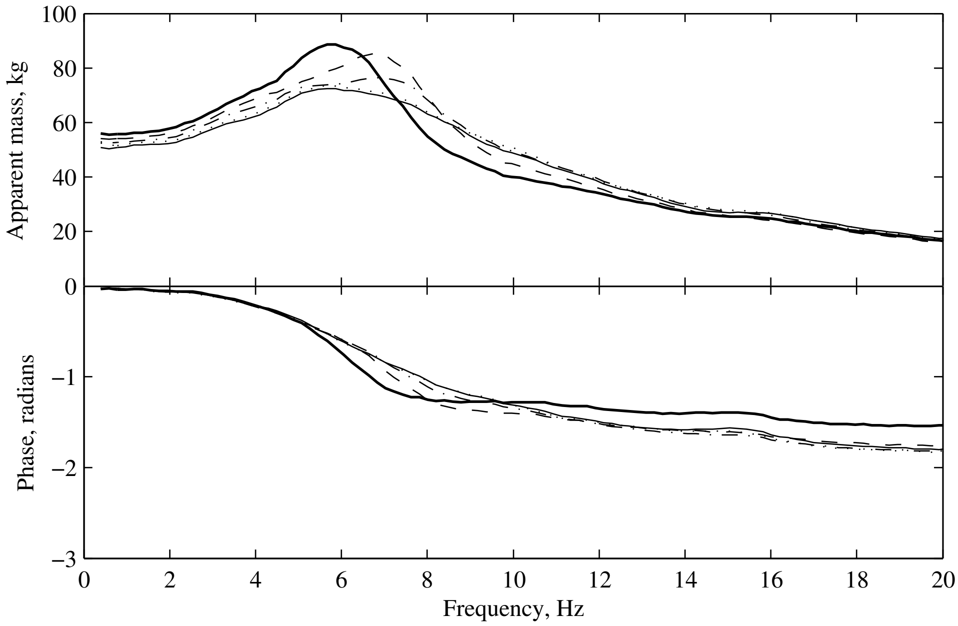

Figure 5.5 Effect of horizontal position of the footrest on apparent mass (medians of 12 subjects with hands in lap): F_{H1} (——), F_{H2} (· · · · ·), F_{H3} (– · – ·), F_{H4} (– – –) and F_{H5} (——).

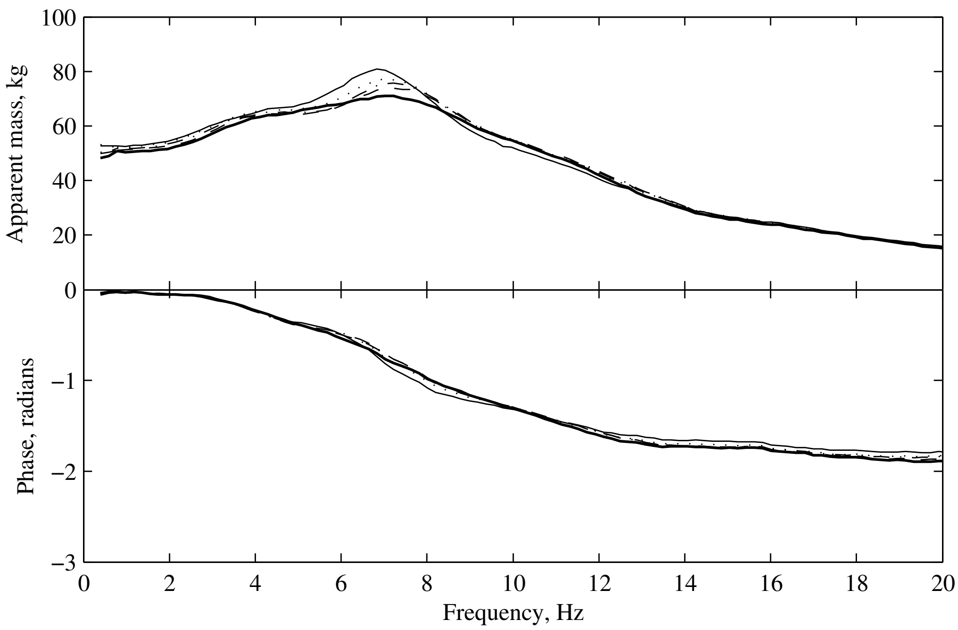

Figure 5.6 Effect of force applied to the steering wheel on apparent mass (medians of 12 subjects with the hands at S_{H3} and the feet at F_{H4}): 0 N (——), 50 N (· · · · ·), 100 N (– · – ·), 150 N (– – –) and 200 N (——) at 1.0 ms^{-2} r.m.s.

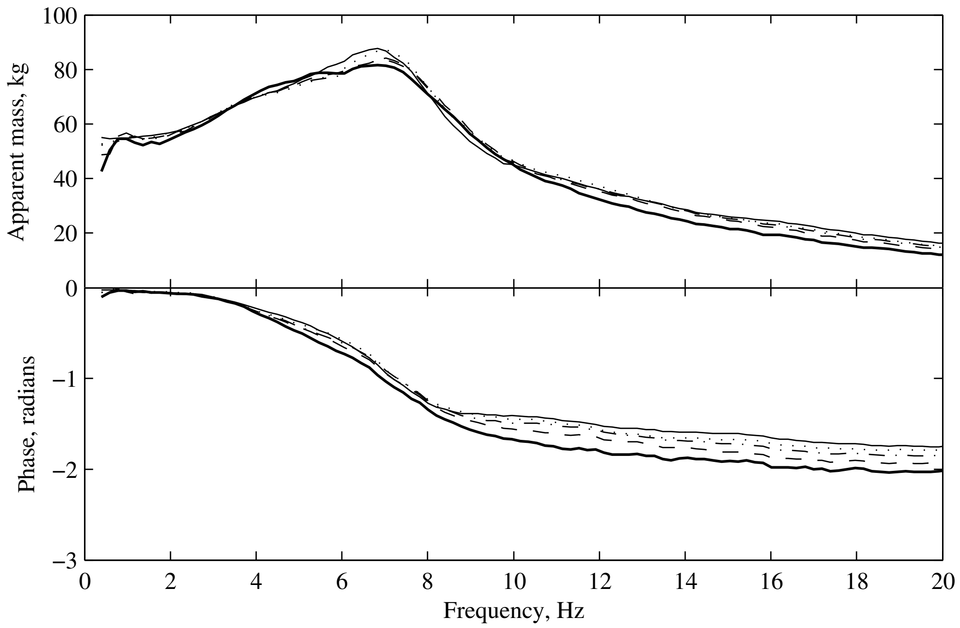

Figure 5.7 Effect of force applied to the footrest on apparent mass (medians of 12 subjects with the hands in lap and footrest at F_{H4}): 0 N (——), 50 N (· · · · ·), 100 N (— · — ·), 150 N (– – –) and 200 N (——).

5.4 DISCUSSION

5.4.1 Effect of backrest and steering wheel contact

The increase in the apparent mass resonance frequency caused by contact with the rigid backrest is consistent with previous studies (e.g. see Chapter 4). This has previously been explained by the backrest providing an additional constraint to the motions of the body. Contact with a reclined backrest has increased the resonance frequency compared to contact with an upright backrest (e.g. see Chapter 4), possibly due to a greater proportion of the body mass being supported on the backrest and increased backrest contact further constraining the motions of the body.

In the present study, both the mass supported on the seat surface and the apparent mass at resonance decreased when the back was supported by a reclined backrest compared to the 'no backrest' condition. Rakheja *et al.* (2002) concluded that both the mass supported on the seat surface and the apparent mass at resonance were increased by a back support, but the 'no backrest' data they used were drawn from previous measurements (i.e. ISO 5982, 2001)) and may not have been directly comparable data (e.g., from subjects of similar weight).

The mass supported on the seat at low frequencies reduced slightly when the hands were placed on the steering wheel, consistent with the steering wheel supporting some of the subject mass. There was also a lower apparent mass around the primary resonance when subjects held the steering wheel; however the ratio between the peak apparent mass and the apparent mass at 0.4 Hz (called 'peak ratio') was unaffected by hand position (≈ 1.6 in both cases). Rakheja *et al.* (2002) found that this ratio was lower when subjects held a steering wheel (≈ 1.4) compared to a hands in lap posture (≈ 1.7). The reason for this difference between the studies is not clear but the postures may have differed: their subjects adopted an uncontrolled 'comfortable' foot position whereas subjects in the present study had a fixed angle of 157.5° (F_{H4}) between the femur and fibular. When Rakheja *et al.* (2002) asked their subjects to position their feet 7.5 cm further from their bodies, the effect of steering wheel contact on the 'peak ratio' was less marked. However, foot position had little effect on the apparent mass when the hands were in the lap, implying an interaction between the effect of foot position and steering wheel contact. In the present study, the steering wheel was adjusted for each subject so that the arm angle was 45°, whereas Rakheja *et al.* used a fixed steering wheel position. In the present study, the apparent mass at resonance decreased as the steering wheel was moved away from the body. The reduced apparent mass at resonance found by Rakheja *et al.* (2002) when subjects held a steering wheel is consistent with the steering wheel being further from the body and the arms straighter. In the present study, and in a study by Wang *et al.* (2004), the resonance frequency was largely unaffected by steering wheel contact, whereas Rakheja *et al.* (2002) found that the resonance frequency decreased with steering wheel contact, possibly due to the postural differences described above.

5.4.2 Effect of steering wheel position

As the steering wheel moved away from the body, the proportion of body weight supported on the seat surface (e.g., the apparent mass at 0.4 Hz) was unchanged but the apparent mass around 4 Hz increased and the apparent mass around the principal resonance decreased. Consequently, at the furthest steering wheel position there were two distinct peaks in the median apparent mass: at 4.4 Hz and 6.6 Hz. The apparent mass varied between subjects, as shown for the five horizontal positions of the steering wheel in Figure 5.8; the inter-subject variability was similar in the other postures. All subjects exhibited evidence of a peak in their apparent mass at a frequency less than their primary resonance, with both peaks affected by the horizontal position of the steering wheel (Figure 5.8). The systematic change in apparent mass around 4 Hz may have been caused by a resonance of the arms and shoulders at this frequency.

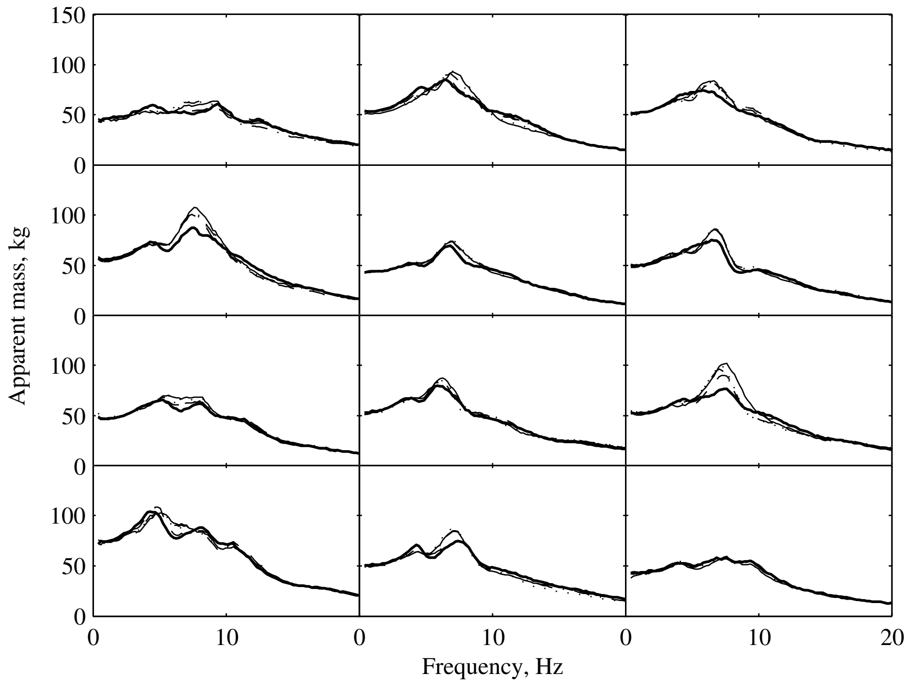

Figure 5.8 Individual apparent masses for 12 subjects with the steering wheel at five different horizontal positions (steering wheel at vertical position S_{V3} and footrest at $_{FH4}$): S_{H1} (——), S_{H2} (· · · · ·), S_{H3} (— · — ·), S_{H4} (– – –) and S_{H5} (——) at 1.0 ms^{-2} r.m.s.

The reduction in the apparent mass at the primary resonance when subjects made contact with the steering wheel suggests the response of the arms interacted with the body movements associated with the primary resonance. As the arms were straightened, the apparent mass at 4.0 Hz increased while the apparent mass around the primary resonance decreased. This might be explained by increased influenced of the arm-shoulder response as the arms were extended. Nishiyama *et al.* (2000) measured the vibration transmitted to the arms from the seat surface of subjects sitting in a car driving posture holding a steering wheel. They found that the transmissibility was dependent on the arm angle, with more vibration being transmitted to the arms as they were straightened. The transmissibility between the seat surface and the mid-point of the biceps increased from 3.7 to 4.5 as the arms straightened from 90° to 180°, while the transmissibility to the centre of the chest reduced from 1.7 to 1.6. Previous studies have found the principal resonance is associated with the motions of the upper-body (Hagena *et al.*, 1985; Matsumoto and Griffin, 1998a), so the decrease in transmission of vibration to the chest as the arms are extended is consistent with the decrease in the apparent mass at resonance in the present study. The transmission of vertical seat vibration to an unsupported hand held in front of the body has peaks at approximately 2 Hz and 5 Hz, with the magnitude of the 2-Hz peak higher and the magnitude of the 5-Hz peak lower when the hand is further from the body (Griffin, 1990). These lower resonance frequencies than in the present study (i.e., 2 and 5 Hz compared with approximately 4 and 7 Hz) may be attributed to the use of an upright posture and the absence of a backrest.

Changes in the position of the arms can lead to other postural changes in the body thereby altering muscle tension and mass distribution. Changes in muscle tension can affect the primary resonance frequency (e.g. (Fairley and Griffin, 1989) while changes in mass distribution can affect the mass supported on the seat surface (e.g. Nawayseh and Griffin, 2003). Neither the frequency of the primary resonance nor the mass supported on the seat surface were significantly affected by arm position, so while an influence of muscle tension and mass distribution cannot be entirely discounted there is no clear evidence of them affecting the results.

Although the horizontal and vertical adjustments of the steering wheel were of the same size, vertical adjustment had less influence on the apparent mass. This may have arisen because the full range of vertical positions of the steering wheel resulted in less change to the angle between forearm and upper-arm than the full range of horizontal positions of the steering wheel.

In this study the handles of the 'steering wheel' were aligned vertically (0°, Figure 5.1) whereas in a car the steering wheel is usually aligned at an angle between 0 and 25°. Changing the angle of the steering wheel may affect the angle between the fore-arm and hand but have less effect on the angle between the forearm and the upper-arm. Changes in the vertical position of the steering wheel altered the angle between the fore-arm and hand but had only a minor influence on the apparent mass, so it is expected that the angle of the steering wheel will also have had only a small influence on the apparent mass measured at the seat.

5.4.3 Effect of footrest position

When the feet are lowered relative to a seat surface, the mass supported on the seat surface and the apparent mass at resonance both increase (Nawayseh and Griffin, 2003). In the present study, similar changes were found when the feet moved forward: the mass supported on the seat surface increased, indicating that the backrest and footrest supported a lesser proportion of the subject weight. If the primary resonance of the body is represented as a single degree-of-freedom mass-spring-damper system, an increase in moving mass with no change in stiffness would decrease the resonance frequency. Nawayseh and Griffin (2003) found the resonance frequency was independent of foot height and so they hypothesised that either the primary resonance frequency depends on the motions of the upper-body regardless of the motion of the legs or that there was a corresponding increase in the stiffness of the thighs as the mass supported on the seat surface increased. In the present study, the resonance frequency tended to increase as the legs were straightened from position F_{H1} (minimum) to position F_{H3} (mid) and then decrease as the legs straightened from position F_{H3} to F_{H5} (maximum): significantly different between F_{H1} and F_{H3}, and between F_{H3} and F_{H5}. The results are consistent with two counteracting influences of foot position on the resonance frequency: as the feet move forward the increased mass on the seat surface tends to decrease the resonance frequency while the increased thigh contact tends to increase their stiffness and the resonance frequency.

5.4.4 Effect of footrest and steering wheel force

As a backrest is reclined, more mass is supported on the backrest, the apparent mass at resonance decreases, and the resonance frequency of the apparent mass increases (see Chapter 4). In the current study, as the force on the backrest increased due to greater forces applied to either the footrest or the steering wheel, the apparent mass at resonance decreased but the resonance frequency was unchanged. This suggests the increase in the resonance frequency when reclining a backrest may be associated with the angle of the upper-body as opposed to the force applied to the backrest. The absence of a change in the resonance frequency with increased force applied to the steering wheel or the footrest suggests these forces did not tense the body in the same way as in previous studies where the resonance frequency was greater in 'tensed' than 'un-tensed' postures (e.g. Fairley and Griffin, 1989; Matsumoto and Griffin, 2002a).

5.5 CONCLUSIONS

The median principal resonance frequency in the apparent mass of the body sitting in the posture of a car passenger (hands in lap, backrest at 15°) was 6.7 Hz compared to 4.8 Hz when sitting upright with no backrest. Both the mass supported on the seat surface, and the apparent mass at resonance, were less in the car passenger posture than when sitting upright with no backrest.

When subjects supported by a backrest held a steering wheel, an additional resonance was evident around 4 Hz. Moving the steering wheel away from the body did not change the proportion of the subject mass supported on the seat surface, but the apparent mass at the primary resonance reduced, and the apparent mass at the 4 Hz resonance increased, suggesting the 4 Hz resonance is associated with the arms and shoulders.

Raising the steering wheel had a similar, but smaller, effect to moving the steering wheel forward.

As the feet moved forward, the mass supported on the horizontal seat surface increased, indicating that the backrest and footrest supported a lesser proportion of the subject weight.

Applying force to either the steering wheel or the footrest did not affect the resonance frequency but reduced the apparent mass at resonance and decreased the mass supported on the seat surface.

The results show that the apparent mass of the human body sitting in the posture of a car driver or car passenger differs from that when sitting upright with no backrest contact. Systematic variations in the apparent mass have been found when changing the positions of the feet and the hands. As the transmission of vibration through a seat is influenced by the apparent mass of the seat occupant, contact with the backrest and hand and foot position can be expected to affect seat transmissibility and should be taken into account when constructing physical or mathematical models of the dynamic response of the body.

CHAPTER 6: EFFECT OF INPUT SPECTRA ON APPARENT MASS

6.1 INTRODUCTION

The apparent masses of human subjects have usually been measured during exposure to broadband random vibration. However, studies have shown that apparent mass, at the seat surface, is affected not only by the magnitude of vibration (e.g. Fairley and Griffin, 1989; Mansfield, 1994; Mansfield and Griffin, 2000) but also by the frequency composition of the vibration (e.g. Fairley, 1986; Mansfield and Griffin, 1998). The apparent mass, and in consequence the seat transmissibility, therefore are dependent on road surface and driving conditions.

Previous studies of the effects of input spectra upon apparent mass have used a very limited number of input magnitudes and frequencies. Fairley (1986) measured the apparent mass of a single subject using sinusoidal vibration of different magnitudes (0.0, 0.5 and 1.0 ms^{-2} r.m.s) and frequencies (2.5, 5 and 10 Hz) added to background random vibration (at 0.25 ms^{-2} r.m.s). It was found for each frequency of the sinusoidal vibration that the frequency of the principal resonance in the apparent mass response decreased as the magnitude of the sinusoidal vibration increased. It was noted that the apparent mass changed in the 5 to 8 Hz frequency band when sinusoidal vibration was added at 2.5, 5, 10 and 20 Hz. Mansfield (1998) measured the apparent mass of 10 subjects exposed to 13 inputs. The stimuli consisted of broadband random vibration between 0.5 and 20 Hz with vibration components added in four different frequency bands: 0.2 to 2.0 Hz, 2.0 to 6 Hz, 6 to 10 Hz and 10 to 20 Hz. The components were added at three different magnitudes such that the overall vibration was 0.5, 0.75 and 1.0 ms^{-2} r.m.s. It was found that adding a sinusoidal component at any frequency affected the apparent mass at resonance.

This study was conducted to systematically quantify the effect of the frequency composition of input spectra and the effect of vibration magnitude on the non-linear response of seated subjects. It was hypothesised that the magnitude and frequency of the principal resonance seen in apparent mass responses is dependent on both the magnitude and the frequency of narrowband components added to a low-level broadband input.

6.2 METHODS AND PROCEDURES

The vertical apparent masses of 12 male subjects were measured on the surface of a rigid seat attached to an electro-hydraulic shaker. No backrest was used in the experiment. Subjects sat with their thighs horizontal and their feet supported on a horizontal footrest attached to the shaker platform. Subjects were instructed to sit in a relaxed upright posture that they felt they could maintain for the full duration of each 45-minute session.

A Kistler 9281 force platform was used to measure the vertical force on the seat surface. The platform had four, single axis, piezo-electric force cells, located beneath each corner of the top plate. The charge output from the four force cells was summed prior to amplification. A Setra 141A ±2g capacitive accelerometer was used to measure the vertical acceleration on the seat surface

Subjects were exposed to 51 vibration stimuli. The stimuli consisted of six broadband random inputs and 45 narrowband inputs. Each stimulus was sampled at 510 samples per second and had a duration of 60 seconds. A random order of presentation of inputs was used to minimize the influence of order effects. The stimuli were presented over two 45-minute sessions, each session scheduled for the same time on consecutive days.

The six broadband inputs were used to investigate the magnitude-dependent non-linearity seen previously in measurements of apparent mass. The broadband random inputs had approximately flat input spectra between 0.125 and 25 Hz. The magnitudes of the inputs were: 0.125, 0.25, 0.4, 0.63, 1.0 and 1.6 ms^{-2} r.m.s.

The narrowband inputs consisted of ½-octave bands of vibration superimposed on a low-level broadband random vibration (0.125 to 25 Hz with a magnitude of 0.25 ms^{-2} r.m.s.). The broadband random vibration was used to ensure that there was some information at all frequencies over the frequency range of interest. A previous study indicated that there were no significant differences in the frequency or magnitude of the principal resonance of apparent mass measured with broadband vibration at 0.25 and 0.50 ms^{-2} r.m.s., indicating that the broadband vibration employed in this study would have little effect on the non-linearity (Nawayseh, 2001). The narrowband components, with ½-octave bandwidth, were presented at five different magnitudes and at nine frequencies (see Table 6.1).

Table 6.1 Vibration components added to a 0.25ms^{-2} r.m.s. broadband vibration; each component was added at five magnitudes (0.25, 0.4, 0.63, 1.0 and 1.6 ms^{-2} r.m.s).

Spectra	Centre frequency of component, Hz	High-pass cut-off frequency, Hz	Low-pass cut-off frequency, Hz
1	1.0	0.84	1.20
2	1.4	1.20	1.68
3	2.0	1.68	2.38
4	2.8	2.38	3.36
5	4.0	3.36	4.76
6	5.6	4.76	6.73
7	8.0	6.73	9.51
8	11.2	9.51	13.45
9	16.0	13.45	19.03

The apparent masses of the subjects were calculated using the cross-spectral density technique with a frequency resolution of 0.25 Hz. Mass cancellation of the mass of the force platform top-plate was performed in the time domain to remove its influence from the data: the acceleration time-history on the seat surface was multiplied by the mass of the force platform which was then subtracted from the measured force response.

6.3 RESULTS AND DISCUSSION

6.3.1 Effect of vibration magnitude

Figure 6.1 shows the median of the modulus of the apparent masses of the 12 subjects, measured with each magnitude of broadband input. As the input magnitude increased, the frequency of the principal resonance decreased, this is consistent with a ‘softening’ of the body at higher magnitudes of vibration. The apparent mass at resonance decreased with an increase in vibration magnitude from 0.125 to 0.40 ms^{-2} r.m.s; at higher magnitudes the apparent mass at resonance remained approximately constant. The frequency of the second resonance, between approximately 8 and 15 Hz, also tended to decrease with increasing vibration magnitude. At higher magnitudes the second resonance is less distinct; this may be because as the frequency of the second resonance decreases it becomes indistinguishable from the first resonance. These results are similar to previous findings of Fairley and Griffin (1989) and Mansfield (1994) although the second resonance seen in the median data in this study is more defined and occurs at a higher frequency than in these earlier studies.

At all frequencies, the apparent mass at 0.25 and 0.40 ms^{-2} r.m.s. was broadly similar; this suggests that the influence of the low-level broadband vibration superimposed upon the narrowband inputs also had minimal effect upon the non-linearity.

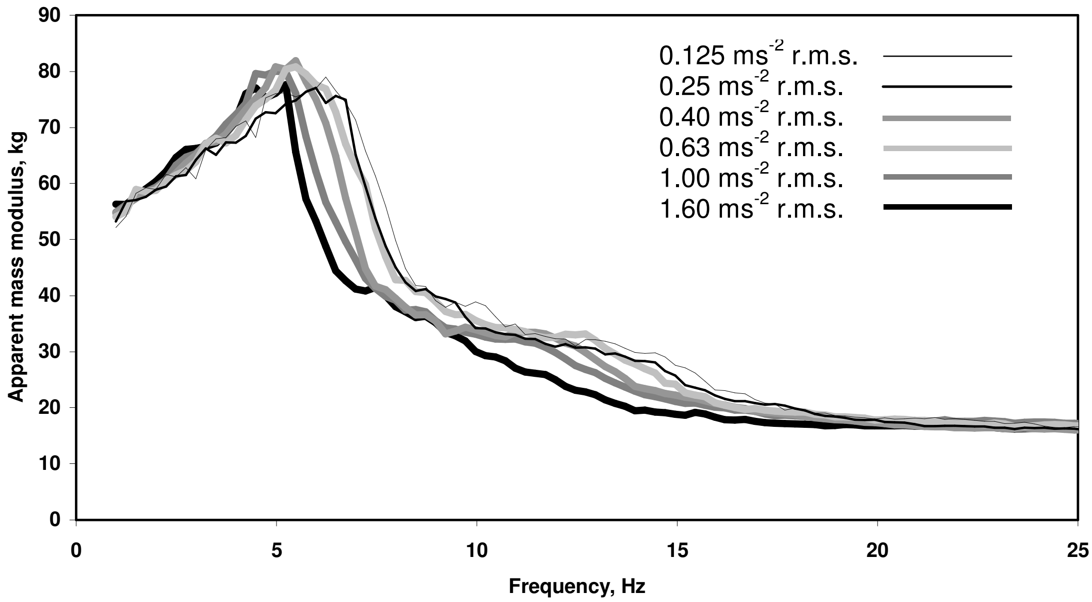

Figure 6.1 Median apparent masses of 12 subjects measured at 6 vibration magnitudes (0.125, 0.25, 0.40, 0.63, 1.0 and 1.6 ms^{-2} r.m.s.).

6.3.2 Effect of vibration input spectra

In Figures 6.2 to 6.5 the median apparent masses of the 12 subjects are shown with a single magnitude of narrow-band component centred at the nine different ½-octave frequencies. Results from the highest magnitude narrowband inputs (1.6 ms^{-2} r.m.s.) are not presented, as there was substantial harmonic distortion evident in the apparent mass response at this magnitude. The harmonic distortion resulted in substantial drops in coherency at frequencies around twice the narrowband input frequency. Similar harmonic distortion in driving point force has been found when exciting the body using sinusoidal vibration (e.g. Hinz and Seidel, 1987; Huang, 2008) and has been suggested to be caused by the thixotropic behaviour of some body tissue (Huang, 2008).

At the lowest magnitudes of narrowband input, 0.25 ms^{-2} r.m.s. (Figure 6.2), the apparent mass responses with the nine narrowband components are similar; this implies that at this magnitude the apparent mass was unaffected by the frequency of the narrowband input. With higher levels of narrowband components, the apparent mass responses with the nine input frequencies increasingly diverge as the magnitude of vibration increases. The variation in apparent mass with the frequency of the narrow-band input is greatest around the downward slope of the principal resonance, between approximately 5 and 8 Hz.

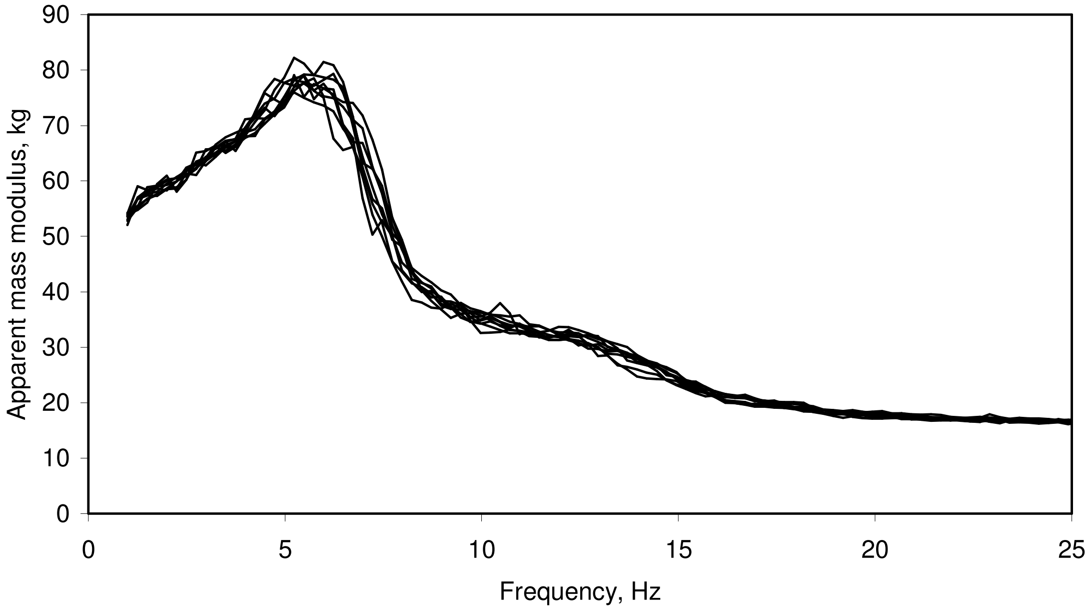

Figure 6.2 Median apparent masses of 12 subjects measured using 0.25 ms^{-2} r.m.s. narrowband inputs, at nine ½-octave frequencies from 1 to 16 Hz (see Table 6.1) superimposed on 0.25 ms^{-2} r.m.s. broadband vibration.

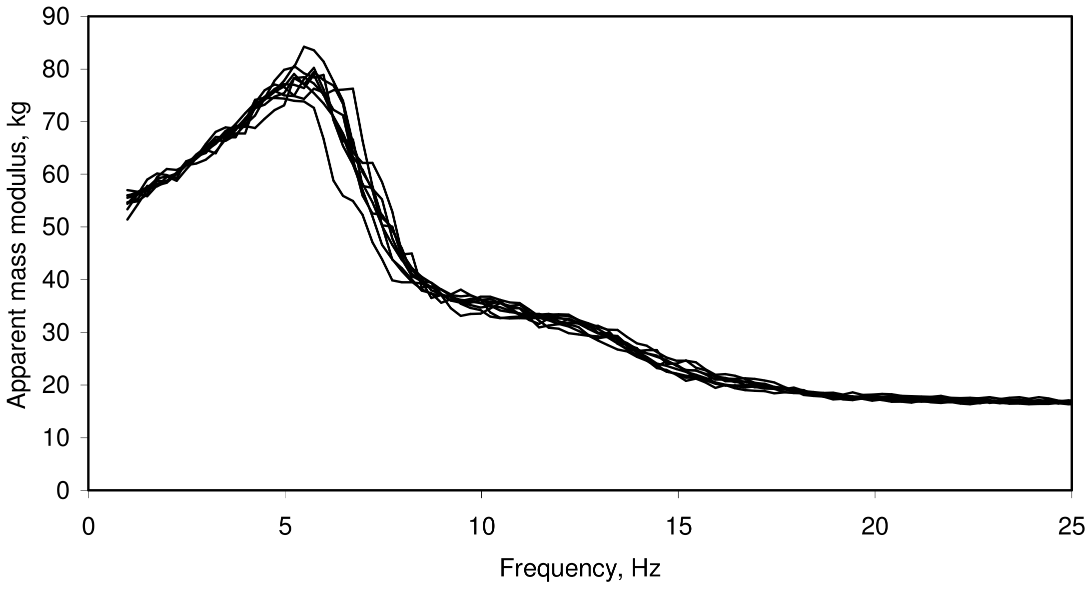

Figure 6.3 Median apparent masses of 12 subjects measured using 0.40 ms^{-2} r.m.s. narrowband inputs, at nine ½-octave frequencies from 1 to 16 Hz (see Table 6.1) superimposed on 0.25 ms^{-2} r.m.s. broadband vibration.

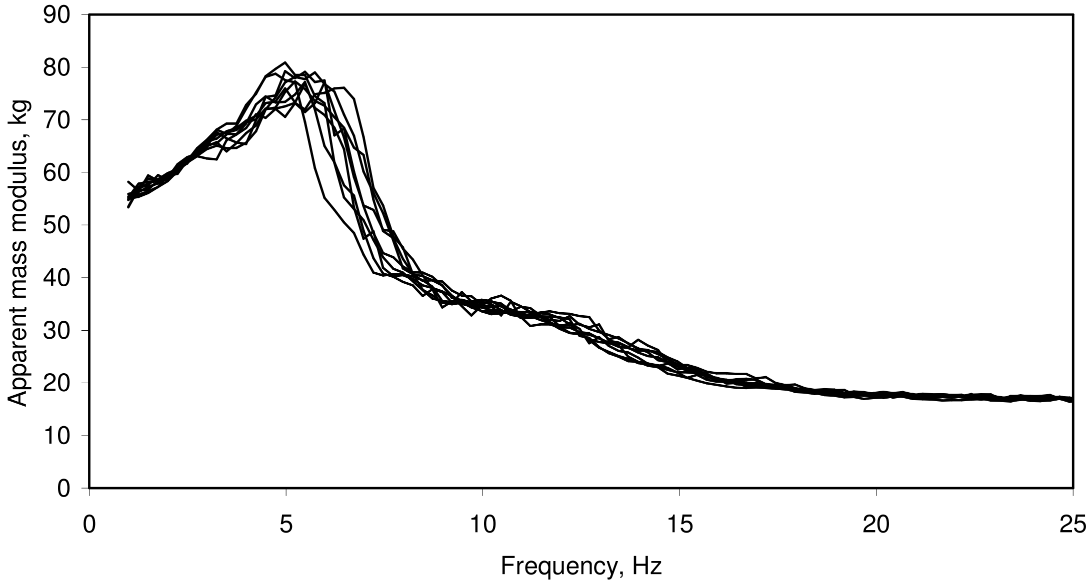

Figure 6.4 Median apparent masses of 12 subjects measured using 0.63 ms^{-2} r.m.s. narrowband inputs, at nine ½-octave frequencies from 1 to 16 Hz (see Table 6.1) superimposed on 0.25 ms^{-2} r.m.s. broadband vibration.

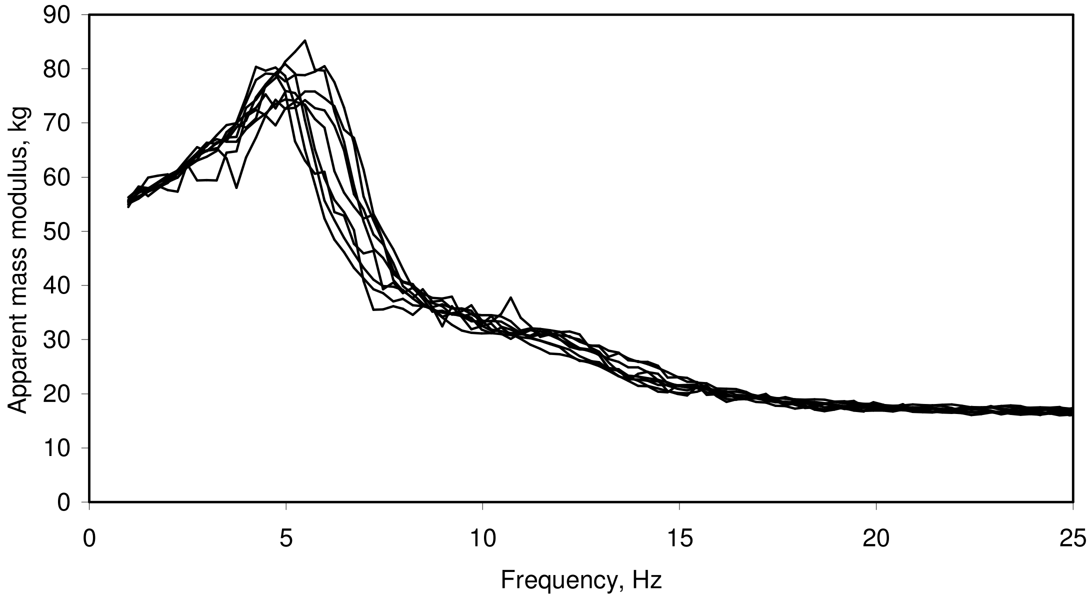

Figure 6.5 Median apparent masses of 12 subjects measured using 1.00 ms^{-2} r.m.s. narrowband inputs, at nine ½-octave frequencies from 1 to 16 Hz (see Table 6.1) superimposed on 0.25 ms^{-2} r.m.s. broadband vibration.

For each subject and each narrowband input, the frequency of the primary resonance in the apparent mass, and the apparent mass at this resonance, was determined. In Figure 6.6 and Figure 6.7 the median of these values are plotted for the first four input magnitudes at each of the nine ½-octave centre frequencies. Vibration at low frequencies (1 to 4 Hz) had the greatest effect on the apparent mass at resonance. With narrowband inputs below 4 Hz, the apparent mass at resonance decreased with increasing input magnitude, while above 4 Hz this trend is generally reversed (Figure 6.6). However, with narrowband inputs at frequencies greater than 4 Hz the apparent mass at resonance was affected less by input magnitude.

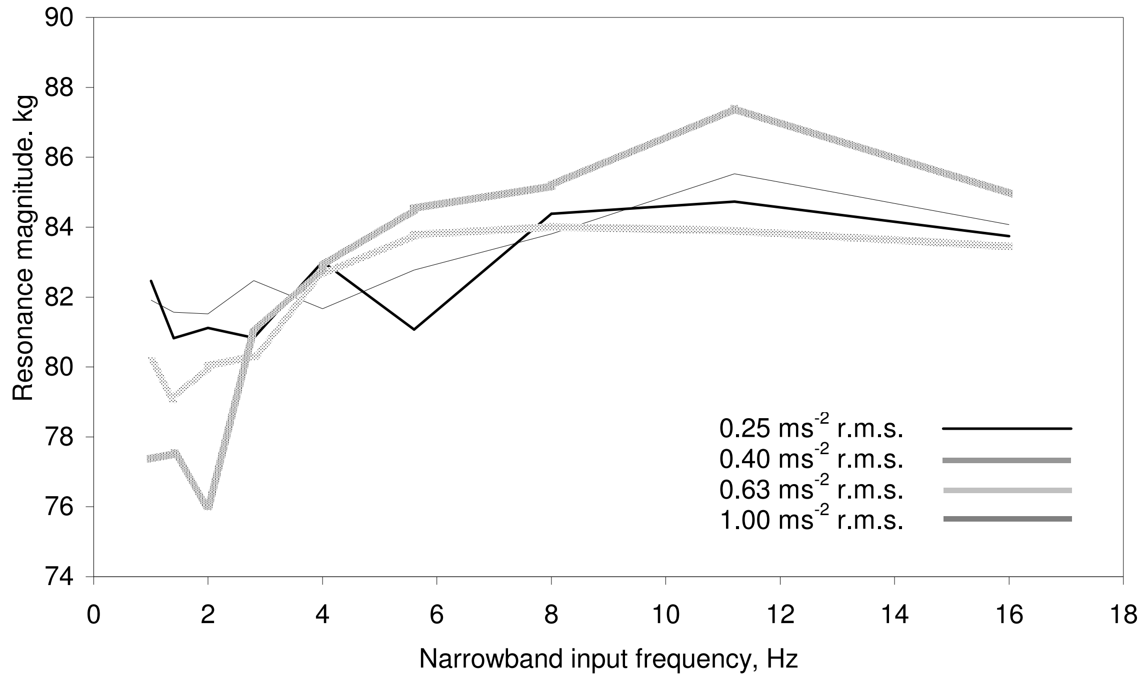

Figure 6.6 Median apparent mass at resonance measured with narrowband inputs at nine ½-octave input frequencies and five input magnitudes from 1 to 16 Hz (see Table 6.1) superimposed on 0.25 ms^{-2} r.m.s. broadband vibration.

With all narrowband centre frequencies, the resonance frequency tended to decrease with increasing input magnitude; this is consistent with measurements made using broadband vibration. In Figure 6.7, the spread of resonance frequencies, for any narrowband input, is indicative of the degree of non-linearity at resonance evidenced by changes of magnitude at the respective narrowband input frequency. This suggests that the magnitude of vibration at low frequencies (< 8 Hz) had the greatest effect on the resonance frequency. With narrowband inputs at higher frequencies the lines converge, indicating less effect on the resonance frequency. With all narrowband input frequencies, there was a significant difference in resonance frequency between the second lowest magnitude (0.40 ms^{-2} r.m.s.) and the highest magnitude (1.0 ms^{-2} r.m.s. of narrowband input (p<0.06). Resonance frequencies measured with the two lowest magnitudes (0.25 ms^{-2} r.m.s. and 0.40 ms^{-2} r.m.s.) were only significantly different with narrowband inputs centred at 4.0, 5.6 and 8.0 Hz. With narrow band inputs at frequencies up to 5.6 Hz, with magnitudes at 0.40, 0.63 and 1.0 ms^{-2} r.m.s., the resonance frequency decreased with increasing input frequency; above 5.6 Hz this trend is reversed.

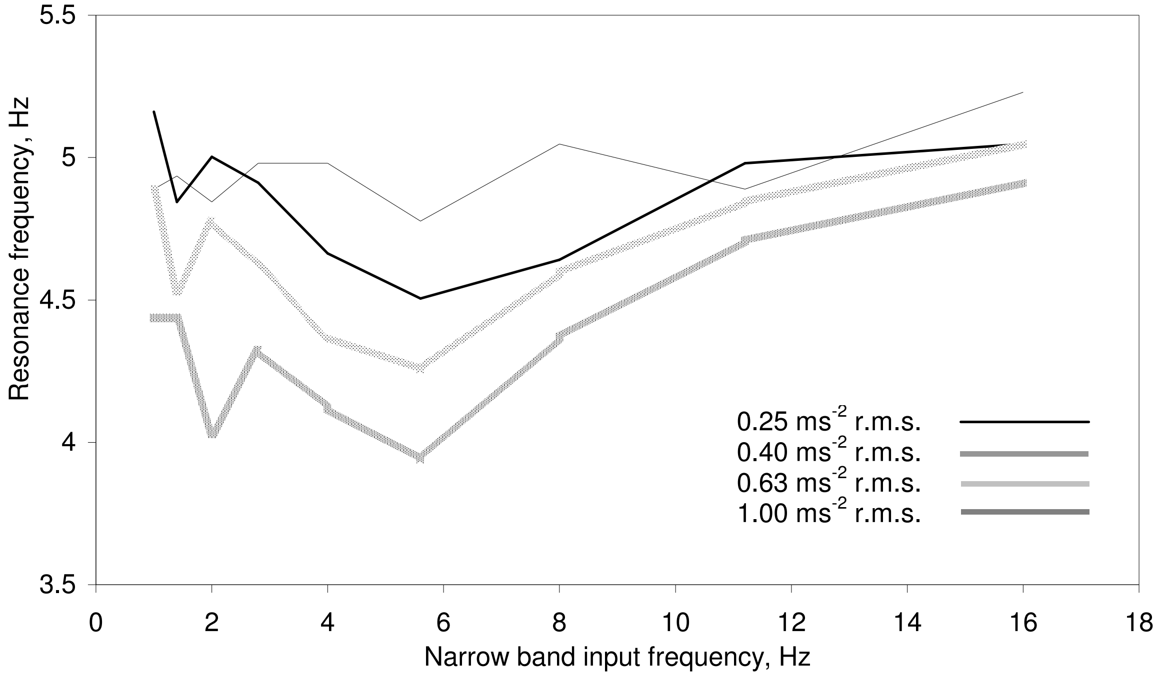

Figure 6.7 Median apparent mass resonance frequency measured with narrowband inputs at nine ½-octave input frequencies from 1 to 16 Hz and four input magnitudes (see Table 6.1) superimposed on 0.25 ms^{-2} r.m.s. broadband vibration.

The inter-subject variability seen in the apparent mass for each narrow band input was much greater than the variations between inputs for the median responses. For instance, with the 1.0 ms^{-2} r.m.s. narrowband input at 1 Hz, the frequency of the first resonance varied from 2.7 to 5.5 Hz between subjects - while the median resonance frequencies, for the nine inputs at this magnitude, varied between 3.9 and 4.8 Hz. For the same test conditions, the apparent mass at resonance varied from 57.6 to 94.6 kg between subjects and between 76.5 and 88.0 kg for the median responses between inputs. Although the effect of input spectra was relatively small when compared to inter-subject variability, the effect of small changes in the resonance frequency upon the apparent mass was large at frequencies around the resonance.

6.4 CONCLUSIONS

The vertical apparent mass of the seated body has been found to vary systematically with variations in both the magnitude and the frequency of the input vibration.

With broadband random inputs, as the magnitude of vibration increased the frequencies of the first and second resonances in the apparent mass response decreased. Up to vibration magnitudes of 0.40 ms^{-2} r.m.s., the apparent mass at the first resonance increased with vibration magnitude; at higher magnitudes the apparent mass at resonance remained approximately constant.

With narrow-band inputs, there was greater variation in apparent mass with the frequency of the narrow-band inputs at high magnitudes than with inputs at low magnitude. The magnitude of vibration at low frequencies (< 4 Hz) had the greatest effect on the apparent mass at the first resonance. With input frequencies greater than 4 Hz the primary resonance was affected less by the input magnitude.

With vibration at all narrowband centre frequencies, the frequency of the first resonance in the apparent mass tended to decrease with increasing input magnitude. The magnitude of vibration below 5.6 Hz was found to have the greatest influence on the frequency of the first resonance. At higher frequencies the effect of input magnitude upon the frequency of the first resonance was reduced.

CHAPTER 7: MODELLING THE INFLUENCE OF FACTORS AFFECTING APPARENT MASS

7.1 INTRODUCTION

Models of the dynamic responses of the human body may: (i) represent understanding of how the body moves (i.e. 'mechanistic models'), (ii) summarise biodynamic measurements (i.e. 'quantitative models'), or (iii) provide predictions of the effects of vibration on human health, comfort, or performance (i.e. 'effects models') (Griffin, 2001). It is now easy to develop and run complex finite element models (e.g. Siefert *et al*., 2006) and multi-body models (e.g. Yoshimura *et al*., 2005) of the body that are limited not by the complexity of the model but by the availability of reliable information on the in-vivo characteristics of body tissues and the measured gross dynamic behaviour of the body. Limitations to the availability of information on the dynamic responses of the body is such that it is very common for models to be developed with a complexity far greater than can be justified by the information on which they are based. While some such complex models may develop to provide useful insights into the dynamic behaviour of the body, their complexity is not yet appropriate for representing the responses needed to predict seat transmissibility (e.g. the apparent mass of the body). Indeed, current models mostly fail to reflect factors that are known to alter the dynamic response of the body and that can be expected also to alter seat transmissibility (e.g. the dynamic non-linearity of the body and the effects of body posture).

Simple lumped parameter models have been found to provide very close representations of the apparent mass of the human body sitting on a rigid seat with no backrest contact (Wei and Griffin, 1998a). Although models with several degrees of freedom are needed to represent the modulus and phase of both the in-line apparent mass and the cross-axis apparent mass, or the motions of the spine (e.g. Matsumoto and Griffin, 2001; Nawayseh and Griffin, 2009), a simple two-degree of freedom model can provide a very accurate representation of the in-line vertical apparent mass (Wei and Griffin, 1998a), and a simple single degree-of-freedom model may be sufficient for very many purposes (Wei and Griffin, 1998a; Fairley and Griffin, 1989).

Laboratory experimental studies have shown large changes in the vertical apparent mass of the body as a result of changes in sitting posture. Compared with sitting without a backrest, it has been reported that the principal resonance frequency of the body increases when supported by a reclined rigid backrest (Rakheja *et al*., 2002; Wang *et al*., 2004; Patra *et al.*, 2006) and that holding a steering wheel reduces the apparent mass at resonance (Rakheja *et al.*, 2002; Wang *et al.*, 2004). Reclining a rigid backrest from 0 to 30 degrees increased the median resonance frequency from 5.5 to 6.4 Hz, whereas the same inclination of a foam backrest decreased the resonance frequency from 5.2 Hz to 4.5 Hz (see Chapter 4). When the hands hold a steering wheel, the magnitude of the primary resonance decreases as the steering wheel is moved further away from the body, and a further resonance at around 4 Hz emerges; moving the feet forward from the seated body increases the apparent mass at resonance (see Chapter 5).

The dynamic responses of the human body are non-linear with respect to vibration magnitude (e.g. Fairley and Griffin, 1989). For example, with subjects sitting upright with no backrest, the resonance frequency in the apparent mass decreased from 5.25 to 4.25 Hz when the magnitude of random vibration increased from 0.35 to 1.4 ms^{-2} r.m.s. (Matsumoto and Griffin, 2002b). Similar non-linearities in biodynamic responses have been observed with subjects supported by an upright rigid backrest (e.g. Mansfield and Griffin, 2002) and with a reclined rigid backrest (e.g. Rakheja *et al.*, 2002). Non-linearity is reduced when muscle tension is increased in the buttocks or abdomen, suggesting that passive or active changes in the muscles are involved in non-linearity (Matsumoto and Griffin, 2002a).

Although experimental data have shown clear effects of posture and vibration magnitude on the apparent mass of the body, a model reflecting the influence of these factors has not previously been developed. This study was designed to determine the simplest possible lumped parameter model of the vertical apparent mass of the human body that could take into account variations in backrest contact, backrest inclination, hand position, footrest position, and vibration magnitude. It was envisaged that such a model could assist the prediction of the vibration transmitted through seats using either anthropodynamic dummies or mathematical modelling, as well as advancing understanding of the influence of these factors on body dynamics. It was hypothesized that there would be systematic trends in model parameters determined by fitted a simple model to experimental data obtained with variations in backrest contact, backrest inclination, hand position, footrest position, and vibration magnitude.

7.2 METHODS AND PROCEDURES

7.2.1 Model description and optimisation

The moduli and phases of experimentally determined apparent masses were fitted to the response of a simple single degree-of-freedom lumped parameter model (Figure 7.1). The model consisted of a base frame with mass, m_0, and a suspended structure represented by a single mass, m_1, connected to the base by spring stiffness, k_1, in parallel with damping, c_1.

The curve-fitting method used the constrained variable function (fmincon()) within the optimisation toolbox (version 3.1.1) of MATLAB (version 7.4.0.287, R2007a). The target error between the measured and modelled apparent mass response was minimised. The target error was calculated by summing the squares of the errors in the modulus (in kilograms) and the phase (in radians) over the frequency range 1 to 20 Hz. Before summation, an empirically determined weighting of 10 was applied to the phase errors so as to obtain good fits. The base mass in the model was fixed at 6 kg; this was considered the minimum mass that could be mechanically reproduced in an anthropodynamic dummy. The values of the other target parameters were allowed to be any positive value.

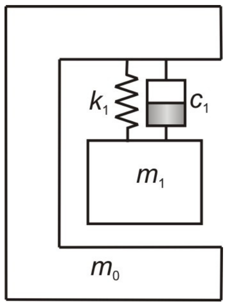

Figure 7.1 One-degree of freedom model.

Depending on the starting values of the model parameters, fmincon() can identify different local minima. To try to ensure the global minimum was found, the error function was minimized for 24 sets of starting values; the set that led to the minimum error was used. The fitted responses were compared to the measured data to check goodness of fit. Where the apparent mass was modelled as a function of a sequential variable (e.g. increasing backrest angle) the parameter set derived for the previous condition was used as an additional starting set for the next condition.

In order to characterise the response of the model, the damping ratios and damped natural frequencies were also calculated. The damping ratio, ζ , was calculated as: $\xi = \frac{c_1}{2\sqrt{k_1 m_1}}$ with the damped natural frequency, f , derived from the un-damped natural frequency f^n, as $f = f^n\sqrt{1-\varsigma^2}$, with $f^n = \frac{1}{2\pi}\sqrt{\frac{k_1}{m_1}}$.

For each condition, the lumped parameter model was fitted to the median apparent mass of the subject group. To model the effects of continuous variables that influence the apparent mass of the body (e.g. backrest inclination), sets of parameters have been indentified for each measured condition. Trends in parameters were then identified as a function of the condition (e.g. backrest angle).

Non-parametric tests (Wilcoxon matched-pairs signed ranks test for two-related samples and Friedman test for *k* related samples) were employed in the statistical analysis.

7.2.2 Experimental measurements

The model was fitted to the vertical apparent mass measured at the seat surface in previous experimental studies of factors affecting the dynamic response of the body: investigating the effects of a seat backrest (Chapter 4), footrest and steering wheel (Chapter 5), and vibration magnitude (Chapter 6).

The experimental arrangement is illustrated in Figure 7.2 (the backrest and hand support were not used in all studies). The experimental conditions are summarised below, with further details given in the respective chapters.

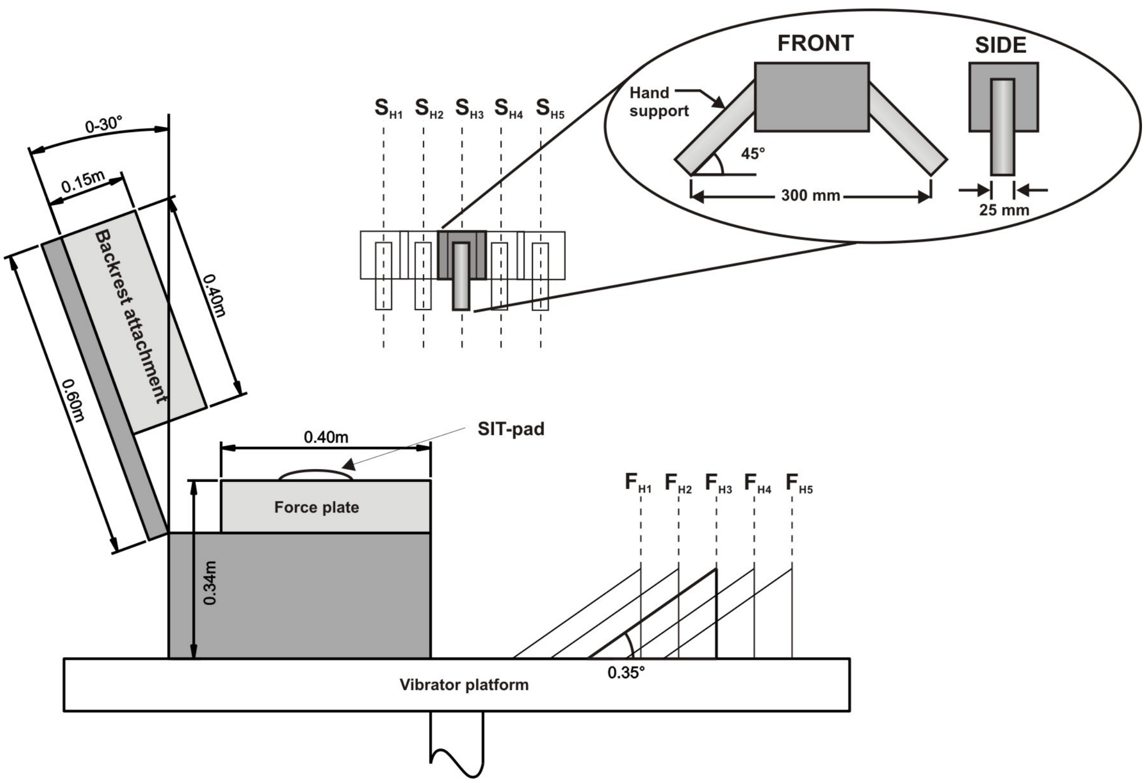

Figure 7.2 Experimental setup used for the measurement of apparent mass (see Chapters 4 to 6).

In each study, the apparent mass of 12 male subjects was measured. With the exception of the study of the effect of input spectra, the vibration input was broadband random vertical vibration with a nominally flat constant bandwidth spectrum over the frequency range 0.125 to 40 Hz with an overall magnitude of 1.0 ms^{-2} r.m.s.

Backrest contact and backrest angle

The apparent masses of subjects sitting upright with no backrest support were measured. Their apparent mass was also measured when they made contact with a rigid flat backrest, and when they made contact with a 100-mm thick foam backrest supported on the rigid backrest, with the backrest inclined from 0 to 30° in 5° increments. The rigid backrest vibrated vertically in-phase with the vertical vibration at the seat surface.

Steering wheel and footrest

The effect on vertical apparent mass at the seat pan of holding a steering wheel, varying the position of a steering wheel, and varying the fore-and-aft position of a footrest was also measured (Figure 7.2). At the closest steering wheel position (SH_1), the forearm and upper arm were at 90°. In the furthest position (SH_5), the arms were outstretched. At the closest footrest position (FH_1), the angle between the femur and fibular was 90°. In the furthest position of the footrest (FH_5), the legs were outstretched and the femur and fibular were at 180°.

Input magnitude

The non-linearity of the apparent masses of subjects was quantified with broadband random inputs (0.125 to 25 Hz) presented at six magnitudes of vibration (0.125, 0.25, 0.4, 0.63, 1.0 and 1.6 ms^{-2} r.m.s.). Subjects sat upright with no backrest support and positioned their feet in a 'normal' driving posture.

7.3 RESULTS

7.3.1 Backrest

The measured apparent masses of the 12 individuals are compared with the apparent mass of the fitted one degree-of-freedom model in Figure 7.3 (magnitude) and Figure 7.4 (phase). Each subplot compares the measured and modelled response for a subject in two conditions: sitting upright with no backrest support and sitting supported by an upright rigid backrest. It can be seen that the simple model was able to provide reasonable fits to all of the measured responses. Between 8 and 15 Hz, another resonance was apparent in the responses of some subjects, with the frequency and magnitude of this resonance varying between subjects: the single degree-of-freedom model was unable to replicate the response of this resonance and so there was some divergence between the measured and fitted modulus in this region. At frequencies greater than about 10 Hz, the modelled phase lag was less than the measured phase lag for most subjects.

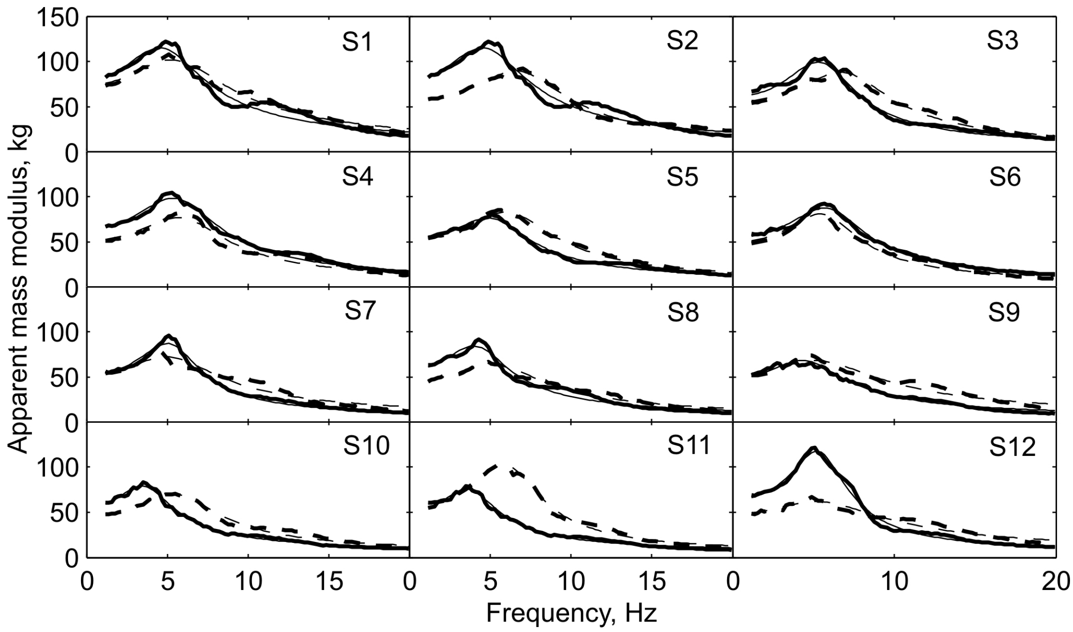

Figure 7.3 Effect of backrest contact on the apparent mass moduli of 12 subjects (S1-12) with hands in lap. Comparison of measured (▬▬ no backrest, - - - - upright rigid backrest) and modelled data (—— no backrest, - - - - upright rigid backrest).

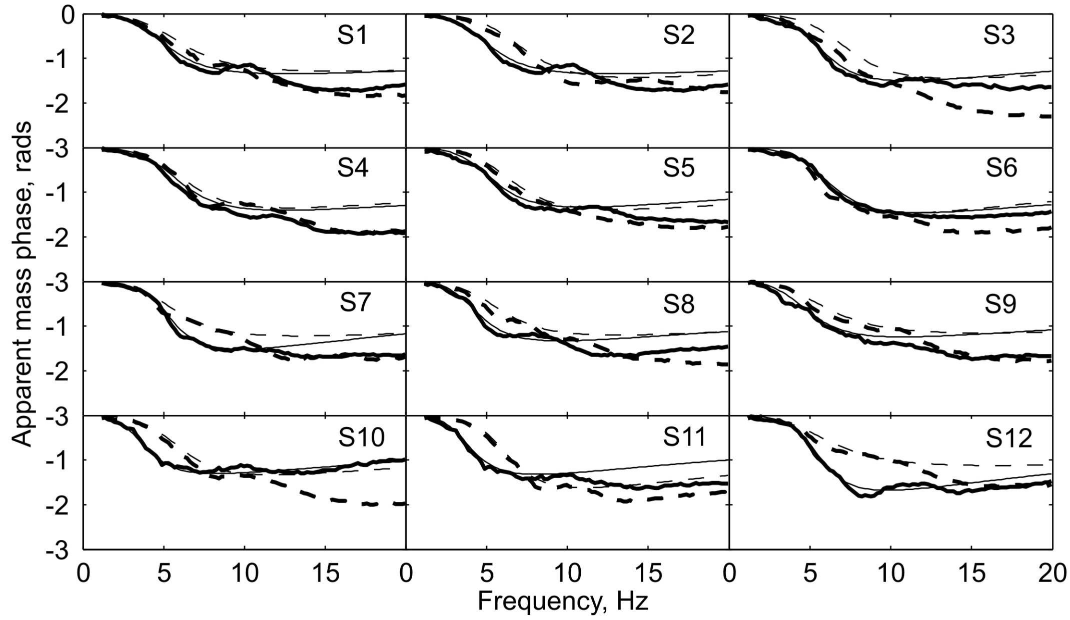

Figure 7.4 Effect of backrest contact on the apparent mass phase of 12 subjects (S1-12) with hands in lap. Comparison of measured (▬▬ no backrest, - - - - upright rigid backrest) and modelled data (—— no backrest, - - - - upright rigid backrest).

The parameters derived for the model for each subject in both backrest conditions are given in Table 7.1. When there was contact with the backrest, the fitted median for the moving mass, m_1 decreased from 54.1 kg to 47.7 kg ($p < 0.01$; Wilcoxon), and the stiffness k_1, increased ($p < 0.01$), resulting in an increase in the derived damped natural frequency from 4.9 to 5.9 Hz ($p < 0.01$). There was greater damping ($p < 0.01$) and a greater damping ratio ($p = 0.05$) when there was backrest support.

Table 7.1 Effect of contact with an upright rigid backrest on parameters generated by fitting a single degree-of-freedom model to the measured vertical apparent masses of 12 subjects (S1-12) and also to the median apparent mass.

	m_0, kg	m_1, kg	k_1, kNm^{-1}	c_1, kNsm^{-1}	f, Hz	ζ, Hz
No backrest						
S1	6.0	74.3	83.3	2.45	4.6	0.49
S2	6.0	54.9	76.3	1.53	5.5	0.37
S3	6.0	58.7	88.2	1.95	5.6	0.43
S4	6.0	45.6	57.1	1.42	5.1	0.44
S5	6.0	48.7	79.2	1.50	5.9	0.38
S6	6.0	46.2	56.5	1.14	5.2	0.35
S7	6.0	51.7	44.1	1.39	4.1	0.46
S8	6.0	42.7	44.3	1.36	4.5	0.49
S9	6.0	48.8	30.9	1.15	3.5	0.47
S10	6.0	45.3	30.6	1.06	3.7	0.45
S11	6.0	57.5	73.2	1.26	5.4	0.31
S12	6.0	46.5	72.7	1.81	5.5	0.49
Median response	*6.0*	*51.4*	*60.9*	*1.55*	*4.9*	*0.44*
Rigid backrest						
S1	6.0	67.5	106.4	2.84	5.4	0.53
S2	6.0	51.3	114.0	1.95	6.9	0.40
S3	6.0	49.5	112.3	1.83	7.0	0.39
S4	6.0	45.3	77.1	1.61	5.9	0.43
S5	6.0	48.4	89.2	1.74	6.2	0.42
S6	6.0	43.7	64.6	1.23	5.7	0.37
S7	6.0	46.7	65.5	1.84	5.1	0.53
S8	6.0	40.0	60.0	1.59	5.3	0.51
S9	6.0	46.4	72.4	2.17	5.1	0.59
S10	6.0	40.7	62.7	1.37	5.6	0.43
S11	6.0	51.5	84.6	1.34	6.1	0.32
S12	6.0	41.8	69.1	2.05	5.2	0.60
Median response	*6.0*	*47.7*	*82.2*	*1.80*	*5.9*	*0.45*

The medians of the moduli and phases of the measured apparent masses of the 12 subjects supported by a rigid backrest reclined in 5° increments (from 0 and 30°) are compared to the fitted responses in Figure 7.5. Again, the single degree-of-freedom model seems to reproduce the median responses up to around 8 Hz and to reflect the trends in the frequency of the primary resonance. The model parameters derived from fitting to the medians of the subject group are shown in Table 7.2 for inclinations of both the rigid backrest and the foam backrest.

The moving mass, m_1, decreased by 8.7 kg ($p < 0.01$) as the rigid backrest was reclined from 0 to 30°. An increase in the damped natural frequency, from 5.9 to 6.5 Hz as the backrest was reclined to 30° ($p = 0.01$), was primarily due to a progressive decrease in the moving mass as opposed to an increase in the stiffness, k_1 ($p = 0.43$). Since the reduction in damping as the backrest was reclined ($p = 0.01$) would tend to increase the apparent mass at resonance, the reduction in apparent mass with increasing inclination was mainly caused by the decreases in the moving mass, m_1.

Between 0 and 15° the moving mass was not affected by backrest inclination ($p > 0.75$, Friedman); reclining the backrest from 15 to 30°, the moving mass decreased ($p < 0.01$)

and the damping increased ($p < 0.01$) similar to the rigid backrest. However, unlike the rigid backrest, there was a decrease in the resonance frequency from 5.0 to 4.6 Hz as the foam backrest was reclined from 15 to 30° ($p < 0.01$). Since the moving mass decreased with increasing inclination of the foam backrest, the decrease in resonance frequency was due to a decrease in the stiffness, k_1 ($p < 0.01$).

The apparent mass between 8 and 15 Hz and the phase at frequencies greater than 8 Hz varied with backrest angle, but this variation was not reflected in the fitted responses.

Table 7.2 Effect of backrest type, and backrest angle, on the parameters generated by fitting the single degree-of-freedom model to the median apparent masses of 12 subjects.

	m_0, kg	m_1, kg	k_1, kNm^{-1}	c_1, kNsm^{-1}	f, Hz	ζ, Hz
Rigid backrest angle						
0°	6.0	47.7	81.5	1.80	5.9	0.46
5°	6.0	47.9	81.7	1.79	5.9	0.45
10°	6.0	46.2	80.0	1.76	5.9	0.46
15°	6.0	44.9	79.8	1.68	6.0	0.44
20°	6.0	43.6	80.5	1.67	6.1	0.45
25°	6.0	42.5	79.4	1.61	6.2	0.44
30°	6.0	39.0	78.8	1.49	6.5	0.43
Foam backrest angle						
0°	6.0	48.3	67.7	1.62	5.3	0.45
5°	6.0	47.7	66.2	1.56	5.3	0.44
10°	6.0	47.9	61.4	1.49	5.1	0.43
15°	6.0	48.4	57.5	1.42	5.0	0.42
20°	6.0	47.7	54.9	1.36	4.9	0.42
25°	6.0	47.0	49.6	1.39	4.6	0.46
30°	6.0	45.1	48.0	1.35	4.6	0.46

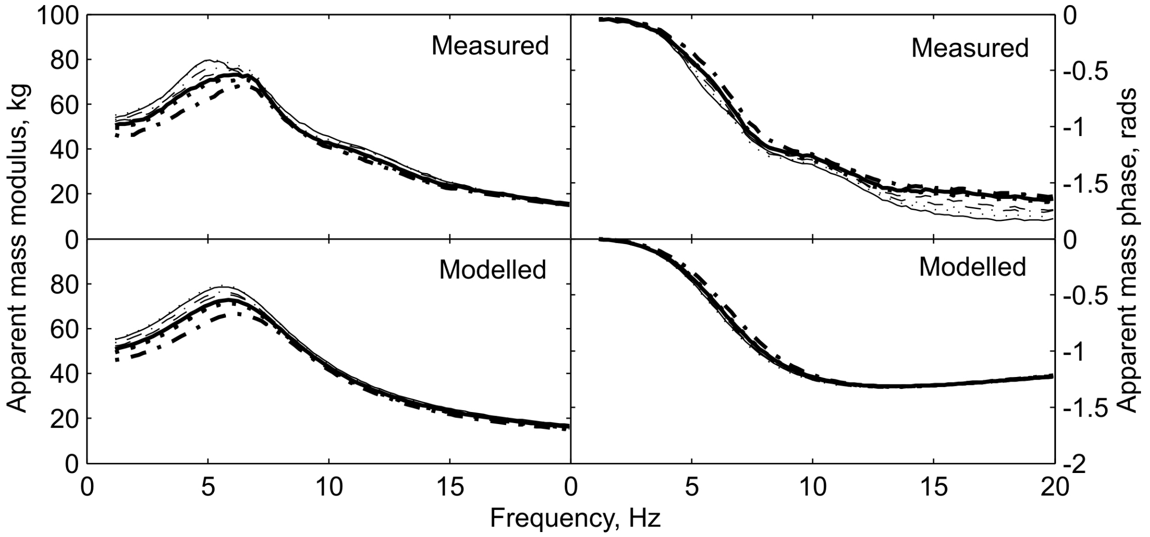

Figure 7.5 Effect of inclination of a rigid backrest on the median vertical apparent masses of 12 subjects measured on the seat. Comparison of modelled and experimental data. ——— , 0°; · · · · · · , 5°; · - · - · - 10°; - - - - - ,15°; ▬▬▬ ,20°; ▪ ▪ ▪ ▪ ▪ ,25°; · ▬ · ▬ · ,30°.

7.3.2 Posture

When subjects held a steering wheel, a resonance was evident around 4 Hz that was not evident with a 'hands in lap' posture (Figure 7.6). There was a tendency for this resonance to become more pronounced as the hands moved further away from the body. The single degree-of-freedom model was not able to represent both resonances, resulting in a single peak fitted to both resonances. Consequently, the frequency and magnitude of the derived natural frequency did not only reflect changes in the primary resonance but was also influenced by the resonance around 4 Hz. The effect of this was that the modelled resonance decreased in frequency more, and reduced in magnitude less, compared to the measured primary resonance; this was the case for fits to both the individual and median data. The influence of the resonance at 4 Hz was least when the steering wheel was positioned at its closest position (S_{H1}); the effects on the primary resonance of moving the steering wheel forward from this position were not reflected in the modelled response, consequently only the derived parameters for the 'hands in lap' and the S_{H1} postures are shown (Table 7.3).

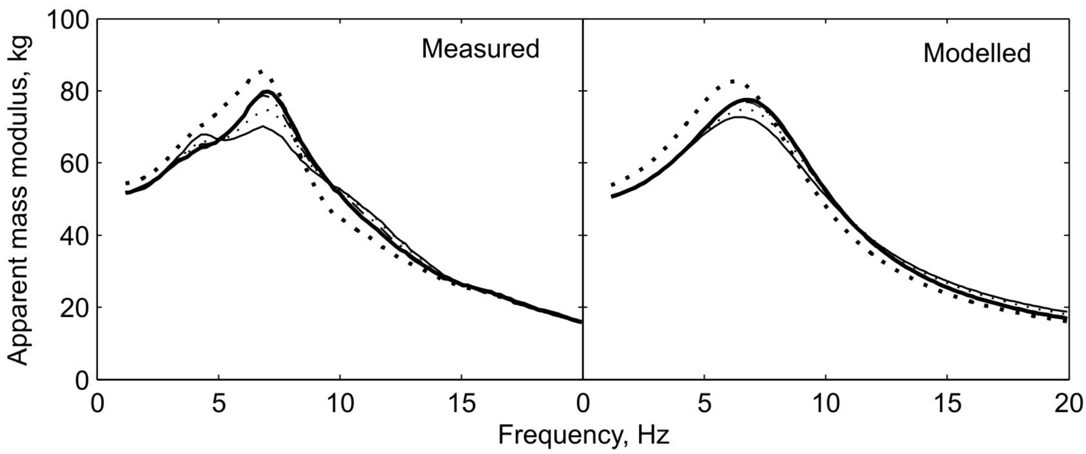

Figure 7.6 Effect of hand position on the median vertical apparent masses of 12 subjects measured on the seat. Comparison of modelled and experimental data with hands on steering wheel (——— , S_{H5} (max); ······· , S_{H4}; ·-·-·- S_{H3}; - - - - - ,S_{H2}; ▬▬▬ ,S_{H1}) and hands in lap (▪▪▪▪▪).

When subjects held a steering wheel in position S_{H1}, the median moving mass, m_1, decreased by 3.0 kg compared to the 'hands in lap' posture; indicative of the steering wheel supporting some of the subject weight ($p < 0.01$). The decrease in moving mass and the increase in stiffness ($p < 0.01$) resulted in an increase in the derived damped natural frequency ($p < 0.01$) when subjects held a steering wheel. The damping ($p = 0.56$) and damping ratio ($p = 0.97$) were not affected by moving the hands from the lap to the steering wheel position S_{H1}.

As the feet moved forward, from a position where the lower-legs and the upper-legs were at 90° (F_{H1}) to a position where they were at 45° (F_{H3}), the moving mass increased (p = 0.02) but none of the other model parameters were significantly affected (Table 7.4). Moving the feet forward further from the mid position (F_{H3}), to a position where the legs were outstretched (F_{H5}), there was a further increase in the mass and also a decrease in the resonance frequency ($p < 0.01$) and in the associated stiffness ($p < 0.01$).

Table 7.3 Effect of hand and foot position on the parameters generated by fitting the single degree-of-freedom model to the median apparent masses of 12 subjects.

Condition	m_0, kg	m_1, kg	k_1, kNm^{-1}	c_1, kNsm^{-1}	f, Hz	ζ, Hz
Hand position						
Hands in lap (backrest at 15°, feet F_{H4})	6.0	46.6	91.3	1.60	6.5	0.39
Hands on steering wheel (backrest at 15°, feet F_{H4}, hands S_{H1})	6.0	43.6	101.7	1.63	7.1	0.39
Footrest position (hands in lap)						
F_{H1} (minimum)	6.0	43.9	95.5	1.83	6.6	0.45
F_{H2}	6.0	44.6	96.9	1.85	6.6	0.44
F_{H3} (mid)	6.0	44.6	96.9	1.85	6.6	0.44
F_{H4}	6.0	46.6	91.3	1.60	6.5	0.39
F_{H5} (maximum)	6.0	48.8	79.3	1.66	5.8	0.42

7.3.3 Input magnitude

The effects of the magnitude of vibration on the parameters derived from fitting to the median responses are shown in Table 7.4. Increasing the magnitude from 0.125 to 1.60 ms^{-2} r.m.s. decreased the natural frequency from 5.8 to 4.6 Hz (p = 0.01) in the derived model. As the moving mass was unaffected (p = 0.86), this was primarily caused by a decrease in the model stiffness from 86.1 to 54.4 kN.m^{-1} ($p < 0.01$). The fitted damping decreased from 1833 to 1465 Nsm^{-1} ($p < 0.01$) as the magnitude increased from 0.125 to 1.60 ms^{-2} r.m.s.. The damping ratio was not affected (p = 0.82).

Table 7.4 Effect of the magnitude of vertical vibration on the parameters generated by fitting the single degree-of-freedom model to the median apparent masses of 12 subjects (hands in lap, no backrest contact).

Condition	m_0, kg	m_1, kg	k_1, kNm^{-1}	c_1, kNsm^{-1}	f, Hz	ζ, Hz
Input magnitude, ms^{-2} r.m.s.						
0.13	6.0	52.4	86.1	1.83	5.8	0.43
0.25	6.0	52.5	79.5	1.82	5.5	0.45
0.40	6.0	53.5	75.4	1.74	5.4	0.43
0.60	6.0	52.1	64.1	1.56	5.0	0.43
1.00	6.0	52.3	60.4	1.52	4.9	0.43
1.60	6.0	51.7	54.4	1.47	4.6	0.44

7.4 DISCUSSION

7.4.1 Relevance to ISO 5982 (2001)

International Standard 5982 (2001) gives idealized values for the apparent mass and the seat-to-head transmissibility of seated people exposed to vertical vibration. The values are intended for the development of mechanical and mathematical models to represent the body and are an amalgamation of several datasets obtained in broadly comparable conditions. The data were acquired with subjects sitting with no backrest and relatively high vibration magnitudes, markedly different from most real world environments.

The single degree-of-freedom model employed in the current study (as shown in Figure 7.1) has also been fitted to the idealized values of apparent mass given in ISO 5982 (2001). It can be seen in Figure 7.7 that, notwithstanding the simplicity of the model used here, the fitted values are generally within the idealized range in ISO 5982 (2001) at frequencies less than 20 Hz, although the phase lag at frequencies greater than 15 Hz is slightly less than the upper limit of the phase lag defined in the standard.

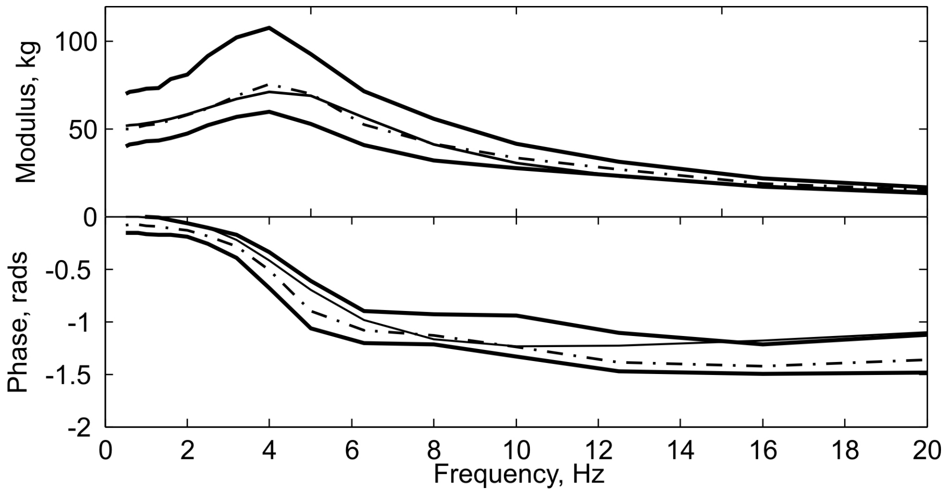

Figure 7.7 Idealized mean (· - - · - -) and limit values (▬▬▬) given in ISO 5982 (2001) compared to the fitted response of the single degree-of-freedom model (———). Model parameters: m_0 = 6.0 kg, m_1 = 45.5 kg, k_1 = 46361 Nm^{-1}, c_1 = 1470 Nsm^{-1}.

The trends in the model parameters quantified in this study (as shown in Tables 7.1 to 7.4) can also be presented as a function of the studied variable (e.g. Figure 7.8 - effect of backrest angle with rigid and foam backrests). Such trends might be used to apply correction factors to idealized values, such as those in ISO 5982 (2001), so as to adjust for differences between the conditions in which the apparent mass has been measured and an environment in which the data are to be used. For a car driver, for example, the backrest conditions and backrest angle, the footrest position, the hand position, and the vibration magnitude would differ from those assumed in ISO 5982 (2001). From the data shown here, corrections to the model parameters might be considered for the effects of backrest contact, backrest angle, steering wheel contact, foot position, and the magnitude of vibration.

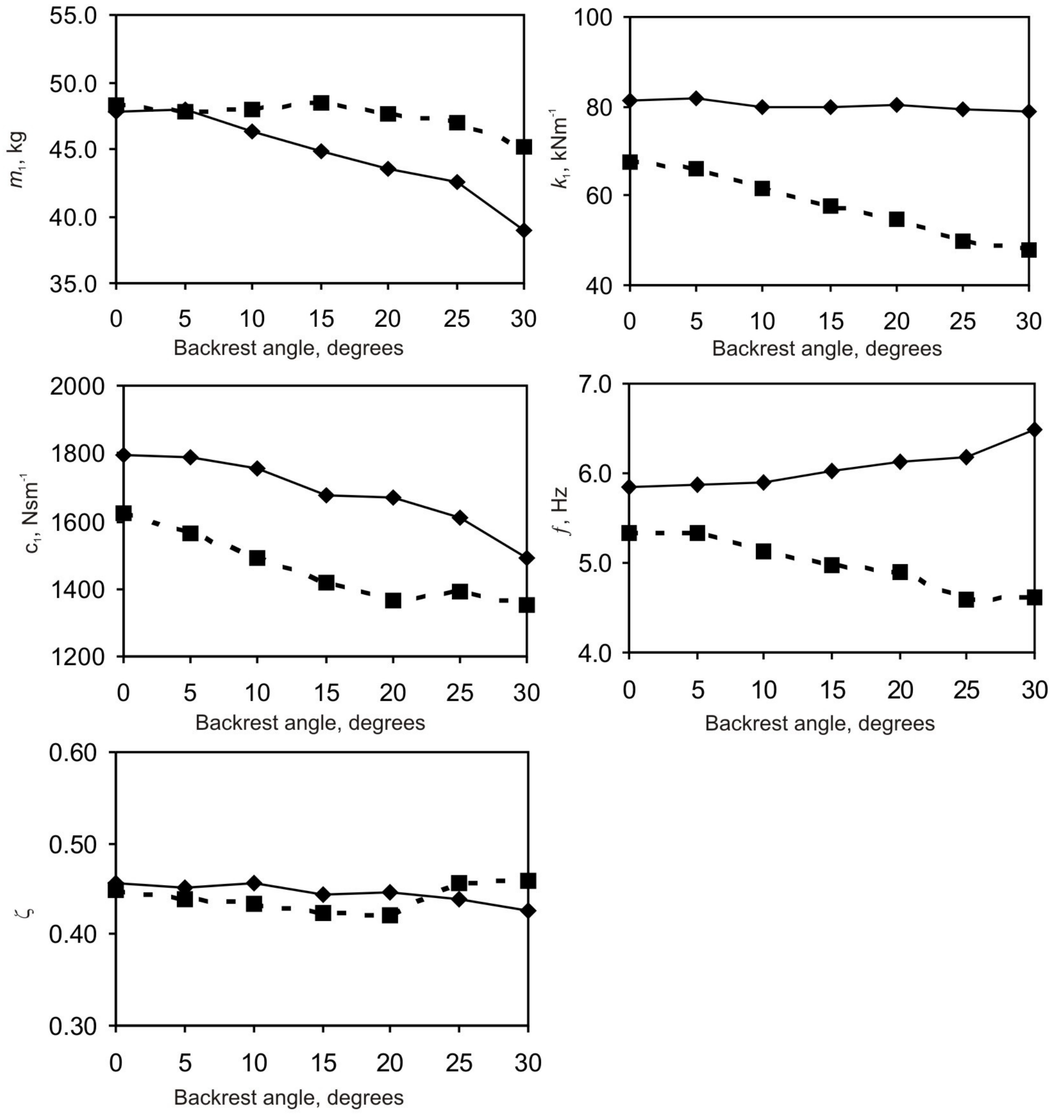

Figure 7.8 Effect of inclination of rigid backrest (——) and foam backrest (- - -) on the parameters generated by fitting the single degree-of-freedom model to the median apparent masses of 12 subjects.

7.4.2 Other applications of the model

Models of the apparent mass of the body that allow for the effects of changes in the posture of subjects or the magnitude of vibration may also be used in the development of anthropodynamic dummies. Variations in model parameters would be difficult to achieve using a dummy constructed with solely passive components (e.g., Gu, 1999; Appendix A) but may be achieved with an active dummy (e.g., Lewis and Griffin, 2002; Cullmann and Wolfel, 2001). The response of an active anthropodynamic dummy is partially controlled by an actuator, so the damping and stiffness can be altered without hardware modification. Any interaction of a dummy with the backrest of a seat could influence the dynamic response at the seat pan, so a dummy based solely on the apparent mass at the seat pan should be de-coupled from the seat backrest to produce the required response at the seat surface.

Wei and Griffin (1998b) described a method to predict seat transmissibility from measurements of the dynamic stiffness and damping of the seat and a dynamic model of the human body. Their study employed the apparent masses of subjects sitting upright with no backrest while exposed to a single magnitude of vibration. A model with variable parameters as described within this study could be used to make predictions for more realistic seating conditions. This assumes that the apparent mass of the body sitting on a rigid flat seat is sufficiently similar to the apparent mass of the body supported on a compliant seat. The contact area and pressure distribution will differ between rigid and compliant seats and it has been suggested that such differences may affect the apparent mass of the body (Hinz *et al.*, 2006).

7.4.3 Model limitations

The response of a two degree-of-freedom model with two single degree-of-freedom structures suspended off a base mass was also considered in this study (Wei and Griffin, 1998a). Where the measured apparent mass showed evidence of additional resonances, the resulting fits were noticeably improved but there were fewer statistically significant trends in the model parameters. This reduction in consistency of trends was caused by the variation in the magnitude and frequency of secondary resonances between subjects and between conditions. The difference between the measured and fitted responses with the single degree-of-freedom model was generally much less than the inter-subject variability and also less than the variability between conditions, particularly at frequencies less than 10 Hz, and it was therefore decided that the fits obtained were acceptable for the present purpose.

There were some minor inconsistencies in parameter trends (e.g. Table 7.2: 20° backrest inclination, higher k_1 value; Table 7.4: 0.4 ms^{-2} r.m.s., higher m_1 value). Depending on the starting parameters, the fmincon() function can converge on local rather than global minima, but by using a single degree-of-freedom model and multiple starting parameters the likelihood of this is reduced. Inspection of the fits to the data suggest the minor inconsistencies in parameters reflect the underlying data as opposed to problems in converging on global minima.

Inter-subject variability has been shown to have a large effect on apparent mass (Fairley and Griffin, 1989). The effect of subject mass on model parameters could be taken into account by fitting the model parameters to the apparent masses of subjects grouped by mass. Increased subject mass tends to increase the apparent mass at all frequencies, and it has been found that inter-subject variability can be reduced by normalising the apparent mass with respect to the subject mass supported on the seat surface (Fairley and Griffin, 1989). However, variability still exists in the normalised data, suggesting that physical characteristics of subjects other than their body mass also contribute to variability in apparent mass. Although some of these factors have been investigated (e.g. Fairley and Griffin, 1989) they are not fully understood. The variability between subjects might be investigated by fitting a model to the responses of individual subjects and using regression analysis to identify associations between subject physical characteristics and model parameters.

Other postural and environmental factors have also been found to affect the vertical apparent mass at the seat surface, including seat pan inclination (Wang, 2004; Nawayseh and Griffin, 2005), the frequency of vibration (Mansfield, 2006), and the thickness of backrest foam (see Chapter 5). Although the influence of these factors on apparent mass may sometimes be small relative to the influence of other factors investigated here, systematic investigations are appropriate to better understand the influence of all factors influencing apparent mass and its practical applications.

An increase in the number of degrees-of-freedom in the model employed here would obviously increase the fit between the model and any experimental data. However, a single degree-of-freedom model provides a surprisingly good fit, especially when considering the large variability in apparent mass between people. An additional degree-of-freedom would be beneficial in some postures and with some individuals, but there would appear to be no justification for developing more complex models to predict seat transmissibility if they do not reflect the relatively large effects of vibration magnitude, posture, individual variability and other factors that influence apparent mass and its application to predicting seat transmissibility.

7.5 CONCLUSIONS

By appropriate variations in model parameters, a single degree-of-freedom model can provide a useful fit to the measured vertical apparent mass of the human body over a wide range of postures and vibration magnitudes at frequencies less than about 20 Hz. The trends in model parameters that have been determined allow apparent mass to be predicted for combinations of conditions that have not been measured. The findings may assist the development of models for predicting seat transmissibility, including the development of anthropodynamic dummies.

CHAPTER 8: EFFECT OF INTER-SUBJECT VARIABILITY ON APPARENT MASS

8.1 INTRODUCTION

Experimental studies have shown a large variability in the apparent mass of the human body and some studies have suggested reasons for some of the differences. The effect of subject characteristics on the vertical apparent mass of the body has been reported for 60 subjects (24 men, 24 women, and 12 children) sitting upright on a rigid flat seat with no backrest contact and with lower legs vertical (Fairley and Griffin, 1989). There was a large variation in apparent mass between subjects at low frequencies, but after normalisation (dividing the modulus of the apparent mass by the static mass supported by the seat) the variability was much reduced. Most subjects had a principal resonance near 5 Hz, with the apparent mass at this frequency about 40% greater than the static mass. It was found that the weight of subjects supported on the seat divided by their sitting height was correlated with their resonance frequency, their age was correlated with their normalised apparent mass at 20 Hz, and their total body weight was correlated with their normalised apparent mass at their resonance frequency. There was no statistically significant effect of subject weight on resonance frequency, in contrast to other studies that have claimed the resonance frequency decreases with increasing subject mass (e.g. Rakheja *et al*., 2002; Patra *et al.* 2006).

Variable effects of gender on the apparent mass the body have been reported. Fairley and Griffin (1989) observed that the mean normalised apparent masses of men, women, and children were similar. Wang *et al*. (2004) suggested females have a greater normalised apparent mass than men at frequencies between 15 and 40 Hz, Lundström *et al.* (1998) suggested females have a slightly lower resonance frequency, and Holmlund *et al.* (2000) claimed that females have a less distinct peak in their mechanical impedance than males. Although the effects of subject weight were controlled in these studies, either by normalising the apparent mass or by comparing groups with matched weights, the effects of other characteristics were not controlled, allowing the possibility that apparent effects of gender may have been confounded by the effects of other variables.

The resonance frequency in the vertical apparent mass of the body reduces as the magnitude of the vibration excitation increases. This non-linearity has been observed when sitting with no-backrest (e.g. (Fairley and Griffin, 1989; Holmlund *et al*., 2000), when sitting with a reclined backrest (Rakheja *et al*., 2002), when standing (Matsumoto and

Griffin, 1998b), and when supine (Huang and Griffin, 1998). It has been reported that the influence of vibration magnitude on the resonance frequency is less when sitting in a car driving posture than when sitting with no backrest support (Patra *et al.* 2008). Inter-subject variability in apparent mass has been reported to be greatest at low magnitudes of vibration, with most variability when supported by a backrest or leaning forward with no backrest, and least variability when sitting upright, either with no backrest or supported by a foam backrest (Mansfield and Griffin, 2002).

Ranges of 'idealized values' of vertical apparent mass of the human body are presented in ISO 5982 (2001). The values were compiled from measurements in conditions assumed to be broadly comparable. Reference values are offered for three groups of body weight (55, 75, 90 kg), with other physical characteristics (e.g. age, gender and stature) not considered. The reference values were derived from either the apparent mass or the mechanical impedance of subjects measured while sitting without the support of a backrest and while exposed to vibration at magnitudes up to 5 ms^{-2} r.m.s. The applicability of the idealised values provided in ISO 5982 to the drivers and passengers of common vehicles is unknown.

This study was designed to determine the relative strengths of any associations between subject characteristics (gender, age, weight, and anthropometric measurements) and the characteristics of the vertical apparent mass of the human body (especially the resonance frequency and the modulus of the apparent mass at 0.6 Hz, at resonance, and at 12 Hz) when seated with and without a backrest.

8.2 METHODS AND PROCEDURES

8.2.1 Apparatus

Vertical vibration was produced using a 1-metre stroke electro-hydraulic vibrator in the laboratories of the Human Factors Research Unit at the Institute of Sound and Vibration Research. Subjects sat on the flat upper surface of a force plate (0.6 m wide by 0.4 m deep) secured to a rigid seat with a rigid flat backrest having adjustable inclination. The upper surface of the force plate (Kistler 9281 B; Kistler, Hook, UK) was 0.34 m above the vibrator platform on which the feet were supported. The feet of each subject were moved forward on the vibrator platform until the thighs were just touching the leading edge of the seat. The signal from the force plate was amplified using a Kistler 5007 charge amplifier. The acceleration of the platform was monitored using an *HVLab* SIT-pad containing a piezo-resistive accelerometer (Entran EGCSY-240D-10; Entran, Potterspury, UK).

8.2.2 Vibration

Gaussian random vibration (band-limited using 8-pole Butterworth filters between 0.125 and 25 Hz) with approximately flat constant bandwidth acceleration spectra were generated and analysed using an *HVLab* data acquisition and analysis system (version 3.81; University of Southampton, UK). Different random signals were generated for each subject. The measured force and acceleration were acquired at 400 samples per second via 133 Hz anti-aliasing filters.

8.2.3 Conditions

The apparent mass of each subject was measured with four backrest conditions:

(i) sitting upright with no backrest;

(ii) sitting upright with a rigid backrest;

(iii) sitting with a rigid backrest reclined to 15°;

(iv) sitting with a foam backrest reclined to 15°.

The apparent mass was measured at three magnitudes of vibration (0.5, 1.0, and 1.5 ms^{-2} r.m.s.) in conditions (i) and (iii), and at only one magnitude (1.0 ms^{-2} r.m.s.) in conditions (ii) and (iv). Each exposure to vibration was 60 s in duration.

The foam squab attached to the backrest in condition (iv) had a uniform thickness of 100 mm. A spacer was placed behind the rigid backrest in conditions (ii) and (iii) so that the length of thigh contact with the seat was similar to that in the other two postures. Using a SIT-bar shaped indenter with a 100-N preload, the 100-mm foam was measured to have a stiffness of approximately 21 kN/m and damping of approximately 109 Ns/m at frequencies between 2 and 20 Hz.

8.2.4 Subjects

The group of 80 adult subjects participating in the experiment was chosen to be representative of the UK car driving population (Table 8.1; Pheasant, 2006; Department of Health, 2008). The subjects were exposed to all conditions in a single session lasting approximately 60 minutes. For each subject the order of presentation of conditions was randomized. Subjects wore a loose fitting lap belt and had access to an emergency stop button. Subjects gave informed consent to participate in the experiment that was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

Table 8.1 Mean and standard deviations of subject characteristics (UK population in brackets).

	All subjects			Women (39 subjects)			Men (41 subjects)		
	Mean	s.d.	Range	Mean	s.d.	Range	Mean	s.d.	Range
Age, years	33.7	13.1	18-65	33.1	11.2	19-56	33.8	14.8	18-65
Weight, kg	70.5	13.4	46-103	62.8 (69.7[a])	11.5	46-98	77.1 (83.5[a])	11.3	58-103
Stature, cm	171.0	11.3	149-192	162.6 (162.0[b])	8.9	149-185	178.5 (176.0[b])	7.1	164-192
Body mass index[c], kgm^{-2}	24.1	3.8	18-34	23.8 (26.8[a])	4.2	18-34	24.2 (27.1[a])	3.4	18-31
Knee height, cm	52.7	4.2	45-61	50.1 (50.0[b])	3.4	45-61	55.2 (55.0[b]	3.1	50-61
Buttock knee length, cm	59.6	4.2	48-69	57.9 (56.5[b])	3.8	48-66	61.0 (59.5[b])	4.0	56-69
Sitting height, cm	85.8	5.1	76-101	82.7 (85.5[b])	3.4	76-92	88.7 (91.5[b])	4.7	80-101

[a] Adults aged 16+ (Department of Health, 2008)
[b] Anthropometric estimates for British adults aged 19-65 (Pheasant, 2006)
[c] (Body mass index, kgm^{-2}) = (mass, kg) / (height, m)^2

8.2.5 Analysis

Transfer functions were calculated between the vertical seat acceleration and the vertical force at the seat surface, to give the apparent masses of the subjects. Apparent mass was calculated using the cross-spectral density (CSD) technique with a frequency resolution of 0.195 Hz. The apparent mass was calculated from the ratio of the cross-spectral density between the force and acceleration at the seat, to the power spectral density of the acceleration at the seat.

Prior to the calculation of the apparent mass, mass cancellation of the mass of the top platform of the force-plate (33.0 kg) was performed in the time domain to remove its influence from the measured force: the acceleration time-history on the seat surface was multiplied by the mass of the force platform and subtracted from the measured force. The coherency between the force and acceleration was calculated after mass cancellation and found to be greater than 0.9 over the frequency range 0.20 to 30 Hz; above 30 Hz the coherency tended to decrease slightly but was still generally over 0.8.

The apparent mass at the primary resonance frequency was assumed to be the greatest apparent mass over the measurement range (0.6 to 20 Hz). The primary resonance frequency was defined as the frequency at which the apparent mass was greatest.

8.2.5.1 Statistical analysis

Parametric statistics were used throughout the analysis. The paired samples *t*-test was used to compare features of the apparent mass between conditions (i.e. between backrests and magnitudes). The independent samples *t*-test was used to compare features of the apparent mass between subjects grouped by their characteristics (i.e. size, age, gender). The standard deviation was used to quantify variability in features of the apparent mass. Variability in apparent mass between conditions was tested using Levene's test of equality of variance.

Linear regression was used to identify predictors of the apparent mass. Initially, the associations between each characteristic of the subjects and the features of the apparent mass were separately analysed by ordinary least squares regression. Then, for each test condition (i.e. for each combination of backrest and vibration magnitude) significant predictors drawn from the physical characteristics were selected for the final regression model using the PASW stepwise procedure (PASW statistics, version 17.0). A significance level of 0.05 was used to enter and retain a variable in the model. Variables significantly associated with each dynamic characteristic for any test condition, together with age and gender, were then entered simultaneously into regression models. Quadratic terms of each of the significant variables were added in turn to the final regression models; in all instances *F*-tests showed that assuming a linear effect did not compromise goodness of fit ($p>0.1$). Differences in the regression coefficients, *B*, between pairs of conditions (e.g. c1, c2) were tested using the null hypothesis Ho: $B_{c1}=B_{c2}$. For each independent variable in the model, *x*, first a dummy variable, *z*, was created coded 1 for c1 and 0 for c2, as well as a variable *zx* that was the product of *z* and the independent variable. Variables *x*, *z*, and *zx* were then used as predictors in the regression equation. The interaction term, *zx,* tested the null hypothesis Ho: $B_{c1}=B_{c2}$, significance ($p<0.05$), indicating that the regression coefficient B_{c1} was significantly different from B_{c2}.

Beta coefficients were calculated by multiplying each of the regression coefficients (*B*) in the multiple regression models by its standard deviation and dividing by the standard deviation of the dependent variable. Thus, a change of 1.0 standard deviations in the predictor variable results in a change of 1.0 standard deviations in the criterion variable.

In general, parametric statistics are more powerful than their non-parametric equivalent and in the case of regression analysis allow the quantification of the influence of each predictor variable on the dependent variable; however parametric statistics assume a Gaussian distribution in the data. Parametric statistics were used in this experiment and in the experiment described in Chapter 9 because of the larger sample sizes (i.e. 80 subjects compared to Chapters 4 to 6 (12 subjects), which allowed more comprehensive checks of the distribution of the data. The Kolmogorov-Smirnov test in SPSS in addition to visual inspection of histograms and Q-Q plots of each variable were used to check for the degree of skew 'non-symmetry' and kurtosis 'peakiness' in each dependent and independent variable. These checks revealed mild negative skew in the ages and BMI's of the subjects; Log transformations of BMI and Age were used to explore (and correct for) any effects of this skew. Regression analyses using, initially, age, gender and BMI, and subsequently log(age), gender, and log(BMI), as predictors of resonance frequency were found to produce almost identical results in terms of the statistical strength of associations. However, by retaining the age and BMI variables in their original units the interpretation of the results is made easier.

8.3 RESULTS

8.3.1 Inter subject variability

When subjects sat upright with no backrest, the frequency of the main resonance in the 80 subjects varied between 3.5 Hz and 6.4 Hz, with the mean resonance frequency around 4.9 Hz (Figure 8.1 and Table 8.2). At very low frequencies, the apparent mass tends toward the static mass supported on the platform, so inter-subject variability in the modulus of the apparent mass at low frequencies was reduced by normalisation (i.e. dividing the apparent mass of each subject by their static mass supported on the seat, assumed to be the apparent mass measured at 0.6 Hz) (Figure 8.1). To test for the effects of normalisation, the apparent mass of each subject at resonance and at 12 Hz was rationalized (divided by the mean response of the subject group at these frequencies), for both the measured apparent mass and the normalized apparent mass. At resonance, the rationalized standard deviation was significantly reduced by normalisation (from 0.255 to 0.105; $p<0.001$, Levene), but at 12 Hz the standard deviation was not significantly reduced by normalisation (from 0.236 to 0.217; $p=0.534$).

Table 8.2 Effect of backrest contact and vibration magnitude on the primary resonance frequency and the apparent mass at resonance, at 0.6 Hz, and at 12.0 Hz. Means (and standard deviations) of 80 subjects.

	Resonance frequency, Hz	Apparent mass at resonance, kg	Apparent mass at 0.6 Hz, kg	Apparent mass at 12.0 Hz, kg
Backrest contact (1.0ms^{-2} r.m.s.)				
No backrest	4.9 (0.6)	98.7 (24.9)	62.0 (12.6)	27.8 (6.6)
Upright rigid backrest	5.2 (0.7)	89.2 (24.8)	58.0 (12.2)	32.6 (6.3)
Reclined rigid backrest	5.9 (0.8)	83.1 (22.6)	55.0 (12.3)	34.7 (6.9)
Reclined foam backrest	5.0 (0.7)	93.8 (23.1)	57.6 (12.1)	27.5 (6.2)
Input magnitude (no backrest)				
0.5 ms^{-2} r.m.s.	5.2 (0.7)	94.9 (25.7)	59.8 (14.5)	29.7 (7.1)
1.0 ms^{-2} r.m.s.	4.9 (0.6)	98.7 (24.9)	62.0 (12.6)	27.8 (6.6)
1.5 ms^{-2} r.m.s.	4.7 (0.6)	99.8 (24.9)	62.1 (12.5)	26.2 (6.1)
Input magnitude (reclined rigid backrest)				
0.5 ms^{-2} r.m.s.	6.4 (1.0)	81.2 (22.9)	53.2 (13.6)	35.9 (7.4)
1.0 ms^{-2} r.m.s.	5.9 (0.8)	83.1 (22.6)	55.0 (12.3)	34.7 (6.9)
1.5 ms^{-2} r.m.s.	5.4 (0.8)	84.0 (22.1)	56.0 (11.9)	33.0 (6.4)

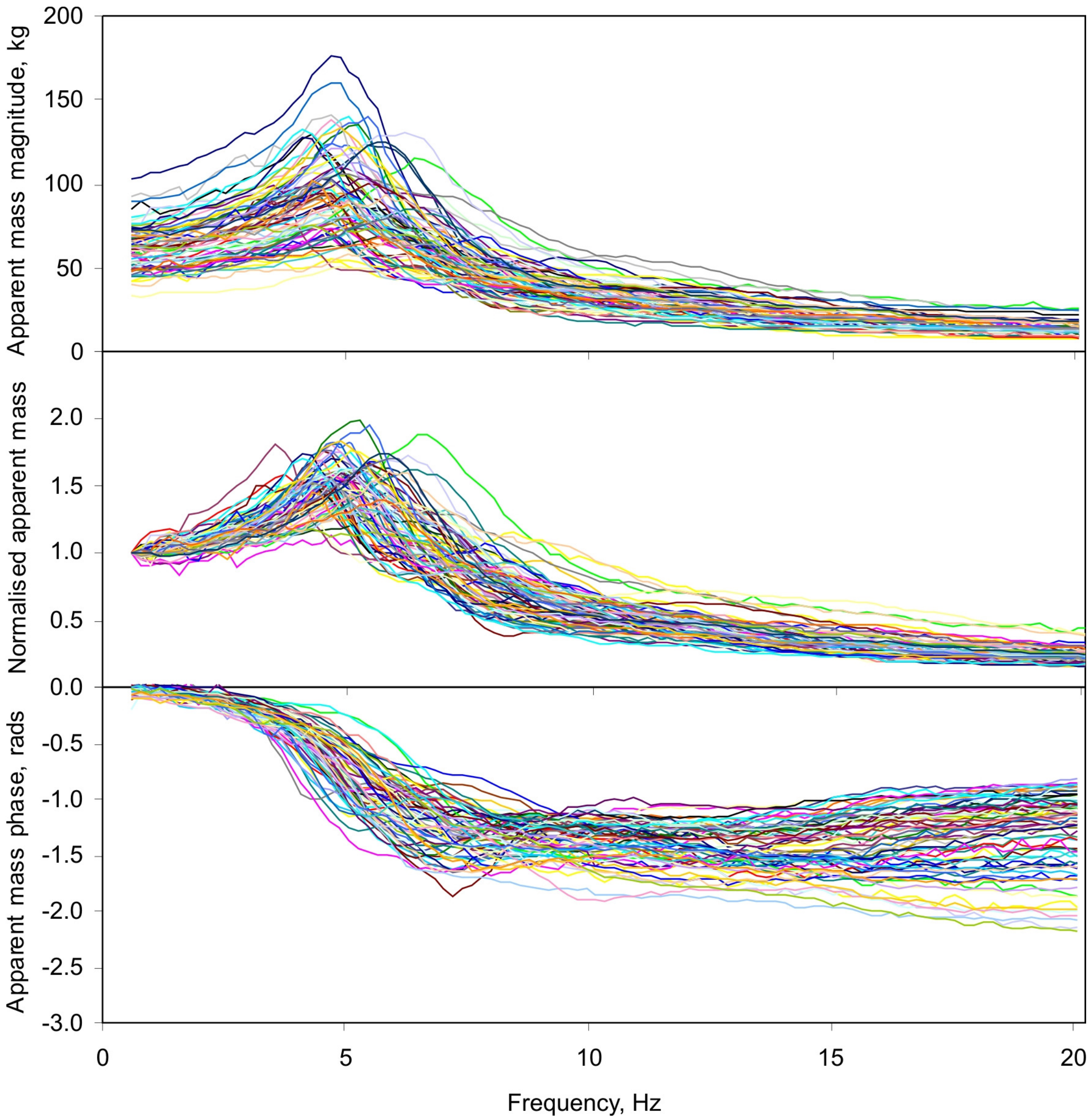

Figure 8.1 Apparent masses of 80 adults (no backrest, excitation magnitude 1.0 ms^{-2} r.m.s.).

8.3.2 Effects of backrest

The mean resonance frequency increased from 4.9 Hz to 5.2 Hz when subjects made contact with an upright rigid backrest (p<0.001), with a decrease in the apparent mass at resonance (p<0.001) and at 0.6 Hz (p<0.001) (Table 8.2). When this rigid backrest was reclined, the resonance frequency increased further to 5.9 Hz (p<0.001), and the apparent mass at frequencies less than the resonance frequency decreased (p<0.001 at 0.6 Hz). The mean resonance frequency with the reclined foam backrest was not significantly different from the resonance frequency without a backrest (p=0.762), but the apparent mass at resonance and at 0.6 Hz was lower (p<0.001).

The means and standard deviations of the apparent mass with each backrest condition are shown in Figure 8.2 and Table 8.2. Inter-subject variability in the resonance frequencies, the apparent masses at resonance, at 0.6 Hz, and at 12 Hz was compared between the backrest conditions. No significant differences in inter-subject variability were found in the apparent mass at resonance, at 0.6 Hz, or at 12 Hz between the four postures (in all cases p>0.39). There was greater variability in the resonance frequencies with the reclined rigid backrest than without a backrest (p=0.004) and with the reclined foam backrest (p=0.010).

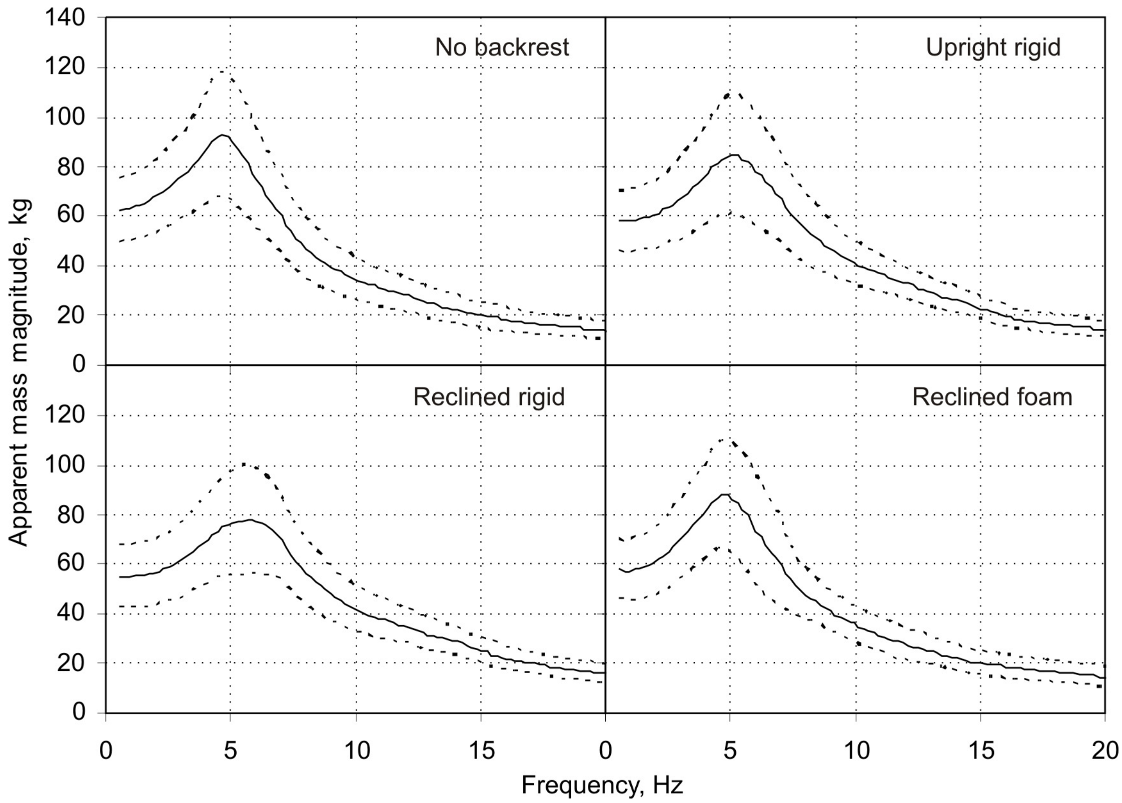

Figure 8.2 Effect of the seat backrest on mean apparent mass and inter-subject variability; 1.0 ms^{-2} r.m.s excitation: mean (——) and ±1 s.d. (· · · · ·).

8.3.3 Effects of magnitude

When there was no backrest, the mean resonance frequency decreased by 0.5 Hz (from 5.2 to 4.7 Hz) as the vibration magnitude increased from 0.5 to 1.5 ms^{-2} r.m.s. (p<0.001; Table 8.2). With the rigid reclined backrest, the mean resonance frequency decreased by 1.0 Hz (6.4 to 5.4 Hz) as the vibration magnitude increased from 0.5 to 1.5 ms^{-2} r.m.s. (p<0.001).

At each vibration magnitude, the variability between the resonance frequencies of subjects was less without the backrest than with the reclined rigid backrest (in all cases $p<0.01$). Without a backrest, and with the rigid reclined backrest, the vibration magnitude did not affect the inter-subject variability in resonance frequency ($p>0.1$) (Figure 8.3). The variability in the apparent mass at resonance, at 0.6 Hz, and at 12 Hz was also not significantly affected by the vibration magnitude ($p>0.3$).

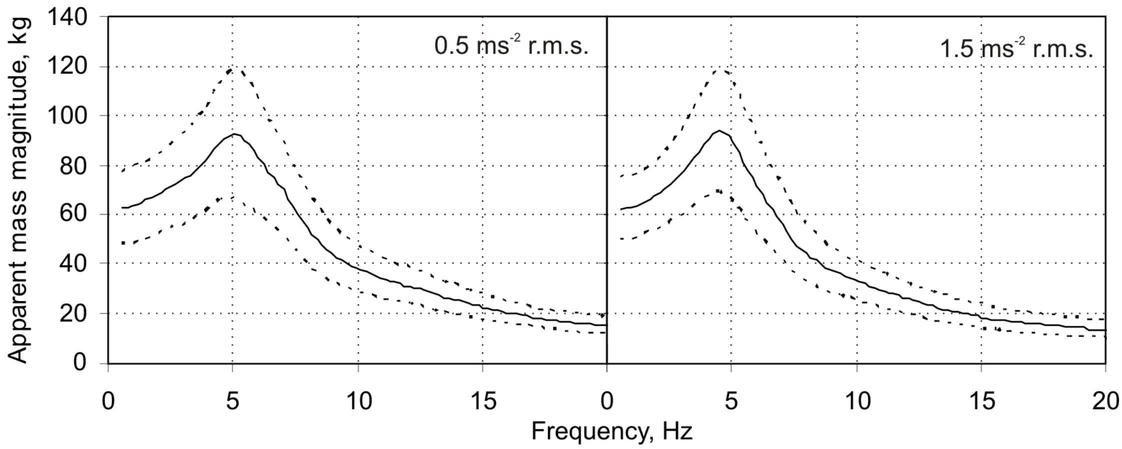

Figure 8.3 Effect of input magnitude on apparent mass and inter-subject variability; no backrest contact: mean (——) and mean ±1 s.d. (· · · · ·). For excitation at 1.0 ms^{-2} r.m.s., see Figure 8.2 (no backrest).

8.3.4 Effects of subject physical characteristics

The 80 subjects were divided into various series of four equal groups according to subject weight, age, stature, and BMI, and the two genders. The means and standard deviations of the resonance frequency and the apparent mass at resonance, at 0.6 Hz, and at 12 Hz were calculated for each group (Table 8.3).

Without the backrest, at both the resonance frequency and at 12 Hz there were significant differences in the apparent mass between all pairings of weight groups ($p<0.01$). However, after normalisation, there were no significant differences between the normalised apparent masses at resonance for the three lightest weight groups ($p>0.08$), although the mean normalised apparent mass at resonance of the heaviest group was significantly greater than that of each of these three lighter groups ($p<0.028$) (Figure 8.4). The only significant pairings at 12 Hz were between Groups 1 and 3 ($p=0.039$), and between Groups 2 and 3 ($p=0.024$). There were no significant differences between weight groups in the phase response at 5 Hz or 12 Hz ($p>0.2$).

Table 8.3 Effect of subject physical characteristics on their primary resonance frequency and their apparent mass at resonance, at 0.6 Hz and at 12.0 Hz with no backrest and with an excitation magnitude of 1.0 ms^{-2} r.m.s. Means (and standard deviations) of 20 subjects, except for gender (41 males, 39 females).

	Resonance frequency, Hz	Apparent mass at resonance, kg	Apparent mass at 0.6 Hz, kg	Apparent mass at 12.0 Hz, kg
Age, years: Median (min, max)				
21 (18,23)	4.6 (0.5)	96.8 (21.6)	61.5 (11.1)	26.2 (5.7)
25 (24,27)	4.8 (0.5)	99.3 (27.0)	59.6 (12.5)	26.8 (5.7)
35 (28,45)	4.9 (0.4)	93.6 (28.3)	59.7 (14.9)	25.4 (5.4)
53 (45,65)	5.5 (0.8)	102.6 (23.8)	65.1 (12.7)	32.8 (7.0)
Gender: Median (min, max)				
Female	4.9 (0.7)	86.0 (20.6)	56.4 (12.1)	25.5 (5.8)
Male	5.0 (0.6)	110.2 (23.4)	66.6 (11.6)	30.1 (6.5)
Weight, kg: Median (min, max)				
54 (46,60)	5.1 (0.8)	71.2 (10.1)	47.7 (6.1)	22.9 (3.9)
64 (60,69)	4.9 (0.7)	88.7 (9.5)	56.4 (6.0)	26.3 (4.6)
74 (69,80)	4.7 (0.6)	106.0 (14.8)	67.3 (4.4)	27.9 (4.9)
88 (80,103)	5.0 (0.6)	126.4 (20.8)	74.6 (12.2)	34.1 (6.9)
Stature, cm: Median (min, max)				
156 (149,163)	4.9 (0.8)	79.5 (17.3)	52.3 (10.5)	24.7 (5.0)
167 (163,171)	5.0 (0.7)	89.3 (18.4)	58.7 (10.9)	26.3 (6.3)
176 (171,181)	5.0 (0.6)	104.6 (24.1)	64.0 (10.7)	30.8 (7.7)
185 (181,192)	4.8 (0.5)	119.0 (21.1)	70.9 (12.1)	29.3 (5.4)
BMI, kgm^{-2}: Median (min, max)				
20 (18,21)	5.1 (0.7)	77.6 (14.1)	50.5 (7.7)	24.2 (4.9)
22 (21,23)	4.7 (0.6)	92.3 (18.0)	59.2 (8.6)	25.4 (4.8)
25 (24,26)	5.0 (0.7)	107.7 (22.9)	64.4 (11.1)	28.5 (5.1)
31 (26,34)	4.9 (0.6)	114.8 (26.3)	71.7 (13.3)	33.1 (7.5)

Relative to the large and systematic effects of subject mass, the effects of age, gender, stature, and BMI on the apparent masses of the subject groups were small (Table 8.3). Stature, gender and BMI were highly correlated with body weight (p<0.001, Pearson correlation) but age was not (p=0.21). Some of the apparent variability in Table 8.3 may be associated with variations in subject mass within the stature, BMI, and gender groups.

However, the normalised apparent masses show only small differences in apparent mass associated with age, stature, BMI, and gender (Figure 8.5).

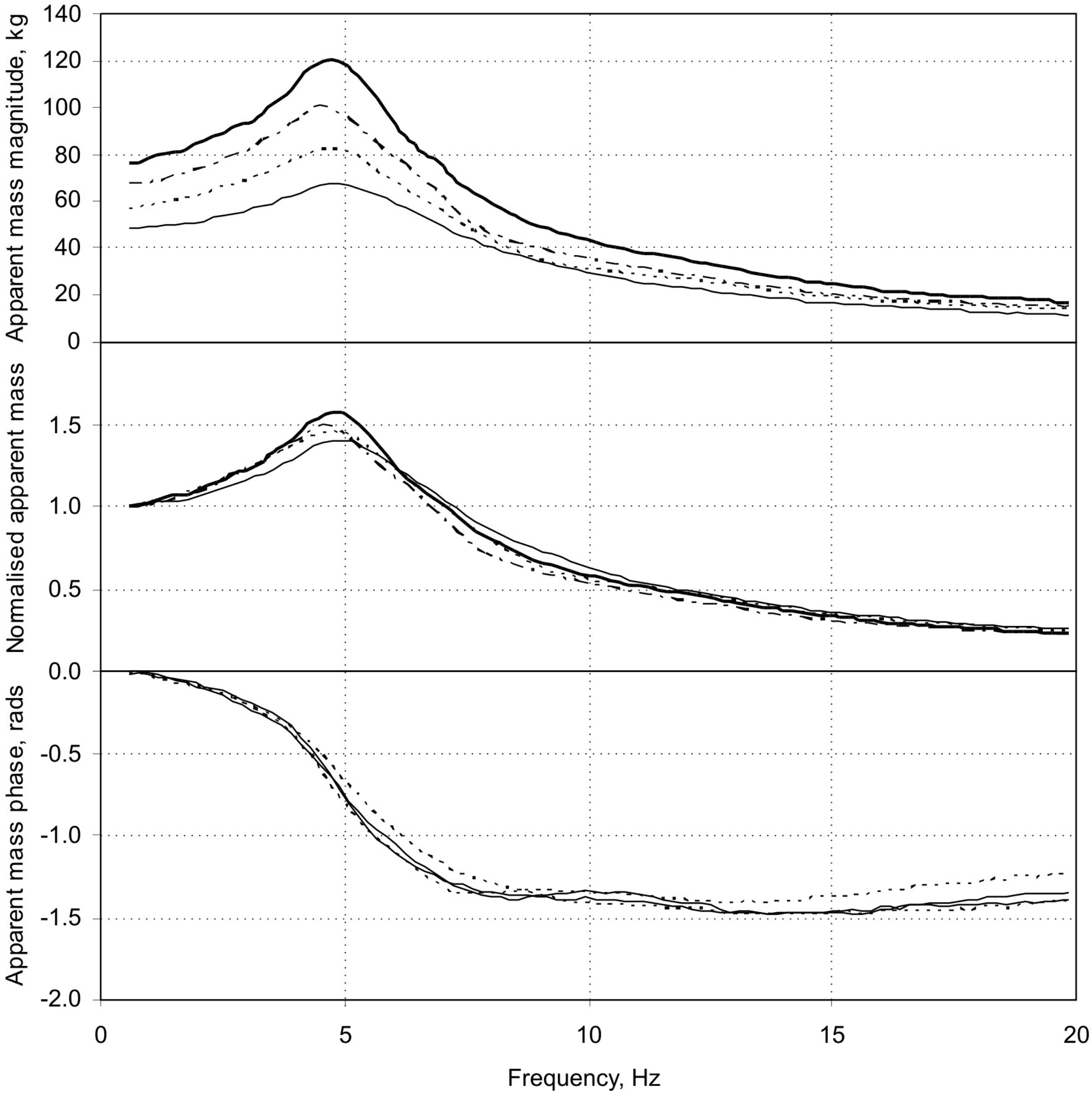

Figure 8.4 Effect of subject weight on measured and normalised apparent mass (no backrest and 1.0 ms^{-2} r.m.s excitation); subjects grouped by weight (20 per group) with mean weights: 54 kg (——), 64 kg (· · · · ·), 74 kg (· — · —), and 88 kg (——).

8.3.5 Bivariate regression analysis

Bivariate regression analysis for the condition with no backrest (Table 8.4) showed that an increase in age of 10 years was associated with an increase of 0.27 Hz in the resonance frequency (Table 8.4; regression coefficient, B=0.027 Hz.year^{-1}; p<0.001). The effect of age on resonance frequency was similar without the backrest and with the reclined rigid backrest (Figure 8.6; B=0.022 Hz.year^{-1}, p=0.007). Age had a positive association with the apparent mass at 12 Hz (p<0.001), but not with the apparent mass at resonance or at 0.6 Hz (p>0.05).

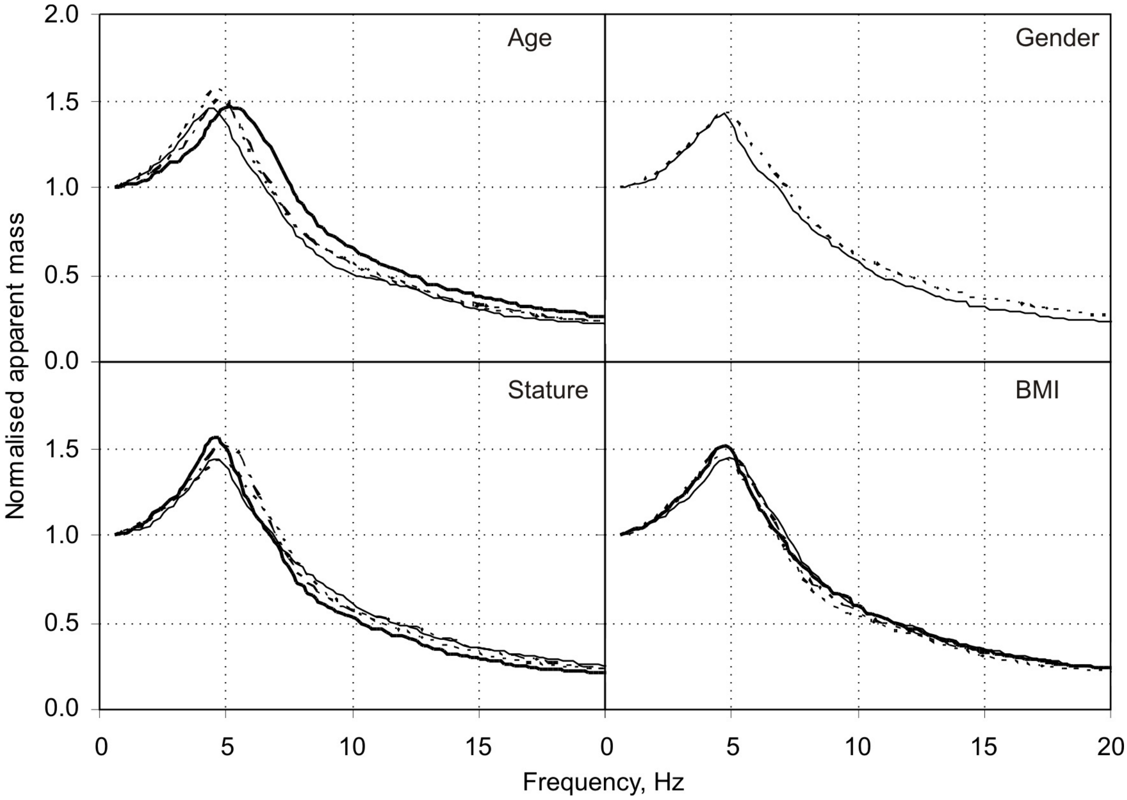

Figure 8.5 Effect of physical characteristics on normalised apparent mass (no backrest, 1.0 ms^{-2} r.m.s excitation); subjects grouped (see Table 8.3 for details) by physical characteristic: Group 1 (——), Group 2 (· · · · ·), Group 3 (· — · —) and Group 4 (——).

Table 8.4 Bivariate regression coefficients showing the influence of subject physical characterises on features of their apparent mass (1.0 ms^{-2} r.m.s. with no backrest).

Variables	Resonance frequency, Hz			Apparent mass at resonance, kg			Apparent mass at 0.6 Hz, kg			Apparent mass at 12 Hz, kg		
	B	*p*	*SEB*	*B*	*p*	*SEB*	*B*	*p*	*SEB*	*B*	*p*	*SEB*
Age (years)	0.027	***	0.004	0.150		0.217	0.131		0.109	0.196	***	0.054
Gender (female=0; male =1)	0.219		0.134	25.465	***	4.876	10.877	***	2.583	4.985	***	1.401
Weight, kg	0.000		0.005	1.640	***	0.107	0.848	***	0.049	0.341	***	0.042
Stature, cm	0.001		0.006	1.280	***	0.206	0.627	***	0.105	0.171	**	0.064
BMI, kgm^{-2}	-0.004		0.018	3.700	***	0.635	2.013	***	0.308	1.012	***	0.167
Knee height, cm	0.000		0.017	3.692	***	0.540	2.001	***	0.272	0.543	*	0.177
Buttock-knee length, cm	-0.009		0.016	2.686	***	0.614	1.360	***	0.310	0.434	*	0.176
Sitting height, cm	-0.009		0.013	2.401	***	0.487	1.241	***	0.244	0.289	*	0.145

B: regression coefficient; *SEB*: standard error of the regression coefficient.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

All of the physical measures (weight – see Figure 8.7, stature, BMI, knee height, buttock-knee length, sitting height) had positive associations with the apparent mass at resonance, at 0.6 Hz, and at 12 Hz. There was a negative association between the resonance frequency and BMI with the reclined rigid backrest (B=0.066 Hz.m^2.kg^{-1}, p=0.009) but not without the backrest (p=0.843). Scatter plots suggest greater inter-subject variability in the relation between resonance frequency and both age and BMI with the reclined rigid backrest than with no backrest (Figure 8.6).

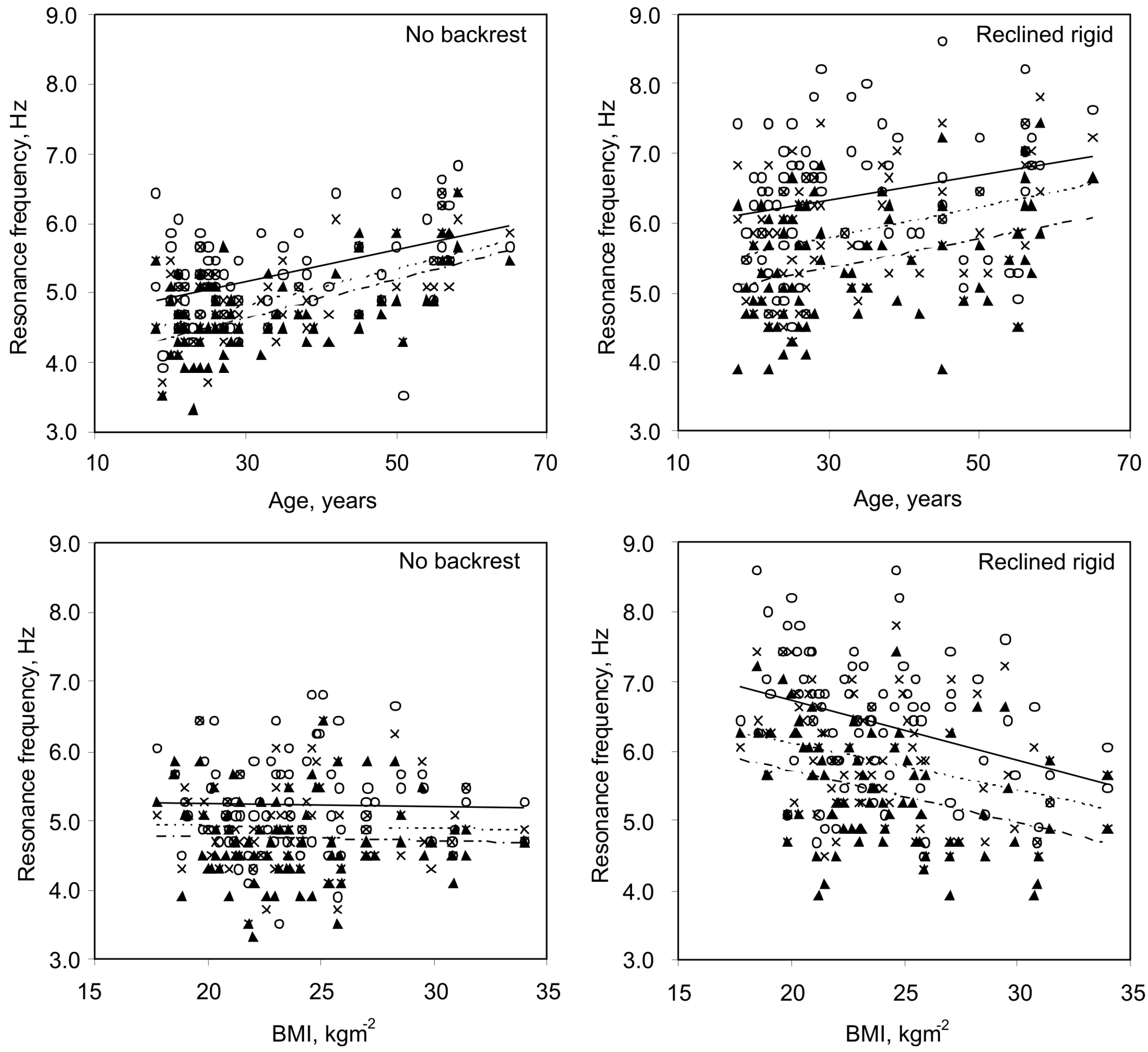

Figure 8.6 Effect of age and body mass index (BMI) on the resonance frequency of 80 adults at three magnitudes of vertical vibration excitation (no backrest and reclined rigid backrest): 0.5 ms^{-2} r.m.s. (○), 1.0 ms^{-2} r.m.s. (×) and 1.5 ms^{-2} r.m.s. (▲). Bivariate regression trend lines are also shown: 0.5 ms^{-2} r.m.s. (——), 1.0 ms^{-2} r.m.s. (· · · ·) and 1.5 ms^{-2} r.m.s. (· — · —).

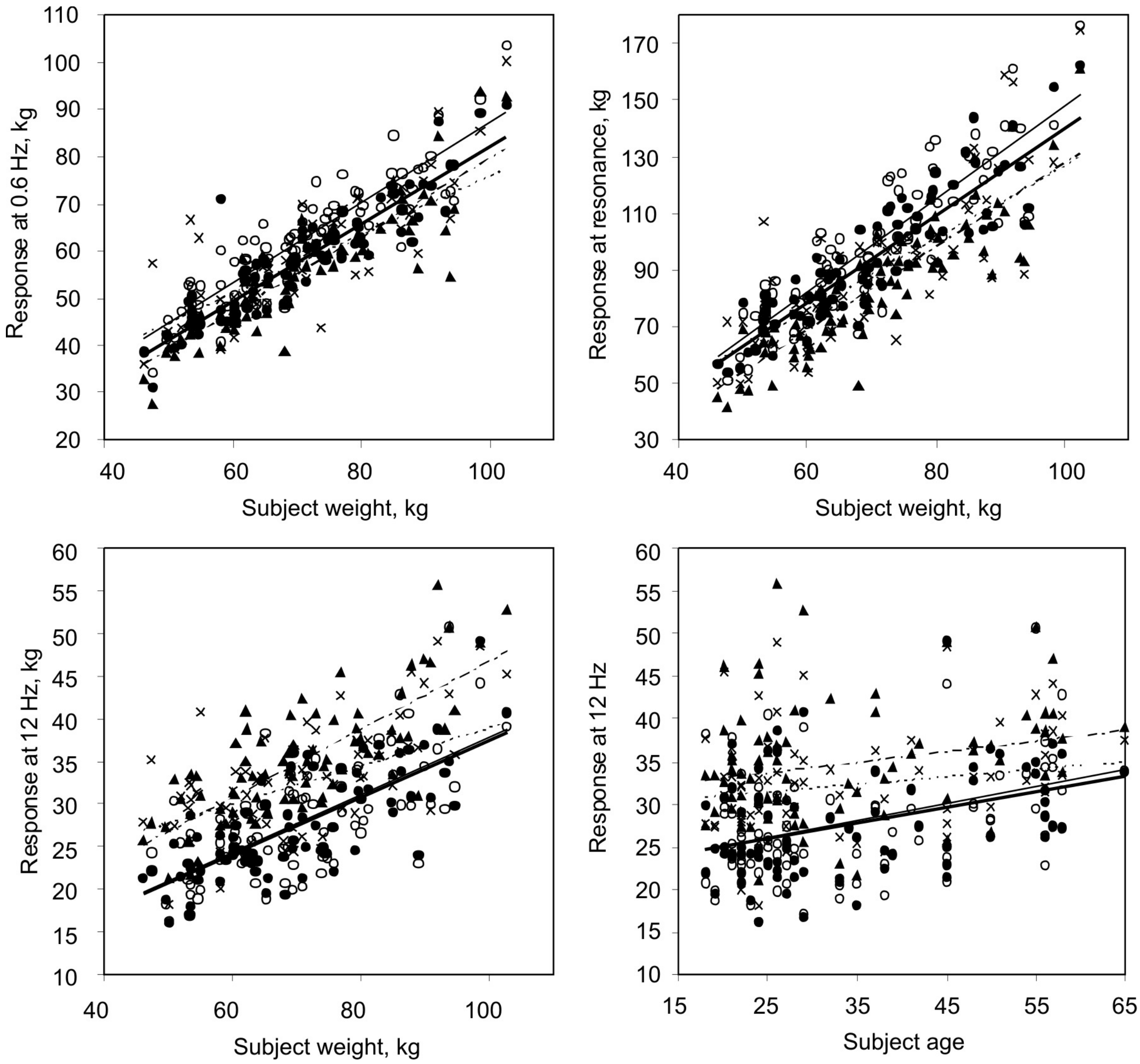

Figure 8.7 Effect of weight and age on the apparent masses of 80 adults at 0.6 Hz, at resonance and at 12 Hz with four different backrest conditions (1.0 ms^{-2} r.m.s. excitation): no backrest (○), upright rigid (×), reclined rigid (▲) and reclined foam (•). Bivariate regression trend lines are also shown: no backrest (——), upright rigid (· · · · ·), reclined rigid (· — · —) and reclined foam (——).

8.3.6 Multiple regression analysis

Multiple regression models investigated how the characteristics of the apparent mass depended on subject characteristics with each backrest condition at an excitation magnitude of 1.0 ms^{-2} r.m.s. (Table 8.5). Having adjusted for the effect of other predictors, age was positively associated with the resonance frequency in all backrest conditions (p<0.001), with the effect greatest when seated with the reclined foam backrest (B=0.36 Hz per 10 years). No significant differences in the association of age with resonance frequency were found between pairs of backrest conditions (in all cases, p>0.118). Body mass index had an inverse association with resonance frequency in the three conditions with a backrest (p<0.093). The association of BMI with resonance frequency was stronger with the reclined rigid backrest (*B*= -0.088 Hz per kgm^{-2}) than without a backrest (B= -0.026 Hz per kgm^{-2}) or with a reclined foam backrest (B= -0.035 Hz per kgm^{-2}) (p=0.017, p=0.037 respectively).

Table 8.5 Multiple regression analysis showing the influence of significant subject physical characteristics (as well as age and gender) on features of their apparent mass with each backrest condition (1.0 ms^{-2} r.m.s. excitation).

	No backrest			Upright rigid			Reclined rigid			Reclined foam		
	B	*p*	*SEB*	*B*	*p*	*SEB*	*B*	*p*	*SEB*	*B*	*p*	*SEB*
Resonance frequency, Hz												
Age (years)	0.028	***	0.004	0.025	***	0.006	0.027	***	0.006	0.036	***	0.004
Gender (female=0; male =1)	0.190		0.108	0.222		0.144	0.567	***	0.154	0.169		0.106
BMI, kgm^{-2}	-0.026		0.015	-0.055	**	0.020	-0.088	***	0.021	-0.035	**	0.014
Constant	4.496			5.618			6.781			4.488		
R^2, %	39.4			27.5			37.3			51.5		
Apparent mass at resonance, kg												
Age (years)	-0.131		0.108	0.045		0.134	0.066		0.097	0.178		0.091
Gender (female=0; male =1)	3.937		3.262	3.288		4.178	3.778		2.933	0.495		2.763
Weight, kg	1.584	***	0.126	1.399	***	0.156	1.384	***	0.111	1.500	***	0.105
Constant	-10.230			-11.350			-17.810			-17.346		
R^2, %	76.7			64.9			77.0			80.5		
Apparent mass at 0.6 Hz, kg												
Age (years)	-0.017		0.051	0.032		0.062	0.044		0.049	0.019		0.045
Gender (female=0; male =1)	-1.030		1.540	0.311		1.931	-2.998	*	1.483	-0.074		1.357
Weight, kg	0.871	***	0.059	0.737	***	0.072	0.867	***	0.056	0.816	***	0.051
Constant	1.876			5.499			-5.579			-0.065		
R^2, %	79.6			69.0			80.2			82.7		
Apparent mass at 12 Hz, kg												
Age (years)	0.143	***	0.041	0.115	**	0.042	0.065		0.037	0.132	***	0.033
Gender (female=0; male =1)	0.635		1.220	0.090		1.319	2.320	*	1.123	-1.748		1.002
Weight, kg	0.304	***	0.047	0.276	***	0.049	0.347	***	0.043	0.354	***	0.038
Constant	1.356			9.557			7.067	**		-0.854		
R^2, %	54.0			45.2			64.2			63.9		

B: regression coefficient; *SEB*: standard error of the regression coefficient.
R^2: percentage of experimental variation accounted for by the model.
*p < 0.05, **p < 0.01, ***p < 0.001.

The apparent mass at resonance, at 0.6 Hz, and at 12 Hz was strongly associated with subject weight, with apparent mass increasing at a rate greater than the increase in subject weight at resonance (*B*= 1.35 to 1.58), slightly less than subject weight at 0.6 Hz (*B*=0.74 to 0.87), and much less than subject weight at 12 Hz (*B*= 0.27 to 0.35) (p<0.001). The apparent mass at 12 Hz was positively associated with age without the backrest, and with the upright foam and reclined foam backrests, but not with the reclined rigid backrest. After adjusting for age and body mass index, males had higher resonance frequencies than females with the reclined rigid backrest at 1.0 ms^{-2} r.m.s (*B*=0.57 Hz, p<0.001,

Table 8.5) and 1.5 ms^{-2} r.m.s (B=0.38 Hz, p<0.05, Table 8.6). With the reclined rigid backrest, the apparent mass was greater for males than females at 0.6 Hz and at 12 Hz (p=0.047, p=0.042, respectively). For each backrest condition, the R^2 values indicate that the models accounted for more of the variability in the modulus of the apparent mass than the variability in the resonance frequency.

Table 8.6 Multiple regression analysis showing the effect of excitation magnitude on the influence of significant subject physical characteristics (as well as age and gender) on features of their apparent mass. See Table 8.5 for excitation at 1.0 ms^{-2} r.m.s.

	No backrest						Reclined rigid backrest					
	0.5 ms^{-2} r.m.s.			1.5 ms^{-2} r.m.s.			0.5 ms^{-2} r.m.s.			1.5 ms^{-2} r.m.s.		
	B	*p*	*SEB*	*B*	*p*	*SEB*	*B*	*p*	*SEB*	*B*	*p*	*SEB*
Resonance frequency												
Age (years)	0.024	***	0.005	0.029	***	0.004	0.024	**	0.008	0.026	***	0.006
Gender (female=0; male =1)	0.320		0.131	0.154		0.110	0.366		0.196	0.376	*	0.150
BMI, kgm^{-2}	-0.024		0.018	-0.026		0.015	-0.107	***	0.027	-0.094	***	0.020
Constant	4.799			4.309			7.962			6.626		
R^2, %	31.5			39.0			24.7			34.1		
Apparent mass at resonance												
Age (years)	-0.018		0.144	-0.068		0.110	0.058		0.109	0.098		0.095
Gender (female=0; male =1)	4.418		4.418	2.024		3.355	4.258		3.307	0.350		2.905
Weight, kg	1.420	***	0.170	1.573	***	0.127	1.348	***	0.125	1.417	***	0.110
Constant	-6.998		11.330	-9.330			-17.213			-18.885		
R^2, %	61.1			75.2			71.7			76.5		
Apparent mass at 0.6 Hz												
Age (years)	0.019		0.096	0.029		0.051	-0.002		0.076	0.079		0.045
Gender (female=0; male =1)	-0.946		2.937	-1.104		1.550	-2.893		2.292	-2.069		1.374
Weight, kg	0.763	***	0.113	0.841	***	0.059	0.841	***	0.087	0.822	***	0.052
Constant	5.807			2.687			-4.149			-3.196		
R^2, %	46.4			78.9			61.0			81.6		
Apparent mass at 12 Hz												
Age (years)	0.124	**	0.046	0.151	***	0.036	0.092		0.046	0.085	**	0.031
Gender (female=0; male =1)	1.556		1.416	0.925		1.083	3.108	*	1.410	1.658		0.949
Weight, kg	0.295	***	0.054	0.267	***	0.041	0.293	***	0.053	0.340	***	0.036
Constant	3.931			1.946			10.735			5.496		
R^2, %	47.6			56.3			50.3			69.6		

B: regression coefficient; *SEB*: standard error of the regression coefficient.
R^2: percentage of experimental variation accounted for by the model.
*p < 0.05, **p < 0.01, ***p < 0.001.

In contrast to the strong effect of weight on the measured apparent mass at resonance, weight was not significantly associated with the normalised apparent mass at resonance with any backrest condition (in all cases, p>0.08; see Table 8.7). The only significant associations with normalised apparent mass at resonance were gender (greater in males; p=0.004) and knee-height (greater with increased knee height; p=0.008), both when seated with the reclined rigid backrest. When there was no backrest, the normalised apparent mass at 12 Hz was positively associated with age (p=0.024) and greater for males (p=0.046). With the reclined rigid backrest, the normalised apparent mass at 12 Hz was also greater for males (p=0.01), and positively associated with weight (p=0.044), but negatively associated with stature (p=0.009) and BMI (p=0.016). With the reclined foam backrest, the normalised apparent mass at 12 Hz was positively associated with age (*p*=0.004). There were no associations between subject characteristics and the normalised apparent mass at 12 Hz when seated with the upright rigid backrest. For all backrest conditions, the R^2 values indicate that subject characteristics explain less of the variability in the normalised apparent mass at resonance and at 12 Hz than they explain in the apparent mass before normalisation (compare Table 8.5 and Table 8.7).

Table 8.7 Multiple regression analysis showing the influence of significant subject physical characteristics (as well as age and gender) on features of their normalized apparent mass with each backrest condition (1.0 ms^{-2} r.m.s. excitation).

	No backrest			Upright rigid			Reclined rigid			Reclined foam		
	B	*p*	*SEB*	*B*	*p*	*SEB*	*B*	*p*	*SEB*	*B*	*p*	*SEB*
Normalised apparent mass at resonance												
Age (years)	-0.001		0.001	0.000		0.001	0.000		0.001	0.002		0.001
Gender (female=0; male =1)	0.085		0.043	0.019		0.047	0.102	**	0.035	-0.002		0.047
Weight, kg	0.003		0.002	0.002		0.002	-0.001		0.001	0.002		0.002
Knee height, cm	0.000		0.006	0.012		0.007	0.013	**	0.005	0.007		0.007
Constant	1.368			0.735			0.780			1.068		
R^2, %	20.3			21.8			38.1			12.2		
Normalised apparent mass at 12 Hz												
Age (years)	0.002	*	0.001	0.002		0.001	0.000		0.001	0.002	**	0.001
Gender (female=0; male =1)	0.059	*	0.029	0.011		0.030	0.098	**	0.029	-0.009		0.023
Weight, kg	0.008		0.008	0.009		0.008	0.016	*	0.008	0.006		0.006
Stature, cm	-0.010		0.007	-0.011		0.007	-0.018	**	0.007	-0.007		0.005
BMI, kgm^{-2}	-0.024		0.023	-0.033		0.023	-0.056	*	0.023	-0.019		0.018
Constant	2.145			2.475			3.910			1.593		
R^2, %	18.4			20.2			33.0			21.0		

B: regression coefficient; *SEB*: standard error of the regression coefficient.
R^2: percentage of experimental variation accounted for by the model.
**p* < 0.05, ***p* < 0.01, ****p* < 0.001.

Without a backrest, and with the reclined rigid backrest, the magnitude of vibration had no significant effect on the associations between the resonance frequency and either age, gender or BMI (in all cases, *p*>0.10) (Table 8.6). Similarly, there was no evidence of any change in the associations between the apparent mass at 0.6 Hz, at resonance, and at 12 Hz and weight, age, and gender with a change in vibration magnitude (in all cases, *p*>0.49). The reduction in the resonance frequency when the vibration magnitude increased from 0.5 to 1.5 ms^{-2} r.m.s. was calculated as a measure of the non-linearity of each subject, but there were no associations between this measure and any of the subject characteristics when there was no backrest (*p*>0.1; stepwise multiple regression analysis). With the reclined rigid backrest, the decrease in the resonance frequency with increased magnitude of vibration was 0.27 Hz greater for the males than for the females (*p*=0.012), with other characteristics having no significant effect on this measure of non-linearity (*p*>0.1).

8.4 DISCUSSION

8.4.1 Predictors of the magnitude of the apparent mass

Standardized regression coefficients (beta coefficients) were calculated to show the relative contribution of the significant predictors of the apparent mass with each backrest condition (Table 8.8). Body weight was much the strongest predictor of the apparent mass at 0.6 Hz, at resonance, and at 12 Hz, with other factors having only marginal effects. The stronger effect of body weight can be seen in the normalised apparent masses of the subjects when they are grouped by body weight, stature, BMI, and gender (compare Figure 8.4 and Figure 8.5).

Table 8.8 Dimensionless beta coefficients, β, showing the relative strength of significant subject physical characteristics (as well as age and gender) in the multiple regression models for each backrest condition (1.0 ms^{-2} r.m.s. excitation).

	No backrest		Upright rigid		Reclined rigid		Reclined foam	
	β	p	β	p	β	p	β	p
Resonance frequency								
Age (years)	0.62	***	0.46	***	0.41	***	0.72	***
Gender (female=0; male =1)	0.16		0.16		0.34	***	0.13	
BMI, kgm^{-2}	-0.16		-0.29	**	-0.39	***	-0.20	**
Apparent mass at resonance								
Age (years)	-0.07		0.02		0.04		0.10	
Gender (female=0; male =1)	0.08		0.07		0.08		0.01	
Weight, kg	0.84	***	0.76	***	0.82	***	0.87	***
Apparent mass at 0.6 Hz								
Age (years)	-0.02		0.03		0.05		0.02	
Gender (female=0; male =1)	-0.04		0.01		-0.12	*	0.00	
Weight, kg	0.92	***	0.82	***	0.95	***	0.91	***
Apparent mass at 12 Hz								
Age (years)	0.28	***	0.24	**	0.12		0.28	***
Gender (female=0; male =1)	0.05		0.01		0.17	*	-0.14	
Weight, kg	0.61	***	0.60	***	0.67	***	0.77	***

β: standardized regression coefficient.
R^2: percentage of experimental variation accounted for by the model.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

8.4.2 Predictors of resonance frequency

The sitting condition influenced whether subject age, body mass index, or gender was associated with the principal resonance frequency in the apparent mass. In all postures, the resonance frequency increased with increasing age, and in all three conditions with a backrest the resonance frequency reduced with increasing body mass index. With the reclined rigid backrest, the resonance frequency was greater in the males (Table 8.8).

The regression coefficients for the association between age and resonance frequency were similar with all backrest conditions: over the 18 to 65 year age range of this study there was a mean increase of 1.1 Hz (reclined rigid backrest with 0.5 ms^{-2} r.m.s.; Table 8.6) to 1.7 Hz (reclined foam backrest with 1.0 ms^{-2} r.m.s.; Table 8.5). The addition of an age^2 term to the regression analysis suggested the rate of 'stiffening' increased with increasing age, although this term did not significantly improve the overall fit of the model (in all cases, $p>0.2$).

In conditions with a backrest, increased body mass index (from 18 to 34 kgm^{-2}) was associated with a decrease in the resonance frequency of 0.56 Hz (reclined foam backrest at 1.0 ms^{-2} r.m.s.) to 1.7 Hz (reclined rigid backrest with 0.5 ms^{-2} r.m.s.). Since body mass index is associated with percentage body fat (e.g. Gallagher *et al.*, 1996), the decreased resonance frequency may be caused by subjects with higher BMI having reduced coupling with the backrest, reducing the effective stiffness of the body measured at the seat surface, similar to the effects of increased thickness of foam with a reclined backrest (see Chapter 4).

When weight and height were added to the stepwise multiple regression models (in addition to BMI) they were not found to be significant predictors of the resonance frequency. This suggests that body mass index was a better predictor of resonance frequency than either stature or body weight. When weight was entered into the multiple regression models in place of BMI, the resonance frequency obtained with 1.0 ms^{-2} r.m.s. decreased with increasing body weight when seated with the reclined rigid backrest ($p=0.01$) and the reclined foam backrest ($p=0.019$), but not with the other two backrest conditions (in both cases; $p>0.1$).

Females tended to have lower resonance frequencies than males after controlling for other factors, but the effect of gender on resonance frequency was only statistically significant with the reclined rigid backrest, where the mean difference was 0.57 Hz (Table 8.5). In contrast to this study, Lundström *et al.* (1998) claimed a slightly lower absorbed power resonance frequency in females than in males when sitting upright with no backrest. The apparent difference may be due to the influence of confounding variables (e.g. age and BMI) whose effects have not been controlled in the statistical analysis of earlier studies.

8.4.3 Other factors influencing apparent mass

The R^2 values in the multiple regression analysis indicate the proportion of the variability in apparent mass accounted for by the predictors in the models. Between 19.5% and 38.9% of the variability in the apparent mass at resonance, and between 48.5% and 75.3% of the variability in resonance frequency was not explained by the models (Table 8.5 and Table 8.6). This suggests other postural and anthropometric factors influenced the apparent masses of the subjects. They were asked to maintain a 'normal sitting posture' during the experiment but there will have been variations in posture between subjects. In addition, there will have been variations in subject build (e.g. distribution and proportion of muscle and fat) not fully reflected in their BMI, as well as changes in muscle tension.

8.4.4 Inter-subject variability in the principal resonance

The reduction in inter-subject variability in the apparent mass at resonance by normalising with respect to sitting weight is consistent with previous observations (e.g. Fairley and Griffin, 1989).

The reduction in the resonance frequency of the body as the magnitude of vibration increased was similar to previous findings (e.g. with subjects sitting with no backrest, (Matsumoto and Griffin, 2002b); with subjects supported by a reclined rigid backrest, (Wang *et al.* 2004). The only subject characteristic affecting the non-linearity was gender, where the reduction in resonance frequency with increased vibration magnitude was significantly less with females than males seated with the reclined rigid backrest. This difference in non-linearity between the genders may have been caused by effects of anatomical differences being more pronounced when supported by the reclined rigid backrest, consistent with the BMI affecting the resonance frequency in this posture (Table 8.5).

8.4.5 Implications of the results

The increase of 1.7 Hz in the resonance frequency with increasing age (from 18 to 65 years) was greater than the increase in the resonance frequency from no backrest to reclined rigid backrest (0.9 Hz) and greater than the maximum reduction in the resonance frequency associated with increasing the vibration magnitude from 0.5 to 1.5 ms^{-2} r.m.s. (1.0 Hz) (Table 8.2). The BMI and gender were also significant predictors of the resonance frequency, particularly with a reclined rigid backrest (Table 8.5). In some applications, such as when the apparent mass is being used to optimise a seat targeted at a specific population, the effects of age, BMI and gender might be sufficiently large for their effects to be taken into consideration.

Reference values of apparent mass are defined in ISO 5982 (2001) for the 50^{th} percentile seated human body, with no allowance for the effects of either the magnitude of vibration or contact with a backrest. Alternative reference values for apparent mass have been proposed taking into account: contact with a reclined rigid backrest, holding a steering wheel, input magnitude (Rakheja *et al.* 2002) and subject weight (Patra *et al.*, 2006). However, the small differences between the modulus and phase of the normalised apparent mass between subject groups in the present study, and the absence of any association between subject weight and normalised apparent mass at resonance (Table 8.7), suggests that reference values for apparent mass might be sufficiently defined by using the normalised apparent mass multiplied by the sitting weight of the target population.

The effects of subject characteristics on seat transmissibility are not yet well understood and so characteristics in addition to those affecting the apparent mass of the body may influence seat transmissibility, and some factors that influence the apparent mass may have little effect on seat transmissibility. Further investigation is required to understand the influence of subject characteristics on the vibration transmitted through seats.

8.5 CONCLUSIONS

Of the physical characteristics of subjects investigated in this study, subject mass had the greatest effect on the apparent mass at 0.6 Hz, at resonance, and at 12 Hz. Subject age, body mass index, and gender were associated with the principal resonance frequency in the apparent mass. There was a mean increase of 1.7 Hz in the resonance frequency as age increased from 18 to 65 years. As body mass index increased from 18 to 34 kgm^{-2}, the resonance frequency decreased by 1.7 Hz. These changes were greater than the increase in resonance frequency between no backrest and a reclined rigid backrest (0.9 Hz), and also greater than the reduction in resonance frequency when increasing the magnitude of vibration from 0.5 to 1.5 ms^{-2} r.m.s. (1.0 Hz). It seems appropriate to consider the effects of age, BMI, and weight when defining reference values for the vertical apparent mass of the human body.

The variability in apparent mass between subjects at resonance was reduced when the effect of static weight was removed by normalisation (i.e. dividing the modulus of the apparent mass by the subject sitting weight), suggesting the required apparent mass may be obtained by multiplying the appropriate normalised apparent mass by the sitting weight of the target population.

CHAPTER 9: INFLUENCE OF APPARENT MASS ON SEAT TRANSMISSIBILITY

9.1 INTRODUCTION

Although the transmissibilities of seats are often measured with human subjects, there have been few studies of the effect of subject characteristics on the transmission of vibration through seats. The resonance frequency of a car seat and the transmissibility at resonance have been reported to be unaffected by the weight or gender of subjects, despite the sitting mass varying between 31 kg and 72 kg (Varterasian and Thompson, 1977). The dynamic stiffness of foam tends to increase as the loading on the seat increases (White *et al.*, 2000; Wei and Griffin, 1998b), so the absence of an effect of subject weight on seat transmissibility might be due to a proportional increase in seat dynamic stiffness with increased load on the seat surface. In a study with 15 males and 15 females, significant positive correlations were found between age and seat transmissibility at resonance and significant negative correlations were found between age the transmissibility resonance frequency within the group of females, but these correlations were not statistically significant within the group of males (Corbridge and Griffin, 1989).

Any effects of body mass index on seat transmissibility have not previously been reported. Body mass index is correlated with body weight and, probably, the contact area with the seat, with both of these factors likely to influence the seat impedance. Age is unlikely to have a direct influence on the impedance of a seat, but changes in apparent mass associated with age may influence seat transmissibility.

Simple lumped parameter models have been found to provide close representations of the apparent mass of the human body sitting upright with no backrest contact (e.g. Wei and Griffin, 1998a). Furthermore, the influence of factors that modify the apparent mass of the body (e.g. backrest contact, backrest inclination, hand position, foot position, vibration magnitude) can be represented by changes in the parameters of such models (see Chapter 7). By extending apparent mass models to include terms representing the dynamic stiffness and damping of the seat, lumped parameter models can also be used to represent the transmission of vibration through seats (Wei and Griffin, 1998b). The various influences on the seat dynamic properties of the backrest, the physical characteristics of the body in the seat, and the vibration magnitude, might be derived from lumped parameter models fitted to both the apparent mass of the body and seat transmissibility.

It was hypothesized that the transmissibility of a seat would be influenced by factors that influence the apparent mass of the body (e.g. age, weight, body mass index, gender, backrest contact, and vibration magnitude). It was expected that factors that increase the compression of the seat or the area of contact with the seat (e.g. increased subject weight and BMI) would increase the dynamic stiffness of the seat.

9.2 METHODS AND PROCEDURES

9.2.1 Apparatus

Vertical vibration was produced by a 1-metre stroke electro-hydraulic vibrator in the laboratory of the Human Factors Research Unit at the Institute of Sound and Vibration Research. Subjects sat on a seat from a mid-sized family car. The backrest of the seat was inclined by 15 degrees from the vertical and the seat cushion was at 12° to the horizontal, as measured using an *H*-point manikin (ISO 20176 (2006). The leading edge of the seat surface was 0.44 m above the vibrator platform on which subjects rested their feet.

Vertical vibration of the platform and the seat was measured using piezo-resistive accelerometers (Entran EGCSY-240D-10; Entran, Potterspury, UK). The accelerometer on the seat surface was contained within an *HVLab* SIT-pad (Whitham and Griffin, 1977). The SIT-pad was located so that the ischial tuberosities were either side of the centre of the pad. The accelerometer on the platform was located directly below the SIT-pad accelerometer.

9.2.2 Vibration

Gaussian random vibration (band-limited using 8-pole Butterworth filters between 0.125 and 25 Hz) with approximately flat constant bandwidth acceleration spectra were generated and analysed using an *HVLab* data acquisition and analysis system (version 3.81; University of Southampton, UK). Different random signals were generated for each subject. The measured accelerations were acquired at 400 samples per second via 133 Hz anti-aliasing filters.

9.2.3 Conditions

The transmissibility of the seat was measured with each subject sitting supported by the backrest and also when sitting in a relaxed upright posture with no backrest support.

With both backrest conditions, the transmissibility was measured at three magnitudes of vibration (0.5, 1.0, and 1.5 ms^{-2} r.m.s.). Subjects were instructed to position their feet in front of them so that the underside of their thighs just made contact with the leading edge of the seat. Subjects wore a loose fitting lap belt and had access to an emergency stop button. The order of presentation of conditions was randomized independently for each subject.

9.2.4 Subjects

A group of 80 adult subjects was formed to be representative of the UK car driving population (Table 8.1; Pheasant (2006); Department of Health (2008)). The subjects were exposed to all conditions in a single session lasting approximately 60 minutes. Subjects gave informed consent to participate in the experiment that was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

9.2.5 Analysis

Transfer functions between the platform accelerometer and the SIT-pad accelerometer were calculated using the cross-spectral density method with a frequency resolution of 0.195 Hz. The transfer functions were determined from the ratio of the cross-spectral density of the input and output acceleration to the power spectral density of the input acceleration. Prior to the calculation of the seat transmissibility, the acceleration data were normalised to remove any DC offsets.

The seat transmissibility at the primary resonance frequency was assumed to be the greatest transmissibility over the measurement range (0.6 to 20 Hz). The primary resonance frequency was defined as the frequency at which the transmissibility was greatest.

9.2.6 Previously reported apparent mass measurements

The vertical apparent masses of the 80 subjects sitting with an upright posture with no backrest were used to form a seat-person model (see Section 9.2.8) and investigate the relation between apparent mass and seat transmissibility. The apparent masses of these subjects have been presented in Chapter 8 and are summarised below.

When measuring their apparent mass, the subjects sat on the flat upper surface of a force plate secured to a rigid seat. Their feet were moved forward on the vibrator platform until their thighs were just touching the leading edge of the seat. Subject sat upright with no backrest support while the seat was excited with broadband random vertical vibration at three magnitudes of vibration (0.5, 1.0, and 1.5 ms^{-2} r.m.s.). Each exposure to vibration was 60 s in duration.

Prior to the calculation of the apparent mass, mass cancellation was performed in the time domain to remove the influence of the mass of the top plate from the measured force. The apparent mass was calculated from the ratio of the cross-spectral density between the force and acceleration at the seat, to the power spectral density of the acceleration at the seat.

9.2.7 Statistical analysis

Parametric statistics were used throughout the analysis. One-way analysis of variance (ANOVA) was used to determine overall significance of differences in features of seat transmissibility when subjects were grouped by their characteristics (i.e. size, age, gender); corrected independent samples *t*-tests were then used to compare features of the seat transmissibility between pairs of groups. Repeated measures ANOVA followed by the paired samples *t*-test was used to compare features of the seat transmissibility between conditions (i.e. between backrests and vibration magnitudes). The standard deviation was used to quantify variability in features of the seat transmissibility. Variability in seat transmissibility between conditions was tested using Levene's test of equality of variance.

Linear regression was used to identify predictors of the seat transmissibility. Initially, the associations between each physical characteristic of the subjects and the features of the seat transmissibility were separately analysed by ordinary least squares regression. Then, for each test condition (i.e. for each combination of backrest and vibration magnitude) significant predictors drawn from the physical characteristics were selected for the final regression model using the PASW stepwise procedure (PASW statistics, version 17.0). A significance level of 0.05 was used to enter and retain a variable in the model. Variables significantly associated with each dynamic characteristic for any test condition, together with age and gender, were then entered simultaneously into regression models. Quadratic terms of each of the significant variables were added in turn to the final regression models; in all instances *F*-tests showed that assuming a linear effect did not compromise goodness of fit (p>0.1). Differences in the regression coefficients, B, between pairs of conditions (e.g. c1, c2) were tested using the null hypothesis Ho: $B_{c1}=B_{c2}$. For each independent variable in the model, x, first a dummy variable, z, was created coded 1 for c1 and 0 for c2, as well as a variable zx that was the product of z and the independent variable. Variables x, z, and zx were then used as predictors in the regression equation. The interaction term, zx, tested the null hypothesis Ho: $B_{c1}=B_{c2}$, significance (p<0.05), indicating that the regression coefficient B_{c1} was significantly different from B_{c2}. Beta coefficients were calculated by multiplying each of the regression coefficients (B) in the multiple regression models by its standard deviation and dividing by the standard deviation of the dependent variable. Thus, a change of 1.0 standard deviations in the predictor variable resulted in a change of 1.0 standard deviations in the criterion variable.

The association of features of the seat transmissibility with features of the apparent mass and other features of the seat transmissibility were separately analysed using bivariate regression analysis.

9.2.8 Lumped parameter models

A seat-person model was used to investigate whether the effects of subject characteristics and vibration magnitude on seat transmissibility could be explained by changes in the apparent mass with these same factors.

A simple single degree-of-freedom lumped parameter model was used to fit the apparent mass (Figure 9.1a). The model consisted of a base frame with mass m_0 and a suspended structure represented by a single mass, m_1, connected to the base by spring stiffness, k_1, in parallel with damping, c_1. The seat transmissibility was represented by adding additional stiffness (k) and damping (c) to represent the dynamic properties of the seat cushion (Figure 9.1b).

Initially, the moduli and phases of the apparent mass model were fitted to the measured individual apparent masses for each magnitude of vibration. Then, by fixing the fitted body parameters, the seat transmissibility model was fitted to each of the individual seat transmissibilities measured at a comparable magnitude to determine the seat stiffness and damping parameters. For each condition, the lumped parameter models were also fitted to the mean measured apparent mass and the mean measured seat transmissibility over the 80 subjects.

The curve-fitting method used the constrained variable function (fmincon()) within the optimisation toolbox (version 3.1.1) of MATLAB (version 7.5.0.342, R2007b). The target error, found by summing the squares of the errors in the modulus and the phase, was minimised. To reduce the influence of the secondary resonances, the upper boundary of the fit was restrained to 1.5 times the measured primary resonance frequency for both apparent mass and seat transmissibility. The lower boundary was set to 1.0 Hz. Before the summation of errors, an empirically determined weighting of 10 was applied to the phase errors in the apparent mass so as to obtain good fits to both the modulus (in kg) and the phase (in rad); similarly a weighting of 10 was applied to modulus errors in the seat transmissibility. The values of the target parameters were allowed to be any positive value.

Depending on the starting values of the model parameters, fmincon() can identify different local minima. In an attempt to ensure that global minima were found, the error function was minimized for 100 randomly selected sets of starting values; the set that led to the minimum total error was used. The fitted responses were compared to the measured data to check goodness of fit.

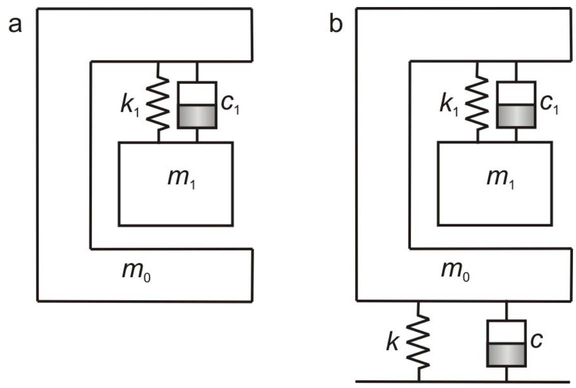

Figure 9.1 Apparent mass model (a) and seat transmissibility model (b).

9.3 RESULTS

9.3.1 Inter-subject variability in seat transmissibility

When sitting supported by the backrest and exposed to 1.0 ms^{-2} r.m.s. vibration, the principal resonance frequency in the seat transmissibility varied over the 80 subjects between 3.5 and 4.7 Hz, with a mean of 4.4 Hz (Figure 9.2 and Table 9.1). The transmissibility of the seat at resonance varied between 1.6 and 2.6 with a mean of 2.0.

Table 9.1 Effect of backrest contact and vibration magnitude on primary resonance frequencies and transmissibilities of the seats at resonance and at 12.0 Hz. Means (and standard deviations) of 80 subjects.

	Resonance frequency, Hz	Transmissibility at resonance	Transmissibility at 12.0 Hz
Input magnitude (no backrest)			
0.5 ms^{-2} r.m.s.	4.18 (0.41)	1.83 (0.24)	0.81 (0.15)
1.0 ms^{-2} r.m.s.	3.93 (0.34)	1.77 (0.23)	0.81 (0.15)
1.5 ms^{-2} r.m.s.	3.76 (0.32)	1.76 (0.21)	0.81 (0.17)
Input magnitude (backrest)			
0.5 ms^{-2} r.m.s.	4.67 (0.38)	2.14 (0.30)	0.72 (0.16)
1.0 ms^{-2} r.m.s.	4.37 (0.35)	2.04 (0.25)	0.72 (0.16)
1.5 ms^{-2} r.m.s.	4.11 (0.31)	1.96 (0.23)	0.71 (0.16)

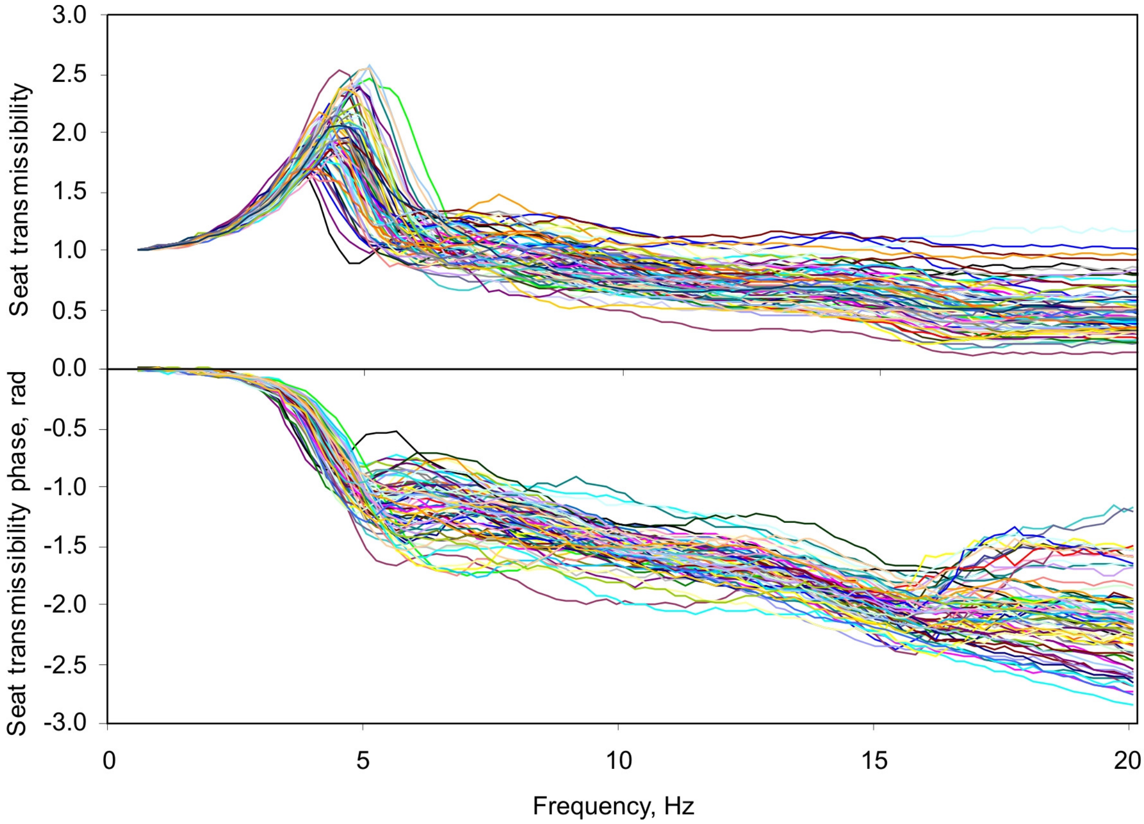

Figure 9.2 Seat transmissibilities for 80 people (backrest; vibration magnitude 1.0 ms^{-2} r.m.s.).

9.3.2 Effects of backrest

The mean resonance frequency increased from 3.9 Hz to 4.4 Hz when subjects made contact with the backrest while exposed to 1.0 ms^{-2} r.m.s. ($p<0.001$), with an increase in the seat transmissibility at resonance ($p<0.001$), and a decrease in the transmissibility at 12 Hz ($p<0.001$) (Table 9.1, Figure 9.3). The means and standard deviations of the seat transmissibility with both backrest conditions are shown in Figure 9.4. There were no significant differences in inter-subject variability between the two backrest conditions in the resonance frequency, the seat transmissibility at resonance, or transmissibility at 12 Hz (in all cases $p \geq 0.15$; Table 9.1).

Table 9.2 Correlation coefficients, *r*, between subject physical characteristics (Pearson's correlation).

	Gender, f=0, m=1	Weight, kg	Stature, cm	BMI, kgm^{-2}	Knee height, cm	Buttock-knee, cm	Sitting height, cm
Age, years	0.04	0.14	-0.04	0.20*	0.05	-0.04	-0.13
Gender, (f=0; m=1)		0.54**	0.71**	0.06	0.63**	0.37**	0.58**
Weight, kg			0.61**	0.71**	0.68**	0.54**	0.50**
Stature, cm				-0.11	0.89**	0.71**	0.79**
BMI, kgm^{-2}					0.06	0.05	-0.07
Knee height, cm						0.69**	0.66**
Buttock-knee length, cm							0.42**

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

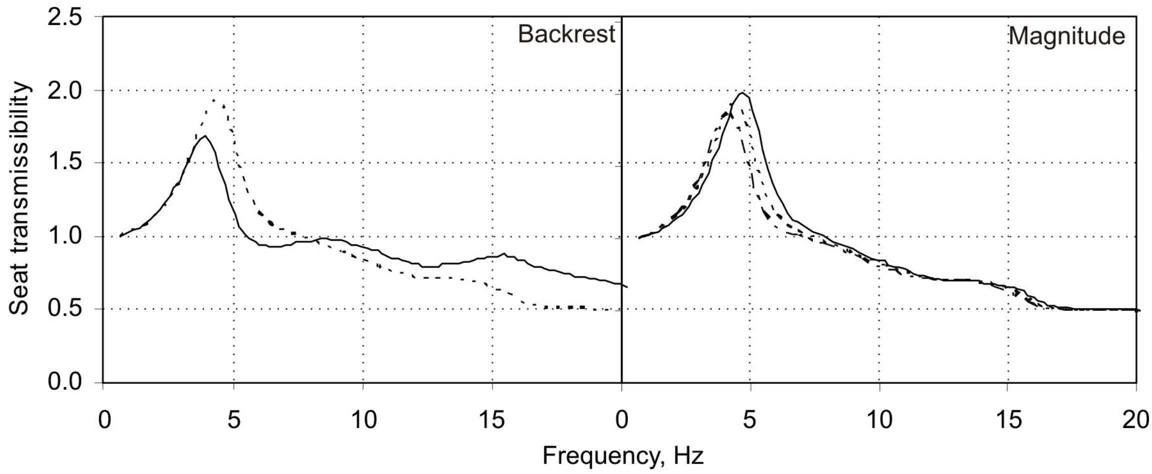

Figure 9.3 Effect of backrest (No backrest ,—— ; Backrest, · · · · ·) and input magnitude (0.5 ms^{-2} r.m.s., ——; 1.0 ms^{-2} r.m.s., · · · · ·; 1.5 ms^{-2} r.m.s., · – · –) on seat transmissibility.

9.3.3 Effects of vibration magnitude

When there was no backrest, the mean resonance frequency decreased by 0.4 Hz (from 4.2 to 3.8 Hz) as the vibration magnitude increased from 0.5 to 1.5 ms^{-2} r.m.s. ($p<0.001$; Table 9.1). With the backrest, the mean resonance frequency decreased by 0.6 Hz (4.7 to 4.1 Hz) as the vibration magnitude increased from 0.5 to 1.5 ms^{-2} r.m.s. ($p<0.001$; Figure 9.3). The decrease in the resonance frequency with increasing vibration magnitude was not significantly different between the two backrest conditions ($p=0.075$). With and without the backrest, as the vibration magnitude increased from 0.5 to 1.5 ms^{-2} r.m.s., there was a decrease in the transmissibility at resonance (in both cases, $p<0.001$), but no change in the transmissibility at 12 Hz ($p=0.10$).

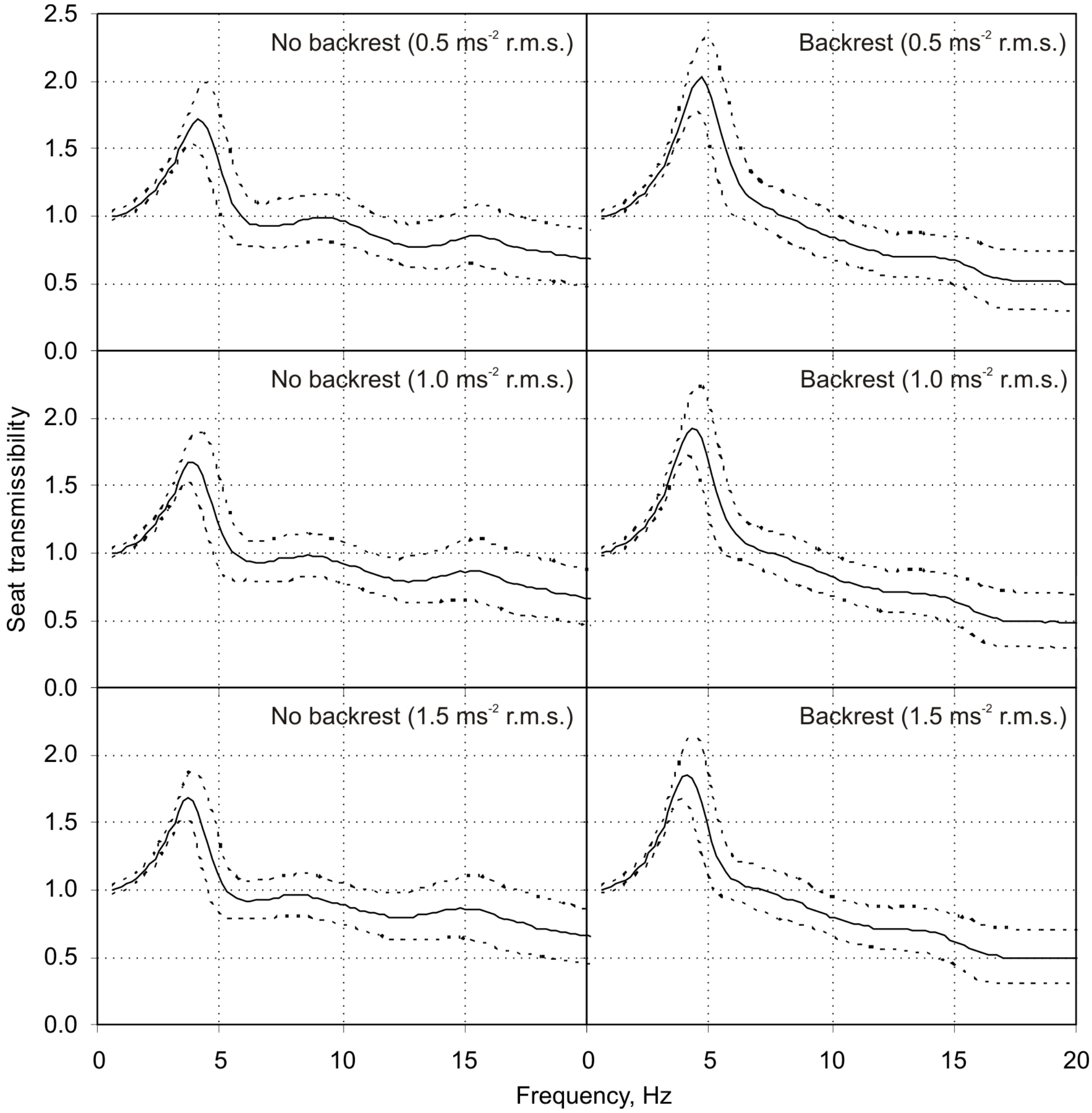

Figure 9.4 Effect of the seat backrest and vibration magnitude on mean apparent mass and inter-subject variability: mean (——) and mean ±s.d. (· · · · ·).

Inter-subject variability in seat transmissibility at resonance was less with 1.5 ms^{-2} r.m.s. than with 0.5 ms^{-2} r.m.s., both when subjects were supported by a backrest and when there was no backrest (p<0.001 and p=0.048, respectively) (Figure 9.4, Table 9.2). Inter-subject variability in the resonance frequency was also less with 1.5 ms^{-2} r.m.s. than with 0.5 ms^{-2} r.m.s. (in both postures, p<0.001). Inter-subject variability in seat transmissibility at 12 Hz was not significantly affected by the vibration magnitude (in both postures, p≥0.76).

9.3.4 Effects of subject physical characteristics

The 80 subjects were divided into four equal groups according to their age, stature, and BMI, and into two groups according to their gender; these groups are defined in Table 9.3. The means and standard deviations of the resonance frequency, the seat transmissibility at resonance, and the seat transmissibility at 12 Hz were calculated for each group for the backrest condition (Table 9.3). The mean transmissibilities of the groups are compared in Figure 9.5 and Figure 9.6.

Table 9.3 Effect of subject physical characteristics on the primary seat transmissibility resonance frequency and the transmissibility at resonance and at 12.0 Hz (backrest support; magnitude 1.0 ms^{-2} r.m.s.). Means (and standard deviations) of 20 subjects, except for gender (41 males, 39 females).

	Group	Resonance frequency, Hz	Transmissibility at resonance	Transmissibility at 12.0 Hz
Age, years: Median (min, max)				
21 (18,23)	1	4.12 (0.26)	1.85 (0.14)	0.79 (0.12)
25 (24,27)	2	4.41 (0.23)	2.05 (0.25)	0.68 (0.18)
34 (28,45)	3	4.34 (0.36)	2.02 (0.16)	0.70 (0.15)
52 (45,65)	4	4.61 (0.35)	2.22 (0.28)	0.70 (0.15)
Gender: Median (min, max)				
Female	1	4.30 (0.34)	2.05 (0.25)	0.77 (0.18)
Male	2	4.44 (0.36)	2.03 (0.26)	0.67 (0.11)
Weight, kg: Median (min, max)				
54 (46,60)	1	4.39 (0.41)	2.11 (0.31)	0.65 (0.15)
64 (60,69)	2	4.35 (0.35)	1.97 (0.22)	0.73 (0.11)
74 (69,80)	3	4.36 (0.34)	2.02 (0.25)	0.81 (0.20)
88 (80,103)	4	4.39 (0.33)	2.07 (0.23)	0.68 (0.12)
Stature, cm: Median (min, max)				
156 (149,163)	1	4.29 (0.34)	2.07 (0.24)	0.80 (0.20)
167 (163,171)	2	4.48 (0.38)	2.11 (0.30)	0.66 (0.16)
176 (171,181)	3	4.38 (0.35)	2.01 (0.22)	0.74 (0.11)
185 (181,192)	4	4.34 (0.34)	1.98 (0.24)	0.68 (0.13)
BMI, kgm^{-2}: Median (min, max)				
20 (18,21)	1	4.50 (0.32)	2.08 (0.28)	0.66 (0.13)
22 (21,23)	2	4.29 (0.41)	1.99 (0.22)	0.70 (0.12)
25 (24,26)	3	4.36 (0.32)	2.01 (0.26)	0.73 (0.15)
31 (26,34)	4	4.35 (0.35)	2.08 (0.25)	0.77 (0.20)

The resonance frequency of the seat transmissibility varied between age groups (p<0.001), with differences found between all pairings of age groups (p≤0.038), other than between Groups 2 and 3 (p=0.492). Seat transmissibility at resonance also varied between age groups (p<0.001), with significant differences between all pairings of age groups (p≤0.044) other than between Groups 2 and 3 (p=0.735).

Relative to the large effects of subject age, the gender, weight, stature, and BMI had smaller effects on the principal resonance in seat transmissibility (compare Figure 9.5 with Figure 9.6). There were no significant variations in either the resonance frequency or the transmissibility at resonance between subjects categorized by gender, weight, stature, or BMI (in all cases, p≥0.12). At 12 Hz there were significant variations between males and females (p=0.003) and between stature groups (p=0.017); however only the differences between stature groups 1 and 2 (p=0.021) and groups 1 and 4 (p=0.028) were found to be significant.

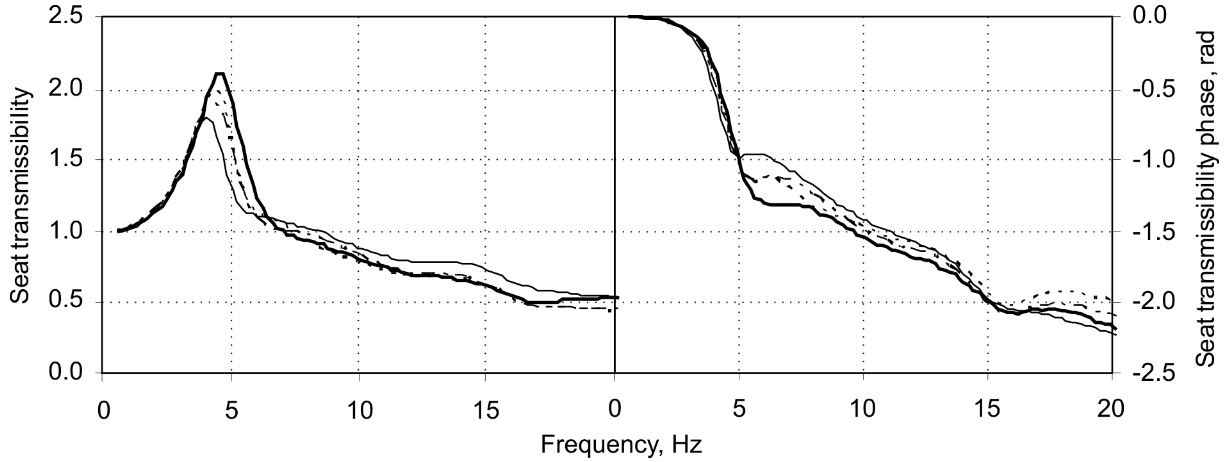

Figure 9.5 Effect of subject age on seat transmissibility (backrest; 1.0 ms^{-2} r.m.s excitation); subjects grouped by age (20 per group) with mean age: 21 years (——), 25 years (· · · · ·), 34 years (· — · —) and 52 years (——).

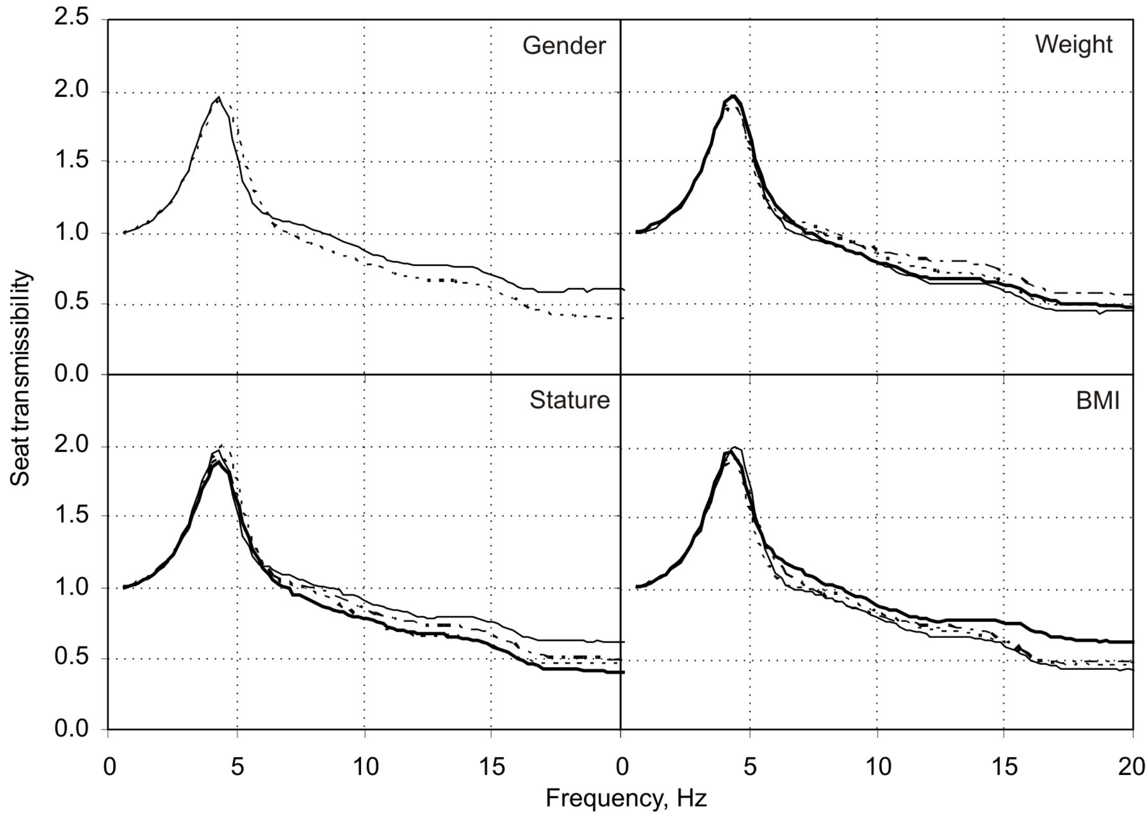

Figure 9.6 Effect of physical characteristics on normalised apparent mass (backrest;1.0 ms^{-2} r.m.s excitation); subjects grouped (see Table 9.3 for details) by physical characteristic: Group 1 (——), Group 2 (· · · · ·), Group 3 (· — · —) and Group 4 (——).

9.3.5 Bivariate regression analysis

For subjects sitting with the backrest, bivariate regression analysis showed that age was the only subject characteristic associated with the seat resonance frequency, with an increase of 0.14 Hz in the resonance frequency for each 10-year increase in age (Table 9.4; regression coefficient, *B*=0.014 Hz.year^{-1}; *p*=0.003). The effect of age on resonance frequency was similar without the backrest (*B*=0.012 Hz.year^{-1}, *p*<0.001; Figure 9.7). The only physical characteristics associated with the seat transmissibility at resonance were age (*B*=0.01 year^{-1}, *p*<0.001; Figure 9.8) and sitting height (B= -0.011 cm^{-1}, *p*=0.044). Subject weight, BMI, and knee height were associated with the seat transmissibility at 12 Hz (*p*≤0.011). The transmissibility of the seat at resonance was positively associated with the resonance frequency (*p*<0.001) and negatively associated with the transmissibility at 12 Hz (*p*=0.001, Table 9.4).

Table 9.4 Bivariate regression coefficients showing the influence of subject physical characterises on predictors of seat transmissibility (backrest; magnitude 1.0 ms^{-2} r.m.s.).

Variables	Resonance frequency, Hz		Transmissibility at resonance		Transmissibility at 12 Hz	
	B *p*	*SEB*	*B* *p*	*SEB*	*B* *p*	*SEB*
Physical characteristics						
Age (years)	0.014 ***	0.003	0.010 ***	0.002	-0.002	0.001
Gender (female=0; male =1)	0.000	0.003	-0.001	0.002	0.001	0.001
Weight, kg	0.144	0.078	-0.023	0.057	-0.102**	0.033
Stature, cm	0.001	0.004	-0.004	0.003	-0.003	0.002
BMI, kgm^{-2}	-0.004	0.011	0.006	0.008	0.012**	0.005
Knee height, cm	0.005	0.010	-0.001	0.007	-0.011*	0.004
Buttock-knee length, cm	0.002	0.010	-0.008	0.007	-0.002	0.004
Sitting height, cm	-0.002	0.008	-0.011 *	0.006	-0.004	0.004
Seat transmissibility (ST) features						
ST resonance frequency, Hz			0.527 ***	0.055	-0.161**	0.047
ST at resonance	1.027 ***	0.107			-0.272***	0.063
ST at 12 Hz	-0.809 **	0.237	-0.700 ***	0.164		
Apparent mass (APM) features						
APM resonance frequency, Hz	0.300 ***	0.059	0.199 ***	0.043	-0.094**	0.028
APM at resonance, kg	-0.001	0.002	0.000	0.001	0.000	0.001
APM at 12 Hz, kg	0.016 **	0.006	0.008	0.004	-0.001	0.003

Abbreviations: *B*, regression coefficient; *SEB*, standard error of the regression coefficient.
**p* < 0.05, ***p* < 0.01, ****p* < 0.001.

Features of the seat transmissibility (measured with backrest with 1.0 ms^{-2} r.m.s. vibration) were regressed against features of the subject apparent mass (measured without backrest at 1.0 ms^{-2} r.m.s.) (Table 9.4). For 1.0 Hz increase in the resonance frequency of the apparent mass there was a 0.3 Hz increase in the resonance frequency of the seat transmissibility (*p*<0.001). The seat transmissibility at resonance was greater (*p*<0.001) and the transmissibility at 12 Hz was less (*p*<0.002) with subjects having greater resonance frequencies in their apparent mass. The apparent mass at resonance was not a significant predictor of any of the seat transmissibility features ($p \geq 0.682$).

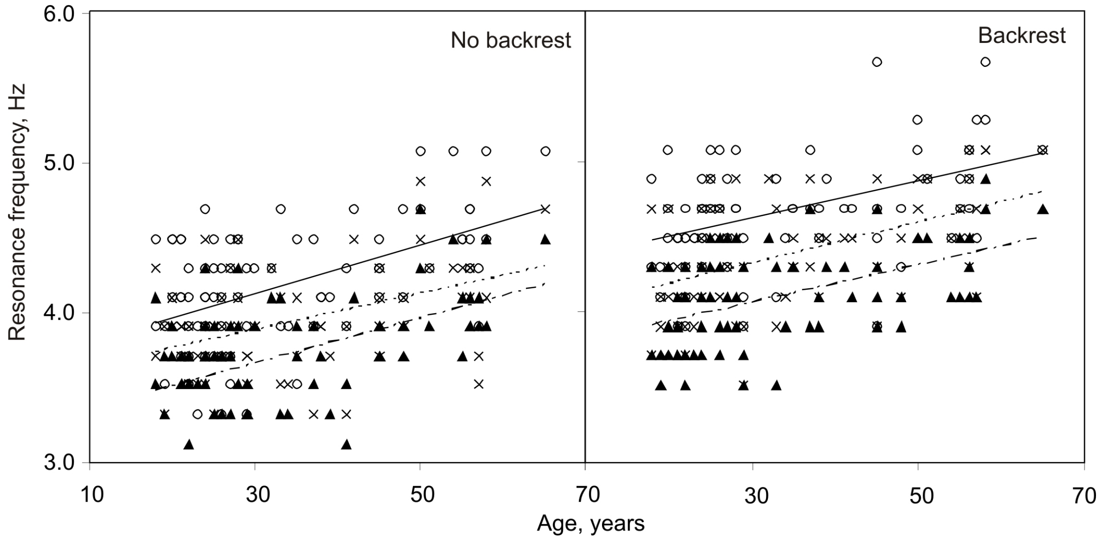

Figure 9.7 Effect of subject age on the seat transmissibility resonance frequency measured with 80 people at three magnitudes of excitation (no backrest and backrest): 0.5 ms^{-2} r.m.s. (○), 1.0 ms^{-2} r.m.s. (×) and 1.5 ms^{-2} r.m.s. (▲). Bivariate regression trend lines are also shown: 0.5 ms^{-2} r.m.s. (———), 1.0 ms^{-2} r.m.s. (· · · · ·) and 1.5 ms^{-2} r.m.s. (· — · —).

9.3.6 Multiple regression analysis

For both backrest conditions and with all three vibration magnitudes, multiple regression models investigated how features in the seat transmissibility (resonance frequency, transmissibility at resonance, and transmissibility at 12 Hz) depended on subject characteristics (Table 9.5). After controlling for the effects of other predictors, age was associated with the resonance frequency with both backrest conditions and all three vibration magnitudes ($p<0.001$). The association was greatest when there was no backrest with a vibration magnitude of 1.0 ms^{-2} r.m.s (B=0.016 Hz.year^{-1}), but the slope did not differ between conditions ($p>0.293$). With the backrest, the mean resonance frequency was significantly greater for the group of males than the group of females with the two lowest magnitudes of vibration (p=0.047, p=0.048, respectively). Interaction variables added to the regression models showed that the effect of gender on resonance frequency was not significantly affected by backrest contact or vibration magnitude ($p \geq 0.23$). Subject age was the only significant predictor of the seat transmissibility at resonance (in all conditions, $p<0.001$), with interaction variables suggesting this association was independent of backrest condition and vibration magnitude ($p \geq 0.33$).

Standardized regression coefficients (beta coefficients) were calculated to show the relative contribution of the significant predictors of seat transmissibility with both backrest conditions and all three magnitudes of vibration (Table 9.5). Age was the strongest predictor of the resonance frequency in all conditions, with gender of secondary importance. The beta coefficients suggest that age, gender and body mass index contributed in approximately equal proportions in all conditions to the variability in seat transmissibility at 12 Hz (Table 9.5). In all conditions, the R^2 values indicate the models accounted for only between 20 and 30% of the variability in the resonance frequency, the transmissibility at resonance, and the transmissibility at 12 Hz.

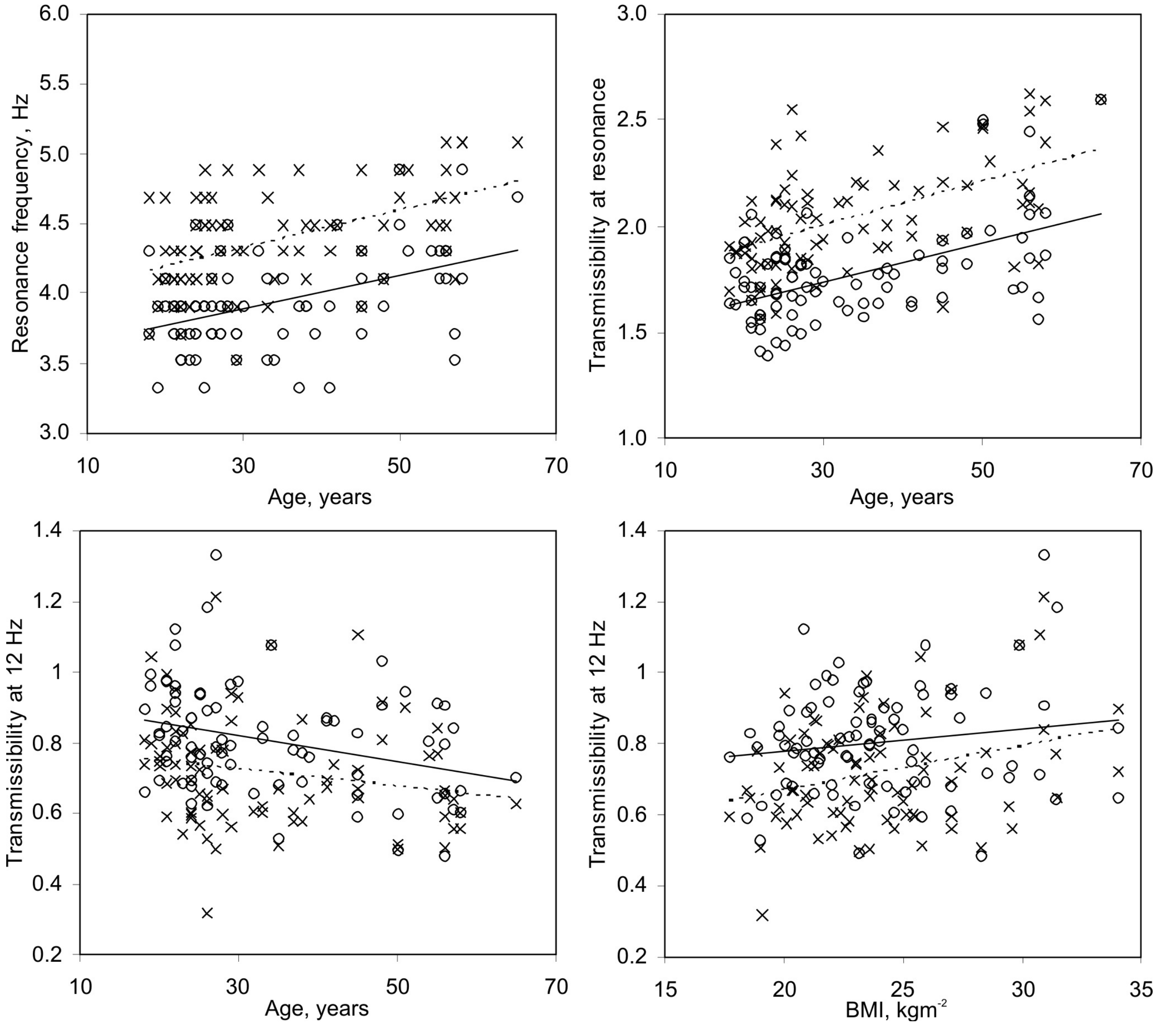

Figure 9.8 Effect of age and body mass index on seat transmissibility features measured with 80 people with two different backrest conditions (1.0 ms^{-2} r.m.s. excitation): no backrest (○), backrest (×). Bivariate regression trend lines are also shown: no backrest (——), backrest (· · · · ·).

Table 9.5 Multiple regression analysis showing the influence of vibration magnitude and backrest condition on predictors of seat transmissibility.

	0.5 ms^{-2} r.m.s.				1.0 ms^{-2} r.m.s.				1.5 ms^{-2} r.m.s.			
	B	*p*	*SEB*	*β*	*B*	*p*	*SEB*	*β*	*B*	*p*	*SEB*	*β*
Backrest												
Resonance frequency, Hz												
Age (years)	0.012	***	0.003	0.40	0.013	***	0.003	0.50	0.012	***	0.002	0.51
Gender (female=0; male =1)	0.154	*	0.076	0.20	0.136	*	0.067	0.19	0.035		0.061	0.06
Constant	4.195				3.849				3.676			
R^2, %	20.7				28.9				26.6			
Resonance magnitude												
Age (years)	0.011	***	0.002	0.47	0.010	***	0.002	0.53	0.008	***	0.002	0.46
Gender (female=0; male =1)	-0.031		0.059	-0.05	-0.029		0.048	-0.06	-0.023		0.046	-0.05
Constant	1.791				1.709				1.701		0.067	
R^2, %	22.6				28.3				21.4			
Transmissibility at 12 Hz												
Age (years)	-0.003	*	0.001	-0.24	-0.003	**	0.001	-0.27	-0.004	**	0.001	-0.30
Gender (female=0; male =1)	-0.110	**	0.032	-0.34	-0.107	**	0.031	-0.34	-0.105	**	0.030	-0.33
BMI, kgm^{-2}	0.014	**	0.004	0.32	0.016	***	0.004	0.37	0.016	***	0.004	0.37
Constant	0.544				0.508				0.513			
R^2, %	24.1				27.5				28.8			
No backrest contact												
Resonance frequency, Hz												
Age (years)	0.016	***	0.003	0.51	0.012	***	0.003	0.46	0.012	***	0.002	0.50
Gender (female=0; male =1)	0.109		0.078	0.13	0.040		0.067	0.06	0.042		0.062	0.07
Constant	3.587				3.504				3.333			
R^2, %	28.4				21.8				25.6			
Resonance magnitude												
Age (years)	0.010	***	0.002	0.52	0.009	***	0.002	0.52	0.008	***	0.002	0.49
Gender (female=0; male =1)	0.029		0.046	0.06	-0.022		0.044	-0.05	-0.045		0.041	-0.11
Constant	1.488				1.472				1.515			
R^2, %	27.7				26.8				25.1			
Transmissibility at 12 Hz												
Age (years)	-0.004	**	0.001	-0.33	-0.004	**	0.001	-0.36	-0.005	***	0.001	-0.41
Gender (female=0; male =1)	-0.111	***	0.030	-0.36	-0.082	**	0.031	-0.27	-0.103	**	0.032	-0.31
BMI, kgm^{-2}	0.009	*	0.004	0.22	0.010	*	0.004	0.23	0.014	**	0.004	0.30
Constant	0.780				0.758				0.712			
R^2, %	26.2				22.0				30.1			

Abbreviations: *B*, regression coefficient; *SEB*, standard error of the regression coefficient; *β*, standardized regression coefficient; R^2: percentage of experimental variation accounted for by the model. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

9.3.7 Modelled seat properties

The two degree-of-freedom seat transmissibility model in Figure 9.1 provided reasonable fits to the measured seat transmissibility for each of the 80 subjects around the primary resonance for both the modulus (Figure 9.9) and phase (Figure 9.10). The fits of the apparent mass with the single degree-of-freedom model were similarly good (not shown). Between 8 and 15 Hz in the apparent mass, and between 6 and 12 Hz in the seat transmissibility, another resonance was apparent with some subjects, with the frequency and magnitude of this resonance varying between subjects. The maximum frequency for fitting the model was therefore fixed at 1.5 times the measured seat resonance frequency, as increasing the frequency range compromised the fit around the primary resonance. The use of a two degree-of-freedom apparent mass model was investigated so as to represent the second resonance but although fits to the apparent mass were improved there was no improvement in the fits to the seat transmissibility at frequencies greater than the primary resonance.

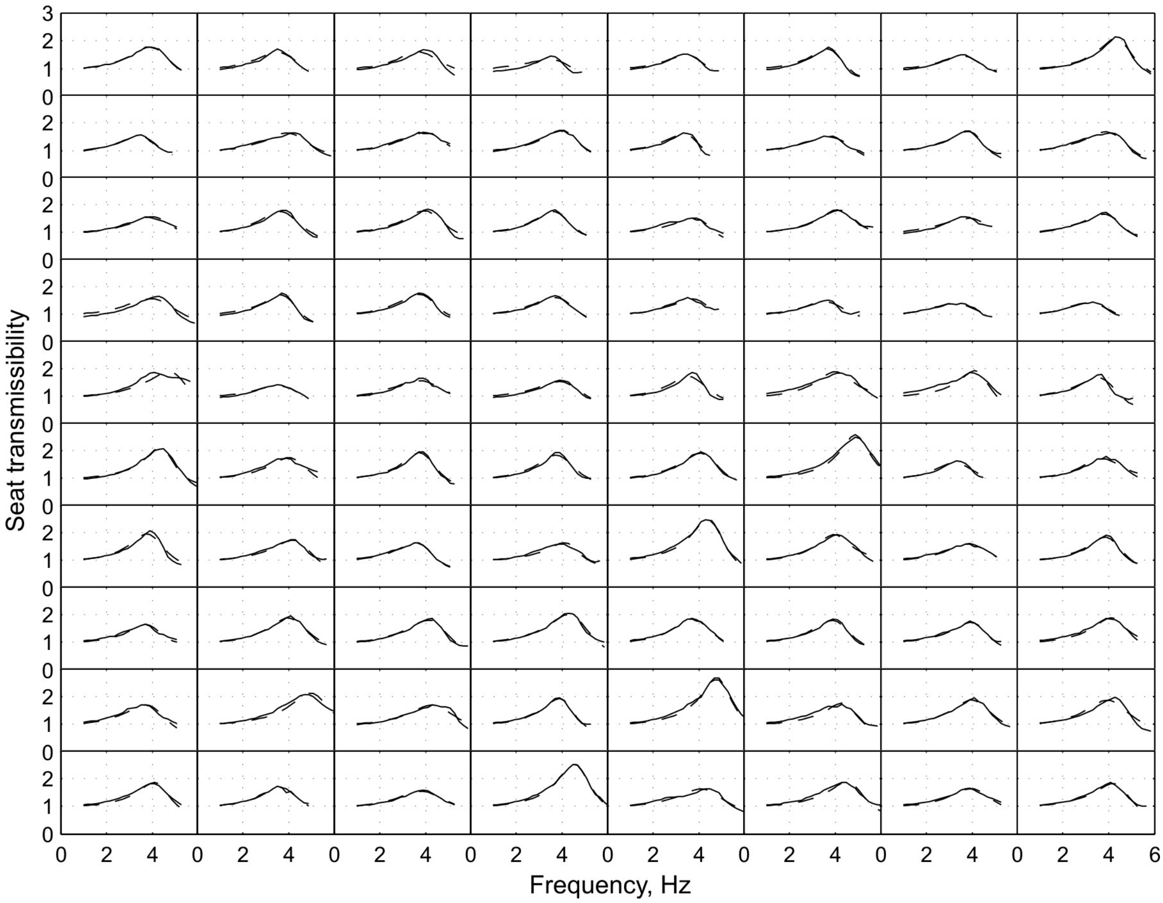

Figure 9.9 Seat transmissibility (modulus) of 80 people (no backrest; excitation magnitude 1.0 ms^{-2} r.m.s.). Comparison of measured (——) and modelled (- - - -) data.

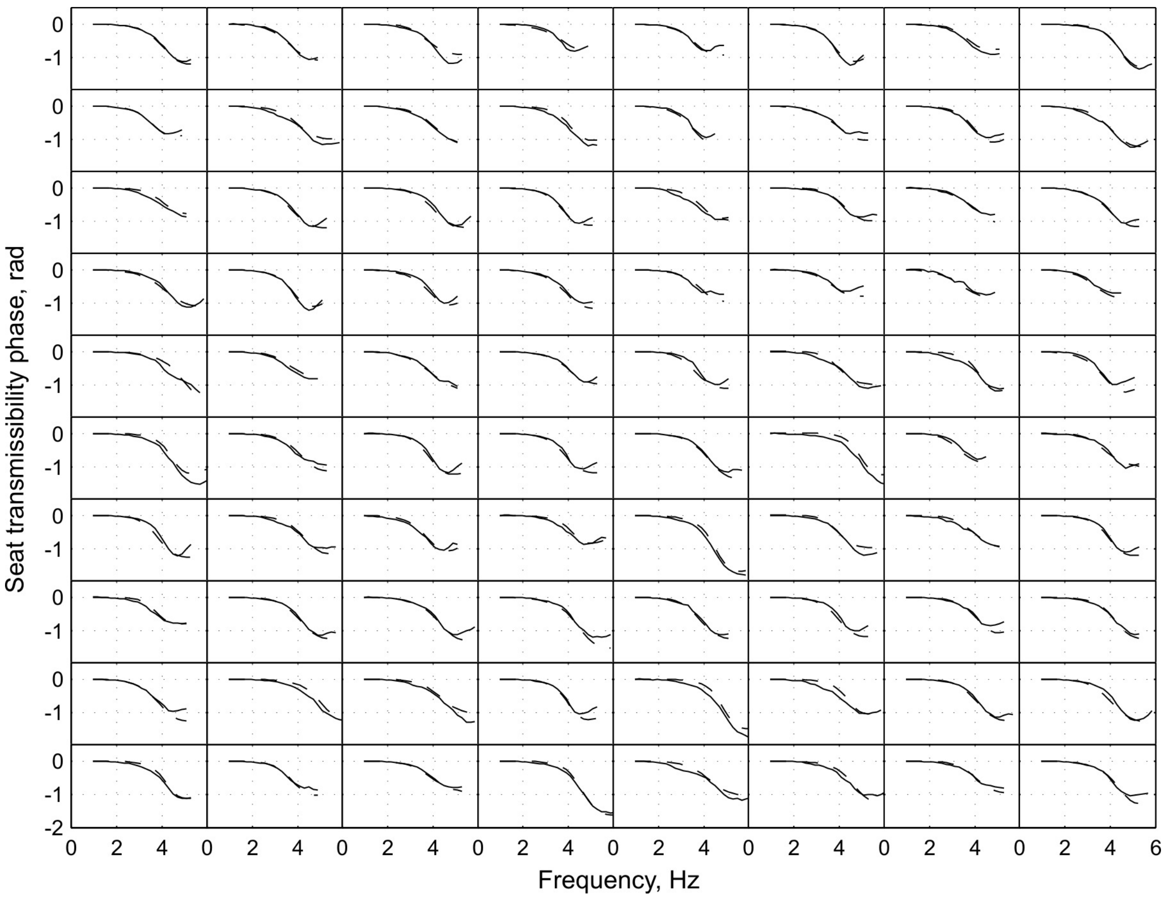

Figure 9.10 Seat transmissibility (phase) of 80 people (no backrest; excitation magnitude 1.0 ms^{-2} r.m.s.). Comparison of measured (——) and modelled (- - - -) data.

9.3.8 Fitted individual seat transmissibilities

The derived seat stiffness was strongly associated with all subject characteristics except age (Table 9.6). Subject weight was the strongest individual predictor, with the R^2 value indicating that weight accounted for 59% of the variability in the derived seat stiffness (Figure 9.11; B=26.80 kN/m.kg^{-1}; p<0.001). The apparent mass at 0.6 Hz, at the resonance frequency, and at 12 Hz were also strong predictors of seat stiffness, with these apparent mass features also strongly associated with subject weight (p=0.001). No statistically significant associations were found between the derived seat stiffness and the resonance frequency of the seat, the seat transmissibility at resonance, or the seat transmissibility at 12 Hz.

Table 9.6 Bivariate regression coefficients showing factors influencing the derived seat stiffness and damping (seat transmissibilities and apparent masses measured with no backrest at 1.0 ms^{-2} r.m.s.).

Variables	*K*, kN/m				*C*, Ns/m			
	B	*p*	*SEB*	R^2, %	*B*	*p*	*SEB*	R^2, %
Physical characteristics								
Age (years)	0.20		223	1.1	-1		6	0.1
Gender (female=0; male =1)	1.47	***	4954	27.8	366	*	150	7.3
Weight, kg	26.80	***	139	59.4	9		6	2.8
Stature, cm	1.25	***	216	30.6	16	*	7	7.4
BMI, kgm^{-2}	3.19	***	690	22.0	-10		21	0.3
Knee height, cm	3.58	***	578	33.6	45	*	18	7.3
Buttock-knee length, cm	2.31	**	646	14.4	16		19	0.9
Sitting height, cm	2.45	***	505	23.7	28		15	4.4
Seat transmissibility (ST) features								
ST resonance frequency, Hz	11.93		9370	2.1	-678	**	241	9.5
ST at resonance	-0.36		14187	0.0	-1375	***	345	17.5
ST at 12 Hz	8.25		17331	0.3	34		464	0.0
Apparent mass (APM) features								
APM resonance frequency, Hz	0.46		4893	0.0	215		129	3.6
APM at 0.6 Hz, kg	1.60	***	144	61.7	17	**	6	10.0
APM at resonance, kg	0.82	***	70	64.5	9	**	3	10.1
APM at 12 Hz, kg	1.59	***	402	17.0	24	*	11	5.5
Seat dynamic properties								
K, N/m					2		4	0.4
C, Ns/m	0.00		4	0.4				

Abbreviations: *B*, regression coefficient; *SEB*, standard error of the regression coefficient; R^2: percentage of experimental variation accounted for by the model. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

The derived seat damping had negative associations with gender, stature, and knee height ($p \leq 0.05$), but individually they only accounted for a small proportion of the variability in damping (in all cases $R^2 \approx 7\%$). The strongest predictor of seat damping was the resonance frequency in the seat transmissibility ($p<0.01$; $R^2=18\%$), with the apparent mass at 0.6 Hz, the apparent mass at resonance, and the apparent mass at 12 Hz also predictors ($p \leq 0.05$). There was no significant association between the derived seat stiffness and the derived damping.

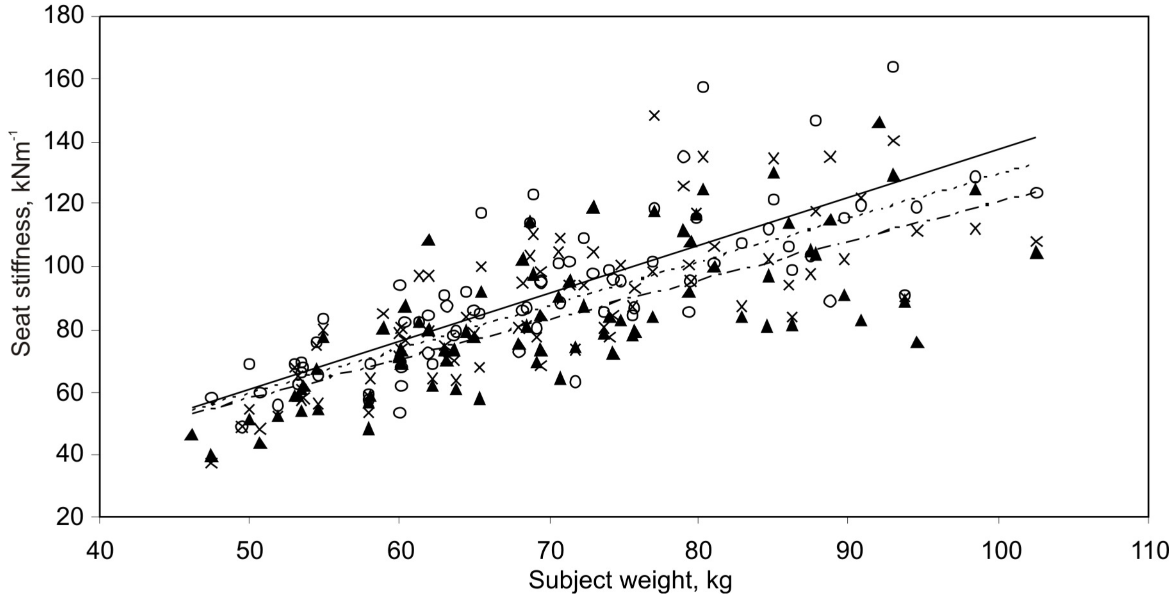

Figure 9.11 Effect of subject weight on the derived seat stiffness at three magnitudes of vertical vibration excitation (no backrest): 0.5 ms^{-2} r.m.s. (○), 1.0 ms^{-2} r.m.s. (×) and 1.5 ms^{-2} r.m.s. (▲). Bivariate regression trend lines are also shown: 0.5 ms^{-2} r.m.s. (——), 1.0 ms^{-2} r.m.s. (· · · · ·) and 1.5 ms^{-2} r.m.s. (· — · —).

9.3.9 Effect of vibration magnitude on seat dynamics

At each of the three vibration magnitudes, the model parameters were similar when the model was fitted to the mean response of the 80 subjects and the mean of the individually fitted parameters (Table 9.7).

Table 9.7 Effect of vibration magnitude on the parameters of the seat transmissibility model.

	K, kN/m	*C*, Ns/m	m_0, kg	m_1, kg	k_1, kg	c_1, kg
Fitted to mean						
0.5 ms^{-2} r.m.s.	97.4	831	9.4	50.8	67083	1495
1.0 ms^{-2} r.m.s.	89.7	777	9.5	50.4	56927	1386
1.5 ms^{-2} r.m.s.	83.6	774	9.2	50.8	53491	1338
Mean of fits to individuals						
0.5 ms^{-2} r.m.s.	92.1	829	13.1	44.8	59799	1318
1.0 ms^{-2} r.m.s.	88.7	783	11.5	48.5	55583	1301
1.5 ms^{-2} r.m.s.	83.2	791	11.1	49.2	52700	1256

The mean of the individually fitted seat stiffnesses decreased from 92.1 to 83.2 kN/m (14%) as the vibration magnitude increased from 0.5 to 1.5 ms^{-2} r.m.s. ($p<0.001$; Table 9.7); significant differences in stiffness were found between all excitation magnitudes ($p\leq0.012$; paired samples *t*-test). There was no effect of vibration magnitude on the derived seat damping ($p=0.584$).

After controlling for the effects of other physical characteristics, subject weight was significantly related to seat stiffness at all three vibration magnitudes ($p<0.001$; Table 9.8,

Figure 9.11), with the association not significantly dependent on vibration magnitude ($p \geq 0.2$). Gender was a significant predictor of seat stiffness at 1.0 ms^{-2} r.m.s. ($p=0.046$), but the beta values suggest gender was of much less importance than weight. Gender was associated with the seat damping at all three vibration magnitudes ($p \leq 0.017$), but the models only accounted for a small amount of the variability in seat damping ($R^2 \leq 11\%$).

Table 9.8 Multiple regression analysis showing the influence of vibration magnitude on predictors of derived seat dynamic properties (apparent masses and seat transmissibility measured with no backrest contact at 1.0 ms^{-2} r.m.s.).

	0.5 ms^{-2} r.m.s.				1.0 ms^{-2} r.m.s.				1.5 ms^{-2} r.m.s.			
	B	*p*	*SEB*	*β*	*B*	*p*	*SEB*	*β*	*B*	*p*	*SEB*	*β*
Seat stiffness *K*, kN/m												
Age (years)	0.15		157	0.08	-0.04		143	-0.02	0.21		132	0.12
Gender (female=0; male =1)	4.56		4829	0.09	8.73	*	4294	0.17	6.56		4022	0.15
Weight (kg)	1.35	***	185	0.68	1.32	***	166	0.68	1.10	***	153	0.65
Constant	-11.18				-7.49				-4.86			
R^2, %	55.8				61.6				57.2			
Seat damping *C*, N/m												
Age (years)	-1		5	-0.01	-2		6	-0.04	0		4	-0.01
Gender (female=0; male =1)	368	**	134	0.30	369	*	151	0.27	350	**	115	0.33
Constant	615				663				618			
R^2, %	9.1				7.4				10.9			

Abbreviations: *B*, regression coefficient; *SEB*, standard error of the regression coefficient; *β*, standardized regression coefficient; R^2: percentage of experimental variation accounted for by the model. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

9.4 DISCUSSION

9.4.1 Predictors of seat transmissibility

Subject age was the strongest predictor of the seat transmissibility resonance frequency: from 18 to 65 years, there was a mean increase in the resonance frequency of the seat with no backrest of 0.56 Hz with 0.5 ms^{-2} r.m.s. vibration and 0.75 Hz with 1.5 ms^{-2} r.m.s. vibration. The resonance frequency in the apparent masses of the same subjects increased by 1.7 Hz over the range 18 to 65 years (see Chapter 8). Subject age was the only subject characteristic to be significantly associated with seat transmissibility at resonance, with the mean transmissibility at resonance of the seat with backrest increasing by 0.52 with 0.5 ms^{-2} r.m.s. vibration and by 0.37 with 1.5 ms^{-2} r.m.s. vibration over the 18 to 65 year age range. Age was not a significant predictor of the apparent masses of the subjects at resonance (see Chapter 8). Because the seat dynamic properties did not vary with subject age (Table 9.8), it seems that the effects of subject age on the seat resonance frequency were largely due to increased resonance frequency in the apparent mass with increased age.

The apparent mass resonance frequency decreases with increasing body mass index (BMI) (see Chapter 8), but there was no evidence of BMI affecting the resonance frequency in the seat transmissibility (Table 9.5). The association between the BMI and the apparent mass resonance frequency was strong when sitting with an upright rigid backrest or a reclined rigid backrest, but not so strong when sitting supported by a foam backrest or sitting with no backrest as in this study (see Chapter 8). The dependence of the apparent mass on the backrest could explain the lack of association between BMI and seat transmissibility resonance frequency. There was no significant effect of BMI on the derived seat stiffness after controlling for age, gender, and weight (Table 9.8). It might be expected that subjects with higher BMI (after controlling for subject weight) would have greater contact area with the seat but also that the pressure, and hence the compression of the seat foam, would be less; these two factors can have opposing effects on seat stiffness (Wei, 2000), and their effects may have cancelled.

The R^2 values indicate that subject characteristics accounted for only 20 to 30% of the variability in seat transmissibility, less than subject characteristics accounted for variability in apparent mass (see Chapter 8). Subject weight accounts for much of the variability in apparent mass at resonance, but after normalising with respect to sitting weight the variability in apparent mass at resonance is significantly reduced (see Section 8.3.1). In the absence of weight as a predictor of seat transmissibility at resonance (or normalized apparent mass at resonance) the low R^2 values suggest that other unmeasured factors account for most of the variability. These factors might include variations in posture between subjects, variations in subject build (e.g. body shape and size distribution and proportion of muscle and fat) not fully reflected in the BMI, as well as changes in muscle tension.

The resonance frequency in the seat transmissibility increased by 0.3 Hz for every 1.0 Hz increase in the apparent mass resonance frequency (Table 9.4); this could partially explain the lower associations of age, BMI, and gender with the resonance frequency in the seat transmissibility than the resonance frequency in the apparent mass.

9.4.2 Effect of subject weight

Subject weight is a strong predictor of apparent mass at resonance and at 12 Hz (see Chapter 8), but it did not significantly affect seat transmissibility at these frequencies or the apparent mass resonance frequency.

The influence of variations in apparent mass with subject weight on seat transmissibility was investigated by fixing the seat parameters in the model (to the mean of the individual fits with 1.0 ms^{-2} r.m.s. vibration). The seat transmissibility model was then used with the apparent mass parameters derived for each of the 80 subjects. The frequency and magnitude of the resonance in the predicted seat transmissibilities were then regressed against subject weight, after correcting for age and gender (Table 9.9). With increasing subject weight (i.e. 46 to 103 kg), the resonance frequency in the transmissibility would be expected to decrease by about 1.0 Hz and the transmissibility at resonance would be expected to increase by 0.46. However, weight was not associated with the predicted seat transmissibility, suggesting the seat dynamic properties changed to compensate for changes in subject weight.

Table 9.9 Multiple regression analysis of predictors of seat transmissibility features where seat parameters are assumed to be independent of physical characteristic (apparent masses and seat transmissibility measured with no backrest contact at 1.0 ms^{-2} r.m.s.).

	Resonance frequency, Hz				Transmissibility at resonance			
	B	*p*	*SEB*	*β*	*B*	*p*	*SEB*	*β*
Age (years)	0.015	***	0.002	0.558	0.007	***	0.002	0.311
Gender (female=0; male =1)	0.221	**	0.070	0.304	0.222	**	0.061	0.351
Weight (kg)	-0.018	***	0.003	-0.642	0.008	**	0.002	0.343
Constant	4.182				0.825			
R^2, %	51.0				50.4			

Abbreviations: *B*, regression coefficient; *SEB*, standard error of the regression coefficient; *β*, standardized regression coefficient; R^2: percentage of experimental variation accounted for by the model. **$p < 0.01$, ***$p < 0.001$.

The dynamic stiffness of a car seat and a foam squab has been measured (Wei and Griffin, 1998b) by applying preloads to the seats through an indenter head shaped like a SIT-BAR (Whitham and Griffin, 1977). Increasing the preload from 300 to 800 N increased the stiffness by 30.7 kN/m with the car seat and by 33.2 kN/m with the foam squab. In the present study, an increase in sitting weight (increasing the force on the seat from 300 to 800 N) was associated with an increase in the derived stiffness of 81.3 kN/m (Table 9.6). The greater increase in stiffness in this study might be explained by heavier subjects having larger contact areas with the seat surface. Wei and Griffin (Wei and Griffin, 1998b) found that the damping of the car seat was little changed by the pre-load, consistent with the absence of an effect of increased loading in the present study (Table 9.8).

9.4.3 Effects of vibration magnitude and backrest

The decrease in the resonance frequency in the seat transmissibility with increased magnitude of vibration is consistent with previous studies (e.g. Corbridge and Griffin, 1989). As vibration magnitude increased from 0.5 to 1.5 ms^{-2} r.m.s., the apparent mass resonance frequency of the present subjects decreased from 5.3 to 4.7 Hz (no backrest, 1.0 ms^{-2} r.m.s.; see Chapter 8). The present and previous studies (e.g. White *et al.*, 2000; Wei, 2000) show that seat dynamic stiffness also decreases with increasing vibration magnitude. Wei (2000) measured the dynamic seat stiffness and damping of a foam squab at different vibration magnitudes using an indenter and found that with various shapes and sizes of indenter, the dynamic stiffness of the foam consistently decreased with increasing vibration magnitude. With a preload of 500 N, and vibration increasing from 0.5 ms^{-2} r.m.s. to 1.5 r.m.s. the stiffness decreased between 1.3% (a buttocks-shaped indenter) to 9.1% (15-cm diameter disk indenter), compared to a decrease of 10.7% in stiffness over the same range of vibration magnitude in the present study. Consistent with this study, Wei also found no systematic change in seat damping with changes in vibration magnitude.

The contribution of the non-linearity of the human body to changes in the seat transmissibility was quantified using the seat-body model to predict seat transmissibility from subject apparent masses at different magnitudes while the seat parameters were fixed to the mean values for all individuals at 1.0 ms^{-2} r.m.s. This analysis suggested the body was the dominant cause of the nonlinearity in seat transmissibility: as the vibration magnitude increased from 0.5 to 1.5 ms^{-2} r.m.s., the model predicted that 0.33 Hz of the 0.41 Hz decrease in the seat transmissibility resonance frequency was caused by the non-linearity of the body.

The increase in the seat resonance frequency and the increase in the seat transmissibility at resonance when subjects made contact with a reclined backrest are consistent with other studies (e.g. Corbridge and Griffin, 1989). There was no evidence to suggest the associations of seat transmissibility with vibration magnitude or subject physical characteristics were significantly affected by backrest contact. Changes in backrest contact and backrest inclination change the posture of the seat occupant and the dynamic response to the body (e.g. see Chapter 4) but they also alter the mechanical properties of the seat by changing the area of the body in contact with the seat and the compression of the cushion.

9.4.4 Limitations of modelling

A seat transmissibility model incorporating a two degree-of-freedom apparent mass model of the body did not reflect the seat transmissibility measured around the second resonance without compromising the fit to the primary resonance, implying deficiencies in either the simple apparent mass model or the simple seat model. Fairley and Griffin (1986) reported that the apparent mass of the body measured in a rigid seat and in a car seat were similar at low frequencies but differed between 12 and 18 Hz. Differences in seat pan inclination (e.g. Wei, 2000) or pressure distribution (e.g. Hinz, 2006) might have contributed to differences between the apparent mass of the body on the rigid and compliant seats and the poorer fit to the second resonance of the seat transmissibility in this study. The simple seat model may also be deficient in that it assumed the stiffness and damping of the seat were independent of frequency. Although a previous study found small variations over the frequency range studied here (e.g. Wei and Griffin, 1998), this may not have been the case for the seat used in this study.

9.4.5 Implications of the results

The strong association between subject age and seat transmissibility implies that when testing seats or defining idealized body responses (e.g. in ISO 5982, 2001) the influence of age should be considered. The weak association between subject weight and seat transmissibility suggests that weight is of less importance than age, and that the apparent mass of the body normalised with respect to sitting weight may be sufficient to define the response of models for predicting the transmissibility of conventional foam cushion seats. Anthropodynamic dummies have been developed for testing seats in place of human subjects (e.g. Cullmann and Wölfel, 2001; Lewis and Griffin, 2002) and standardized dummy responses have been proposed to represent different weights of subjects (e.g. 5th and 95th percentiles). While seat loading can affect the dynamic performance of suspension seats (e.g. Stayner, 1972) this research suggests there is less justification for using variable weight dummies to test conventional seats. There is considerable variation in the dynamic properties of seats and seat foams (e.g. Wei, 2000) – so while other studies have also found no correlation between subject weight and either the resonance frequency or the transmissibility at resonance for a sprung cushion train seat (Corbridge and Griffin, 1989) or a car seat (Varterasian and Thompson, 1977), further investigation seems appropriate.

9.5 CONCLUSIONS

Age was the strongest predictor of seat transmissibility resonance frequency and the only significant predictor of the seat transmissibility at resonance. Age, gender and body mass index were associated with the transmissibility at 12 Hz. Despite these significant associations, the regression models showed that the physical characteristics of subjects only accounted for 20 to 30% of the variability in the resonance frequency of the seat and the seat transmissibility at resonance.

Subject weight was not significantly associated with seat transmissibility, even though weight has a strong association with the apparent mass of the body at resonance and at 12 Hz. There is evidence that the seat stiffness may have increased with increasing subject mass so as to compensate for increased sitting weight.

Seat transmissibility resonance frequency reduced with increasing magnitude of vibration due to non-linearity in the apparent mass of the body and, possibly, non-linearity in the seat. The non-linearity of the body accounted for about 80% of the 0.41 Hz decrease in resonance frequency as the magnitude of vibration was increased from 0.5 to 1.5 ms^{-2} r.m.s. The resonance frequency in the seat transmissibility and the transmissibility at resonance increased when subjects made contact with the seat backrest.

CHAPTER 10: GENERAL CONCLUSIONS

The review of previous studies in Chapter 2 raised three major questions: How does the seating environment affect the apparent mass of the seated body, (ii) How do subject physical characteristics affect the apparent mass of the body, and (iii) How does the apparent mass of the body affect the vibration transmitted through a seat?

Experimental studies have been undertaken to address these questions (see Chapters 4 to 9). These studies are summarised and discussed in Section 10.1 below. The main conclusions of the research are presented in Section 10.2. Questions that have been raised during the research and recommendations for further research are discussed in Section 10.3.

10.1 DISCUSSION

10.1.1 Factors affecting apparent mass

Experimental studies were undertaken to understand and compare the effects of different elements of the seating environment (i.e. the seat backrest, the footrest and steering wheel and the vibration spectrum) and the variability between people (i.e. their physical characteristics) on the vertical apparent mass of the seated body. Changes in apparent mass with the seating environment were represented by fitting a single degree-of-freedom lumped parameter model to the apparent mass in each condition (see Chapter 7). Trends in model parameters were identified as a function of the model variables (e.g. backrest angle, footrest position, steering wheel position, input magnitude). These trends gave insights into the biodynamic mechanisms involved.

The vertical apparent mass of the human body sitting on a flat rigid seat was found to depend on backrest support (see Chapter 4). Sitting supported by either an upright rigid or an upright foam backrest, the median static mass supported on the seat surface (i.e. the apparent mass at 0.4 Hz) decreased by approximately 10 kg compared to a 'no backrest' posture. This suggests that the backrests supported a proportion of the subject weight in shear. Contrary effects on the resonance frequency were observed when the backrests were reclined (from 0 to 30°, in 5° increments) – with a rigid backrest the resonance frequency increased (from 5.47 to 6.35 Hz), while with a 100-mm foam backrest, the median resonance frequency decreased (from 5.18 to 4.49 Hz). The simple single degree-of-freedom model showed that the increases in resonance frequency when reclining a rigid backrest could be largely replicated in the modelled response by decreasing the moving mass parameter. The decrease in resonance frequency when reclining a foam backrest was largely represented by decreasing the stiffness parameter, perhaps indicating increased compliance of the foam reducing the ‘body stiffness’.

The effect of the position of the footrest and steering wheel was considered in Chapter 5. When subjects held a steering wheel and were supported by a backrest reclined to 15° there was an additional resonance evident in the median apparent mass at a lower frequency than the primary resonance. This resonance at around 4 Hz increased in prominence as the angle between the forearm and upper-arm increased, and simultaneously the main resonance occurring around 6.8 Hz decreased in magnitude - with the arms fully extended these resonances were of similar magnitude. The resonance at 4 Hz may have been caused by the response of the arms and shoulders; the reduction in the apparent mass at the primary resonance suggests that the responses of the arms interacted with the body movements associated with the primary resonance. The simple single degree-of-freedom model was unable to represent both resonances, resulting in a single peak fitted to both resonances; a two degree-of-freedom model improved the fit but there were fewer significant trends in model parameters. Moving the footrest away from the body increased the mass supported on the seat surface and the apparent mass at resonance. Applying force to either the steering wheel or the footrest reduced the apparent mass at resonance and decreased the mass supported on the seat surface.

The apparent mass was shown to vary not just with the magnitude of vibration, but also with the spectrum of vibration (see Chapter 6). The apparent mass resonance frequency of the body decreased as the magnitude of broadband vibration was increased, consistent with a decrease in the stiffness parameter in the simple model. This non-linearity was found to depend on the frequency of excitation – with the magnitude of narrowband excitations below 8 Hz having the greatest influence on the resonance frequency and the magnitude of narrowband excitations below 4 Hz having the greatest influence on the resonance magnitude. The effect of frequency on the non-linearity was found to increase with increase in input magnitude. The vibration spectra at the seat surface will vary between vehicles and between test conditions (i.e. road surface, vehicle speed, etc.); the results of this study show that the dynamics of the body and hence the transmission of vibration through seats will also be influenced by these factors.

In Chapter 8, multiple regression models were used to investigate the relationships between the physical characteristics of 80 subjects (41 males and 39 females, aged 18 to 65) and their apparent masses. After controlling for the influence of other physical characteristics, bodyweight was found to be the strongest predictor of the apparent mass at 0.6 Hz, at resonance, and at 12 Hz, with other factors having only a marginal effect. The principal resonance frequency was most consistently associated with age. As age increased from 18 to 65 years the apparent mass resonance frequency increased by up to 1.7 Hz. This change was greater than the 0.9-Hz increase in resonance frequency between sitting without a backrest and sitting with a rigid backrest reclined to 15°, and greater than the 1.0-Hz reduction in resonance frequency when the magnitude of vibration increased from 0.5 to 1.5 ms^{-2} r.m.s. The association of body mass index with apparent mass resonance frequency depended on backrest condition: the association was strong when sitting with an upright rigid backrest or a reclined rigid backrest, but not so strong when sitting supported by a foam backrest or sitting with no backrest. With a reclined rigid backrest, the resonance frequency decreased by up to 1.7 Hz as body mass index increased from 18 to 34 kgm^{-2}.

In general, the simple single-degree-of-freedom model was able to closely represent the measured changes in the apparent mass with the seating environment. An additional degree-of-freedom was beneficial in some postures (e.g. when subjects held a steering wheel) and with some individuals, but there were fewer statistically significant trends in the model parameters. As the difference between the measured and fitted responses with the single degree-of-freedom model was generally much less than the inter-subject variability and also less than the variability between conditions, there appears little justification for developing more complex models to predict seat transmissibility if they do not reflect the relatively large effects of vibration magnitude, posture, individual variability and other factors that influence apparent mass and its application to predicting seat transmissibility.

10.1.2 Factors affecting seat transmissibility

The study described in Chapter 9 was designed to determine how the apparent mass of the body, as well as principal factors affecting the apparent mass of the body (i.e. physical characteristics, backrest contact, and magnitude of vibration) affect seat transmissibility.

The transmission of vertical vibration through a car seat was measured with the same 80 subjects used in the study investigating inter-subject variability in apparent mass. Linear regression models showed that the strongest predictor of both the frequency of the principal resonance in seat transmissibility and the seat transmissibility at resonance was subject age, with other factors having only marginal effects. From 18 to 65 years, there was a mean increase in the resonance frequency of the seat of up to 0.75 Hz, and an increase in the mean transmissibility at resonance of up to 0.52. Body mass index did not affect the seat transmissibility resonance frequency. The weak association of body mass index with apparent mass resonance frequency when subjects were supported by a foam backrest as in this study could explain the lack of association with seat transmissibility resonance frequency.

The transmissibility of the seat at 12 Hz depended on subject age, body mass index, and gender. Although subject weight was strongly associated with apparent mass, weight was not strongly associated with seat transmissibility.

10.1.3 Effects of apparent mass on seat transmissibility

Regression of features of seat transmissibility with features of apparent mass showed that a 1.0-Hz increase in the resonance frequency of the apparent mass was associated with a 0.3-Hz increase in the resonance frequency of the seat transmissibility (see Chapter 9). The apparent mass at resonance, a feature strongly associated with subject weight, was not a predictor of any of the seat transmissibility features.

A simple two degree-of-freedom seat-body model was developed to explore the effects of variations in apparent mass on seat transmissibility. Initially, the body parameters in the model were fitted to the measured individual apparent masses. Then, by fixing the fitted body parameters, the seat transmissibility model was fitted to each of the individual seat transmissibilities to determine the seat stiffness and damping parameters. This approach showed that the changes in seat transmissibility with age were predictable from the changes in apparent mass with age (i.e. there was no change in seat properties). With increased sitting weight, the dynamic stiffness of the seat appeared to increase so as to compensate for increases in apparent mass associated with increased load on the seat.

The contribution of the non-linearity of the human body to changes in the seat transmissibility with input magnitude was quantified using the seat-body model. Seat transmissibility was predicted by fixing the seat parameters and using body parameters determined by fitting the apparent mass model to the mean apparent mass at different input magnitudes. This analysis suggested that 0.33 Hz of the 0.41 Hz decrease in the seat transmissibility resonance frequency, when increasing the input magnitude from 0.5 to 1.5 ms^{-2} r.m.s, was caused by the non-linearity of the body.

Interaction with a backrest affects apparent mass (e.g. see Chapter 4) and also influences seat transmissibility (e.g. see Chapter 9). However, changes in seat transmissibility with changes in backrest condition are not easily predicted. Changes in backrest contact and backrest inclination change the posture of the seat occupant and the dynamic response of the body, but they also alter the mechanical properties of the seat by changing the area of the body in contact with the seat and the compression of the cushion. Furthermore, as both apparent mass and seat transmissibility are affected by the type of backrest (e.g. foam or rigid; Chapter 4 and Appendix B) appropriate apparent mass values, which take into account the mechanical properties of the backrest, should be used to predict transmissibility. In Chapter 9, apparent mass and seat transmissibility were measured with two different seats, resulting in some differences in subject posture and backrest properties between the seats. Consequently, it was not possible to determine the relative contributions of changes in apparent mass and changes in the dynamics stiffness of the seat on the seat transmissibility.

Some differences in seat transmissibility have been observed when subjects varied the positions of their arms or feet (see Sections 2.3.4 and 2.3.5). As with changes in backrest interaction, changes in the position of subjects' arms and feet affect the distribution of weight on the seat and therefore are likely to affect the effective dynamic stiffness of the seat. Ideally predictions of seat transmissibility should take into account the influence of these effects.

Table 10.1 Summary of findings from experimental studies. Unless stated otherwise, subjects sat in a relaxed upright posture, with no backrest support, hands in lap and were exposed to broadband random vibration at 1.0 ms^{-2} r.m.s. (all findings statistically significant).

Authors	Subjects, Conditions, Stimuli	Findings
Chapter 4 Effect of backrest	**Subjects:** 12 males, 21 to 48 years **Backrest:** Rigid backrest @ 0, 5, 10, 15, 20, 25° 100-mm foam backrest @ 0, 5, 10, 15, 20, 25° 50 and 150-mm foam backrests @ 0, 10, 20, 30° No backrest	- Making contact with an upright rigid or foam backrest reduced the mass supported on the seat surface - Contact with either upright backrest had little effect on resonance frequency - Resonance frequency increased from 5.47 to 6.35 Hz as rigid backrest was reclined from 0 to 30° - Resonance frequency decreased from 5.18 to 4.49 Hz as 100-mm foam backrest was reclined from 0 to 30° - Thickness of foam on the backrest had greater influence on apparent mass as the backrests were reclined - With the backrest reclined to 20° or 30° increasing foam thickness reduced the resonance frequency
Chapter 5 Effect of steering wheel and footrest	**Subjects:** 12 males, 22 to 48 years **Backrest:** Rigid backrest @ 15°, No backrest **Hand positions:** Hands in lap, Hands on 'steering wheel' (5 horizontal positions, 3 vertical positions) **Foot positions:** 5 horizontal positions **Steering wheel force:** 5 forces applied to the steering wheel **Footrest force:** 5 forces applied to the footrest	- Additional resonance at 4 Hz when subjects held steering wheel - 4-Hz resonance became more pronounced as hands were moved away from body - Little effect of vertical steering wheel position - Moving feet further from the body increased mass on the seat surface - Increasing force on steering wheel or footrest reduced the apparent mass at resonance
Chapter 6 Effect of input spectra	**Subjects:** 12 males **Broadband vibration:** 0.125, 0.25, 0.4, 0.63, 1.0 and 1.6 ms^{-2} r.m.s. **Narrowband vibration:** narrow bands at ½-octave intervals (from 1 to 16 Hz) each at 5 magnitudes (0.25, 0.4, 0.63, 1.0 and 1.6 ms^{-2} r.m.s.) superimposed upon low-level broadband vibration (0.25 ms^{-2} r.m.s.)	- Resonance frequency decreased from 5.8 to 4.6 Hz as broadband magnitude increased from 0.125 to 1.6 ms^{-2} r.m.s. - Nonlinearity was found with all nine narrowband input frequencies.

		- Vibration magnitude had the greatest effect on the resonance frequency and resonance magnitude when narrowband components were added near the resonance frequency
Chapter 8 Effect of subject characteristics on apparent mass	**Subjects:** 80 (41 males, 39 females), 18 to 65 years, 46 to 103 kg **Backrest:** No backrest, rigid backrest@15°, foam backrest@15° **Vibration:** 0.5, 1.0, 1.5 ms^{-2} r.m.s.	- Subject mass had greatest effect on apparent mass at 0.6 Hz, at resonance, and at 12 Hz - Subject age, BMI and gender were predictors of apparent mass resonance frequency: - Subject age: up to 1.7 Hz increase from 18 to 65 years - BMI: up to 1.7 Hz increase from 18 to 34 kgm^{-2} - Gender: Males up to 0.57 Hz higher than females - Age and mass affected apparent mass at 12 Hz - Little effect of backrest condition or input magnitude on inter-subject variability or associations of physical characteristics with apparent mass characteristics - Variability at resonance reduced by normalisation: no effect of subject weight on normalised apparent mass
Chapter 9 Effect of subject characteristics on seat transmissibility	**Subjects:** 80 (41 males, 39 females), 18 to 65 years, 46 to 103 kg **Seat:** Car seat **Backrest:** Backrest @ 15° or No backrest **Vibration:** 0.5, 1.0, 1.5 ms^{-2} r.m.s.	- Age was the only predictor of seat transmissibility resonance frequency and transmissibility at resonance - No significant effects of weight on seat transmissibility - Seat stiffness increased to compensate for effects of additional sitting weight on seat transmissibility - Non-linearity of the body accounted for most of the non-linearity in seat transmissibility - Seat transmissibility resonance frequency and transmissibility at resonance increased when subjects made contact with a backrest

10.2 CONCLUSIONS

There were large and systematic changes in the vertical apparent mass of the seated human body with changes in backrest support, hand and foot position, and input spectra.

The resonance frequency of the body increased slightly when the back was supported by either an upright rigid or upright foam backrest. Reclining a rigid backrest increased the resonance frequency but reclining a foam backrest decreased the resonance frequency. When subjects held a steering wheel, the mass supported on the seat surface decreased and there was an additional resonance at 4 Hz in the apparent mass. Moving the steering wheel away from the body reduced the apparent mass at resonance and increased the apparent mass around the 4 Hz resonance. As the feet moved forward, the mass supported on the seat surface increased, indicating that the backrest and footrest supported a lesser proportion of the subject weight. Applying force to either the steering wheel or the footrest reduced the apparent mass at resonance and decreased the mass supported on the seat surface. The body is non-linear with vibration magnitude, the resonance frequency decreasing as the magnitude is increased. The extent of this nonlinearity was found to be dependent on the predominant excitation frequency: the magnitude of vibration at frequencies less than 4 Hz has the greatest effect on the apparent mass at resonance, while vibration at frequencies less than 8 Hz has the greatest effect on the resonance frequency.

A simple lumped parameter model was able to represent closely the measured changes in the apparent mass with seating environment by changes to the parameters in the model. Trends in model parameters, identified as a function of the model variables, allow the apparent mass to be predicted for unmeasured conditions.

The physical characteristics of 80 seated adults affected their apparent masses and the transmission of vibration through a seat on which they sat. Multiple regression models showed that subject age was a strong predictor of apparent mass resonance frequency - as age increased from 18 to 65 years, the apparent mass resonance frequency increased by up to 1.7 Hz. This change was greater than the 0.9-Hz increase in resonance frequency between sitting without a backrest and sitting with a rigid backrest reclined to 15° and greater than the 1.0-Hz reduction in resonance frequency when the magnitude of vibration increased from 0.5 to 1.5 ms^{-2} r.m.s. Subject age was also much the strongest predictor of the seat transmissibility resonance frequency and the transmissibility at resonance. The strongest predictor of the vertical apparent mass at 0.6 Hz, at resonance, and at 12 Hz was body weight, but weight was not strongly associated with seat transmissibility. A lumped parameter seat-person model was used to show that the dynamic stiffness of the seat increased with increased loading so as to compensate for increases in apparent mass associated with increased sitting weight.

10.3 RECOMMENDATIONS

International Standard 5982 (2001) gives idealized values for the apparent masses of seated people exposed to vertical vibration. The standard presents an 'averaged' response of several datasets acquired in broadly similar measurement conditions. Currently, the values do not take into account the large effects of posture, input excitation, and variability between subjects, reported in the data here. One approach to representing this variability might be to apply corrections directly to the idealized values in the standard to take into account deviations from a 'standard' condition. However, in practice this might be difficult to implement, particularly when combining multiple factors that might affect the apparent mass. An alternative approach would be to use an adjustable parameter model such as that described in Chapter 7. By fitting the response to a 'standard' condition, then identifying trends in model parameters as a function of the model variable (i.e. backrest angle, age, input magnitude, etc.), the response could be corrected so that it is able to represent a range of conditions and subject groups. While it has been demonstrated that a simple lumped parameter model is able to represent systematic changes in individual variables (i.e. backrest type, backrest angle, foot position, hand position, and excitation magnitude), further research is required to see whether these effects can be superimposed to represent conditions where several factors deviate from a 'standard' condition.

The simple lumped parameter model used in Chapter 7 could be fitted to the individual apparent mass responses of each of the 80 subjects. Trends in model parameter could then be identified as a function of each physical characteristic; these trends may lead to further insights into the biodynamic causes of inter-subject variability. A further advantage of fitting the model to individual apparent masses is that each curve can be represented by a set of four model parameters, allowing concise representation of the responses.

Older subjects tended to give higher seat transmissibility resonance frequencies. In general vibration below approximately $\sqrt{2}$ times the resonance frequency of the seat is amplified by the seat (see Section 2.3.1) and therefore seats occupied by older subjects will tend to amplify vibration to a higher frequency. The strong association between subject age and seat transmissibility implies that when designing seats for a particular demographic group the influence of the age of the target population should be considered. Likewise when measuring the transmissibility of seats, a subject group should be chosen with a similar age distribution to the target population.

Subject weight was not found to have an important influence on seat transmissibility in this study. While further work is required to detail the relationship between subject physical characteristics and seat transmissibility on other seats, particularly the influence of subject weight, this research implies that the apparent mass of the body normalised with respect to sitting weight may be sufficient to define the response of models for predicting the transmissibility of conventional foam cushion seats. Furthermore, there appears little justification in developing anthropodynamic dummies to represent different weight groups (e.g. 5th and 95th percentile) for testing conventional non-suspended seats.

Methods have been developed to predict seat transmissibility from measurements of the dynamic stiffness of a seat and the apparent mass of the body. Current methods propose that a preload is applied to the seat representative of the seated weight of the represented subject or subject group, with the preload applied through a fixed shape indenter. In practice, the contact area and pressure distribution on a seat will vary between subjects – factors that will affect the seat dynamics and hence the prediction of seat transmissibility. By using indenter heads representative of the target population, predictions may be improved. However, since subject weight was not a predictor of seat transmissibility it may not be necessary to measures the dynamic stiffness of conventional seats at more than one preload.

Further research is required to determine whether the changes in seat transmissibility observed when a subject interacts with a backrest, holds a steering wheel, or adjusts the position of their feet, can be explained by changes in their apparent mass. Measurements of apparent mass and seat transmissibility made with subjects sitting in the same seating environment could establish the relative influence of changes in the dynamics of the body and changes in the dynamics of the seat on seat transmissibility. One approach to this would be to predict the transmissibility of a seat from the apparent mass measured on a flat rigid seat, but with subjects adopting the 'correct' backrest, hand support, and foot support. However, as there are some indications that the apparent mass of the body is different on a compliant seat compared to a rigid seat (e.g. Fairley and Griffin, 1986), this may affect the accuracy of any prediction. An alternative approach would be to measure the apparent mass and seat transmissibility simultaneously in the same compliant seat. Two methods have been proposed to determine apparent mass in a compliant seat (see Section 2.2.4.5). The first is to use a dynamic pressure mat to measure the dynamics force on the seat surface (e.g. Hinz *et al.* 2006). The second method is to subtract the apparent mass of the seat from the combined apparent mass the seat and person (e.g. Fairley and Griffin; 1986). However, both these methods require further research to assess their feasibility and any limitations in their use.

APPENDIX A: USE OF AN ANTHROPODYNAMIC DUMMY TO MEASURE SEAT DYNAMICS

A.1 INTRODUCTION

Recent research has developed devices that present a seat with the same vertical impedance as a human subject (i.e. an anthropodynamic dummy). Because of the inherent stiffness and damping of the human body, replacing a subject with a rigid mass of the same weight as the body does not give an appropriate loading. It has been shown by Mansfield (1998) and Lewis (1998) that devices based on a single degree-of-freedom mass, spring damper system can give similar measured of vertical seat isolation results to those obtained human subjects.

Various anthropodynamic dummies have been developed and tested on either car seats or suspension seats (e.g. Suggs *et al.*, 1969; Matthews, 1967, Mansfield, 1998). The non-linearities in dummy response with changes of input magnitude in the previous devices have restricted the application of dummies to either low magnitudes (e.g. car seats) or higher magnitudes (e.g. suspension seats). A dummy that can provide representative impedance of the human body over a range of magnitudes (and automotive applications) is desirable.

To some extent it could be desirable to use an anthropodynamic dummy with a slightly incorrect impedance if it gave a measure of seat dynamic performance that is more repeatable than that obtained with human subjects. The variability in seat response with subject impedance currently makes it difficult for the automotive industry to specify seat performance. An important measure of comparison of the performance of anthropodynamic dummies with subjects is therefore the comparative variability in results.

This study was conducted to assess the performance of a newly developed dummy. The assessment was undertaken by comparing the transmissibilities (and SEAT values) of three different seats when measured using human subjects and the dummy. In addition, the results are compared with those obtained using an equivalent rigid mass.

A.2 METHODS AND PROCEDURES

The anthropodynamic dummy is shown in Figure A.1. It consisted of a 46.0kg moving mass constrained to move vertically on two steel precision shafts. These shafts were attached to aluminium top and base plates to make up a 7.4kg static mass. Four compression springs were fitted between the moving mass and the base plate, with a combined stiffness of 24800 N/m. A low friction viscous dashpot damper was mounted between the moving mass and the top plate. In a previous study (Lewis, 1998) the device had been shown to give linear response (i.e. little variation in apparent mass) over a range of input magnitudes appropriate for seat testing. A SIT-BAR (Whitham and Griffin, 1977) was fitted to the base and to the back of the dummy in order to interface the dummy with seat. The backrest support was articulated to allow the angle and position of the dummy on the seat to be adjusted.

Figure A.1 Anthropodynamic dummy

The dynamic performances of three seats were evaluated. The seats were chosen so as to encompass a range of possible applications: a foam cushion car seat, a long stroke (65mm) suspension seat and a short stroke (40mm) suspension seat.

The transmissibilities of the seats were determined using a broadband vibration (0.25 to 40 Hz) with approximately equal energy at each frequency, over the measured range. The magnitude of the input signal was 1.2 ms^{-2} r.m.s. for the automotive seat and 2.0 ms^{-2} r.m.s. for both suspension seats.

The seat effective amplitude transmissibilities (SEAT values) of each seat were also calculated. The SEAT values was defined as the ratio of the vibration dose value (VDV) measured on the seat surface compared to the VDV measured on the floor. The VDV is given by:

$$VDV = \left[\int_{t=0}^{t=T} a_{\omega}^{4}(t)dt \right]^{1/4} \qquad \text{A.1}$$

where, $a(t)$ is the frequency-weighted acceleration using frequency weighting W_k (International Organization for Standardization, 1977). The SEAT value gives a measure of the effectiveness of the seat in improving the ride comfort for a particular input spectrum. SEAT values for the car seat were calculated using acceleration time histories recorded at the seat attachment point in a car driven over a development test track. For the suspension seats, pseudo-random acceleration time histories, with shaped power spectral densities conforming to applicable classes in ISO 7096 (2000) were used.

An *HVLab* acquisition system was used to generate the acceleration time histories and output an analogue signal to a 1m vertical electro-hydraulic actuator. Entran EGCSY-240D*-10 accelerometers were used to measure *z*-axis vibration at the seat guide and at the base of the dummy. With human subjects (and the rigid mass), vibration on the seat surface, beneath the ischial tuberosities of the subject was measured using an *HVLab* SAE pad. Acceleration signals were conditioned and acquired directly into the *HVLab* system at 200 samples per second via anti-aliasing filters set at 50 Hz.

In the first experiment, transmissibility and SEAT values for each seat were determined when loaded with: (a) three human subjects, (b) the anthropodynamic dummy and (c) the rigid mass. The three human subjects weighed 70, 53 and 82 kg. The mean subject mass was 68.7 kg and the mean age 24.7 years. The rigid mass was made up of bags of lead shot to 53.2 kg. The input signals for each seat are given in Table A.1.

Table A.1 Acceleration signals used in the tests. (EM3 – Wheel loader, EM5 – Wheel dozer, Soil Compactor, Backhoe loader, EM8 – Compact Loader, EM9 – Skid steer loader.)

Seat	Broadband magnitude (m/s^2 r.m.s.)	Input 2	Input 3
Automotive	1.2	Road data - car 1	Road data – car 2
Long-stroke suspension	2.0	EM3	EM5
Short-stroke suspension	2.0	EM8	EM9

In the second set of measurements, the inter-subject and intra-variability of seat dynamics with subjects was compared to that obtained with the dummy and with the rigid mass. These measurements were conducted with the long-stroke suspension seat. To establish inter-subject variability, seven subjects (6 male, 1 female) were used, with a mean age and weight of 28.8 years and 73.9 kg.

Intra-subject variability was measured using a single subject (aged 40 years, weight 73 kg), the dummy and the rigid mass; each measured seven times. Between runs, the subject was asked to stand up, reset the driver weight adjustment to the minimum position, sit back down, then readjust the suspension to the 'correct' position. Between runs the dummy and the rigid mass were lifted off the seat, the driver weight adjustment was reset, the dummy repositioned on the seat, and finally the weight adjustment adjusted to the 'correct' position.

A.3 RESULTS AND DISCUSSION

A.3.1 Comparison of results with subjects, dummy and mass

Figures A.2 to A.4 show the transmissibility of each seat measured with three subjects, with the dummy and with rigid mass. The SEAT values calculated for each of these seats and loadings are summarised in Table A.2.

Table A.2 Comparison of SEAT values with subjects, dummy and rigid mass

Seat type	Input	Subject 1	Subject 2	Subject 3	Average	Dummy	Mass
Foam cushion car seat	Car 1	0.62	0.71	0.79	0.71	0.71	1.05
	Car 2	0.63	0.74	0.89	0.75	0.79	1.09
Short-stroke suspension	EM8	1.14	1.02	1.08	1.08	1.01	1.18
	EM9	0.93	0.77	0.86	0.85	0.82	0.98
Long-stroke suspension	EM3	0.71	0.67	0.72	0.70	0.71	0.83
	EM5	1.06	0.96	1.10	1.04	1.01	1.24

Automotive seat

With the automotive seat, the natural frequency measured with the dummy is close to that measured with the subjects (Figure A.2). The seat transmissibility measured with the dummy generally lies within the range obtained with the human subjects. However, around 8 Hz, the transmissibility obtained with the subjects shows a second resonance and the response is greater than that measured with the dummy. As a single degree-of-freedom device, it is unrealistic to expect the dummy to reproduce this second resonance sometimes seen with human subjects. The resonance of the transmissibility of the seat measured with the rigid mass occurred at higher frequency, and with a much greater amplification, than with the subjects. With both inputs, loading the seat with the dummy yielded similar SEAT values to the average of that obtained with the three subjects. With the rigid mass on the seat the SEAT values were significantly higher than with the subjects.

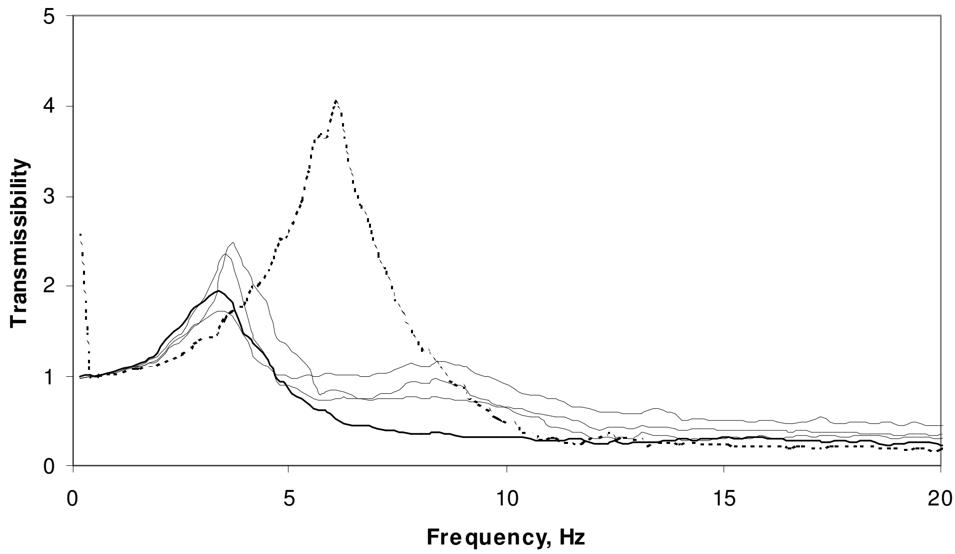

Figure A.2 Seat transmissibilities for foam-cushion car seat measured with: —— subjects; ━━, anthropodynamic dummy; - - - -, rigid mass.

Long-stroke suspension seat

The transmissibility of the long-stroke suspension seat is shown in Figure A.3. The dummy accurately reproduced the magnitude and frequency of the primary seat resonance measured with the subjects. Again the response with the dummy lies within the responses obtained with the subjects at most frequencies, except around the second resonance. Although the magnitude of the primary resonance measured with the rigid mass is similar to that obtained with the subjects, it occurs at a higher frequency and has a much broader peak. At frequencies greater than 11 Hz the mass underestimated the transmissibility compared to that measured with the subjects. With both input spectra, the SEAT values calculated with the dummy gave similar results to those obtained with the subjects, but in both cases the SEAT values were slightly underestimated. The mass gave significantly higher SEAT values for both inputs, although the overestimation was not as great as with the automotive seat.

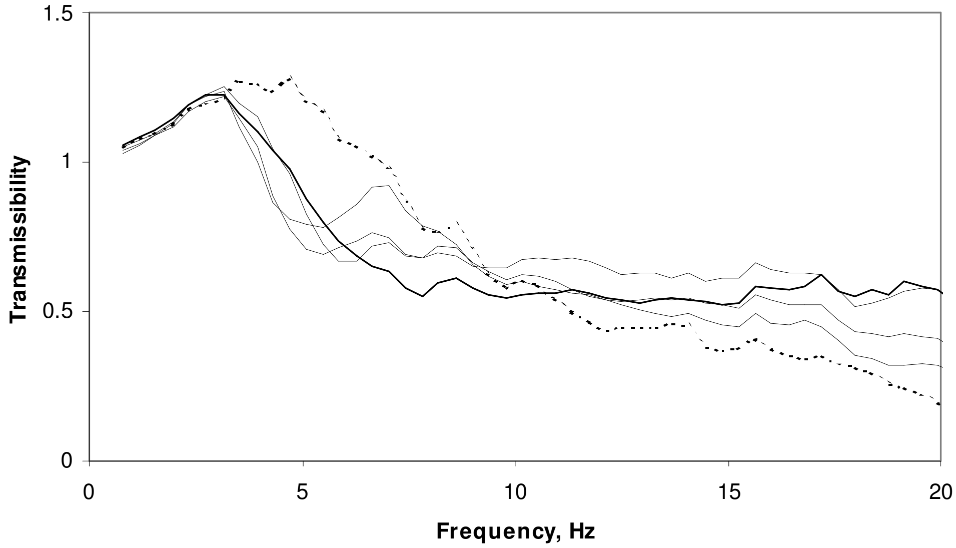

Figure A.3 Seat transmissibilities for long-stroke suspension seat measured with: —— subjects; ▬▬, anthropodynamic dummy; - - - -, rigid mass.

Short-stroke suspension seat

The measured transmissibility of the short-stroke suspension is shown in Figure A.4. The response of the dummy lies within the range of subject response at frequencies up to 16 Hz. The second subject resonance seen in the other two seats is less pronounced and therefore the dummy was able to reasonably replicate the response around this region. The seat transmissibility measured with the rigid mass again shows a much broader peak than that observed with the subjects and the resonance occurred at higher frequency. The SEAT values with the dummy were close to those measured with the subjects.

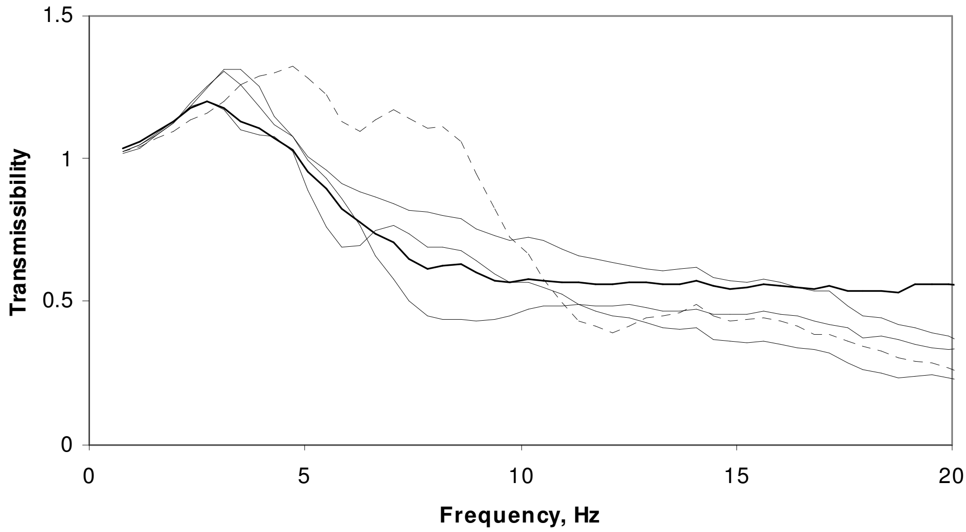

Figure A.4 Seat transmissibilities for short-stroke suspension seat measured with: —— subjects; ▬▬, anthropodynamic dummy; - - - -, rigid mass.

A.3.2 Repeatability of results with subjects, dummy and mass

In Figure A.5, the transmissibility of the long stroke suspension seat, loaded with seven subjects, is compared to the mean transmissibility, over seven runs, with the anthropodynamic dummy and the rigid mass. The seat transmissibility with one subject, measured seven times, is compared to the mean response of the dummy and the rigid mass in Figure A.6. Seven measurements with the anthropodynamic dummy and the rigid mass are compared to the mean seat transmissibility obtained with the seven subjects in Figure A.7 and Figure A.8 respectively. SEAT values measured on the long-stroke suspension seat, for subjects, the anthropodynamic dummy and the rigid mass are presented in Table A.3.

Table A.3 Repeatability in SEAT values measured with subjects, dummy and rigid mass

Run	7 subjects	1 subject (7 runs)	Dummy (7 runs)	Mass (7 runs)
1	0.67	0.66	0.68	0.83
2	0.71	0.67	0.69	0.82
3	0.72	0.67	0.70	0.85
4	0.67	0.69	0.70	0.82
5	0.70	0.71	0.71	0.84
6	0.71	0.70	0.71	0.85
7	0.61	0.69	0.71	0.83
Max	0.72	0.71	0.71	0.85
Min	0.61	0.66	0.68	0.82
Average	0.68	0.68	0.70	0.83

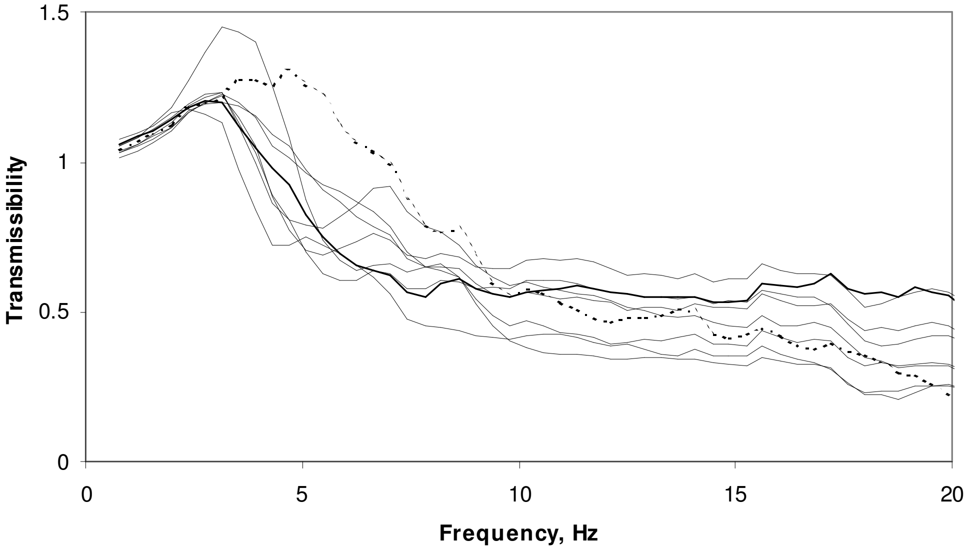

Figure A.5 Repeatability in measurements of seat transmissibility using 7 subjects (long stroke suspension): —— subjects; ▬▬, mean of 7 runs with dummy; - - - -, mean of 7 runs with rigid mass.

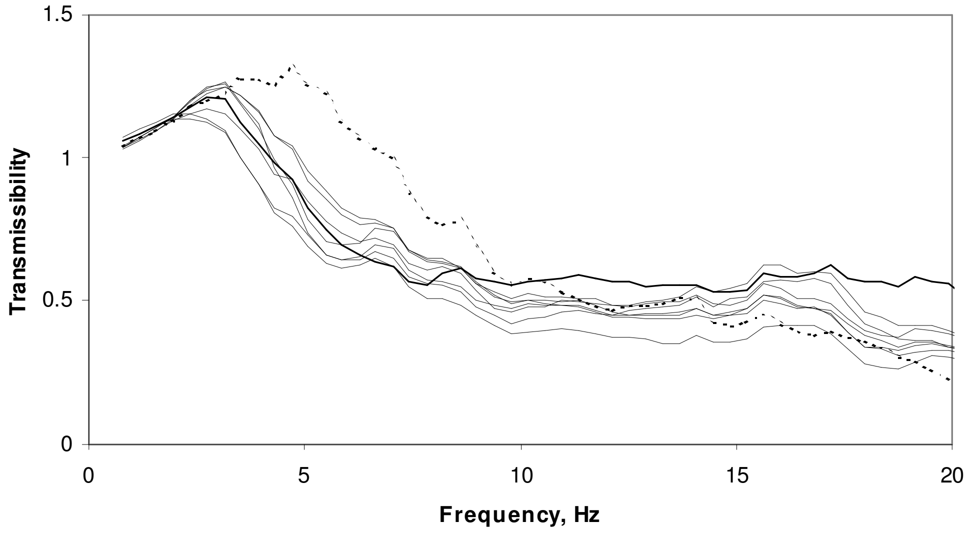

Figure A.6 Repeatability in measurements of seat transmissibility using one subject 7 times (long stroke suspension): —— subject; ▬▬, mean of 7 runs with dummy; - - - -, mean of 7 runs with rigid mass.

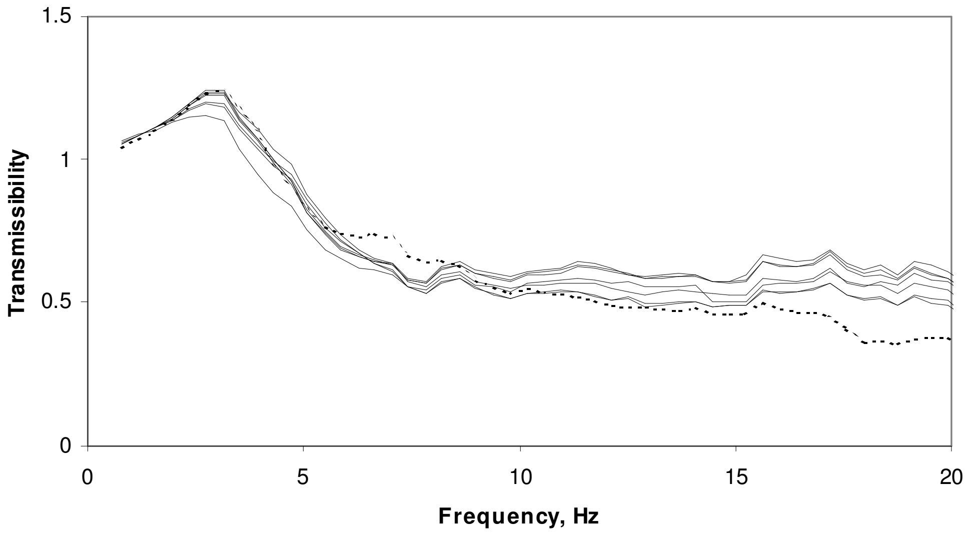

Figure A.7 Repeatability in measurements of seat transmissibility using anthropodynamic dummy 7 times (long stroke suspension): ——, dummy; - - - -, mean of 7 subjects.

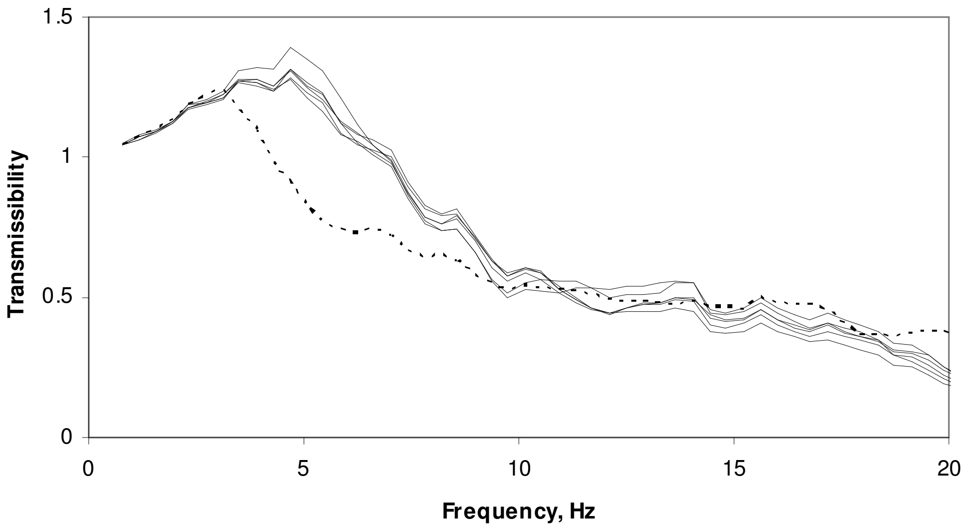

Figure A.8 Repeatability in measurements of seat transmissibility using rigid mass 7 times (long stroke suspension): ——, rigid mass; - - - -, mean of 7 subjects.

Transmissibility

Figure A.5 shows that at frequencies above 2 Hz there was a large amount of variability in the transmissibility measured with the seven different subjects. The frequency of the primary resonance was similar for all subjects but the transmissibility at resonance varied from 1.18 to 1.45. The transmissibility associated with the second peak in the transmissibility also varied between subjects and, in some cases, was almost nonexistent. With one subject seven times the repeatability of the transmissibility measurements was far greater, showing that the variability in Figure A.5 is due primarily to inter-subject variability and not inter-subject variability. The transmissibility measured with the dummy was more repeatable than using seven different subjects and even more repeatable than using one subject seven times. At all frequencies up to 16 Hz, the seat response measured with the dummy follows the mean response obtained with the seven subjects. Transmissibilities measured with the rigid mass were highly repeatable over repeat runs but, between 3 and 10 Hz, the measured seat transmissibilities were higher than with subjects.

SEAT values

Average SEAT values over seven runs with the dummy and over seven subjects were similar. However, the range of values calculated with the subjects was much greater than with the dummy. SEAT values calculated for repeat runs with one subject were spread over a slightly greater range than with the dummy. The rigid mass yielded repeatable SEAT values over the seven runs but the SEAT values were far greater than those obtained with subjects.

A.4 CONCLUSIONS

The transmissibilities of three seats loaded with subjects and the dummy were similar at frequencies below about 20 Hz. The first seat resonance measured with the dummy had a similar frequency and transmissibility to that obtained with human subjects. All three subjects showed a second lesser resonance around 8Hz that was not reproduced with the dummy; this was more apparent for the car seat than the suspension seats. When the car seat was loaded with a rigid mass, the transmissibility at resonance was much higher and occurred at higher frequency than with the human subjects. For the suspension seats the resonance measured with the mass occurred with a similar transmissibility to that with human subjects but at a higher frequency and with a broader peak. For all three seats, the SEAT values calculated with the dummy were similar to the mean values calculated with the subjects. The SEAT values obtained with the rigid mass were greater than those obtained with subjects, particularly for the car seat.

The dummy gave more repeatable results than using different subjects or repeat testing using the same subject. Although the rigid mass gave reproducible measurements of seat transmissibility and SEAT values, the seat transmissibilities were not consistent with those obtained using human subjects.

APPENDIX B: EFFECT OF BACKREST INTERACTION ON SEAT CUSHION TRANSMISSIBILITY

B.1 INTRODUCTION

The seat and the reactive mass of the body act as a coupled dynamic system: changes occurring in the dynamic properties of the body will affect the response of the seat and, likewise, changes in the properties of the seat will affect the response of the person. Therefore it is likely that the presence and dynamic characteristics of a backrest will affect the dynamic response of the body and hence the transmission of vibration through the seat cushion. It is hypothesised that backrest bulk properties and the coupling of the back to the backrest may affect the dynamic properties of the backrest. These properties may also be affected by the angle of inclination of the backrest relative to the seat cushion. This paper describes an experiment to investigate the effect of different backrests and different angles of inclination of backrests on the transmission of vertical vibration through a seat cushion.

B.2 METHODS AND PROCEDURES

A rigid seat with the facility to adjust backrest angle was used for all tests. A foam squab of dimensions 480mm X 480mm X 100mm was stuck to the seat surface. Attachments were secured to the seat back so as to alter the backrest condition; these could be implemented without affecting the posture of the subject. The general arrangement and location of transducers are shown in Figure B.1.

The seat was attached to the platform of a 1m-stroke vertical electro-hydraulic actuator in the Human Factors Research Unit at the Institute of Sound and Vibration Research. An *HVLab* acquisition system was used to generate the acceleration time histories and output an analogue signal to the actuator. An Entran EGCSY-240D*-10 accelerometer was used to measure *z*-axis vibration on the vibrator platform. Vibration on the seat surface, beneath the ischial tuberosities of the subject, was measured using an *HVLab* SAE pad. Acceleration signals were conditioned and acquired directly into the *HVLab* system, at 400 samples per second, via anti-aliasing filters set at 50 Hz.

The transmission of vibration through the seat was measured with different backrest conditions, these are summarised in Table B.1. The transmissibilities of the seat were determined using a broadband input (0.25 to 40 Hz) with a flat constant bandwidth spectrum. The magnitude of the unweighted input signal on the vibrator platform was 1.0 ms^{-2} r.m.s.

All conditions were tested with the backrest at 90° to the seat surface; in addition the 'soft-foam' and 'stuck-to-rigid backrest' conditions were also tested with the seat back inclined to 100° and 110°. For measurements made with 'no backrest contact' the seat back was removed. In the case of measurements with foam backrests, a block of foam was attached with hook-and-loop tape to the seatback; the 'soft foam' and 'hard foam' blocks measured 480mm X 480mm X 100mm. The 'soft-foam covered' condition was facilitated using a piece of fabric stretched over the front surface of the foam block and attached to the ends with hook-and-loop tape. In the 'stuck-to-rigid backrest' condition the subjects skin was effectively stuck to the backrest surface in shear by using a high friction rubber compound adhered to a rigid backrest surface. The 'lubricated' condition was intended to minimize the contact friction between the subject and the backrest; cosmetic oil was applied to a smooth plastic surface of a plate attached to the seat back to facilitate this.

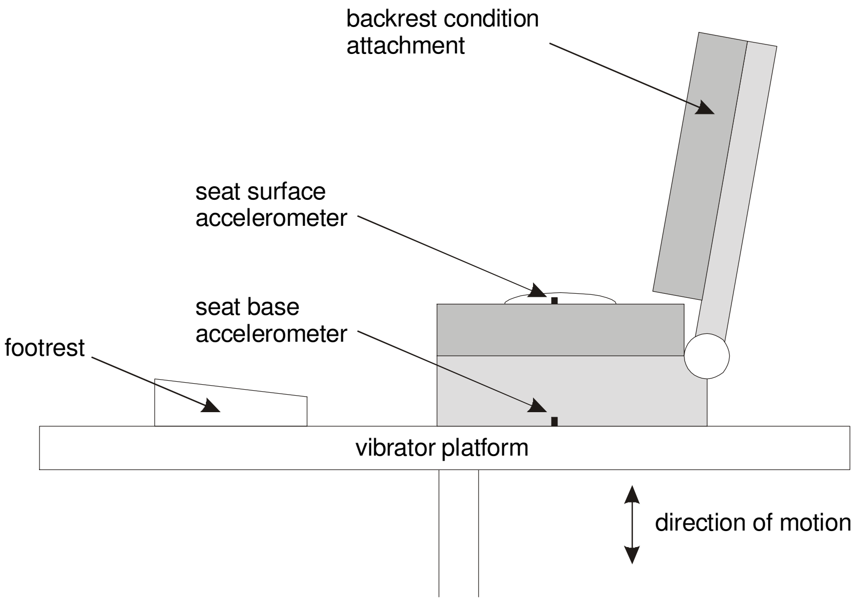

Figure B.1 General arrangement for seat and transducers

Table B.1 Test conditions and backrest angles

Backrest angle	No backrest contact	Soft foam backrest	Soft foam covered	Hard foam backrest	'Stuck' to rigid backrest	Lubricated rigid backrest
90	X	X	X	X	X	X
100		X			X	
110		X			X	

Measurements of transmissibility of the seat cushion were made using 12 male subjects. Subjects removed their tops; this ensured the subjects' skin interacted directly with the backrest surface. Subjects were instructed to sit in a 'relaxed comfortable but upright posture', with their hands resting in their laps. Subject characteristics are described in Table B.2. The subjects' feet rested on a footrest, at an angle of 5° relative to the platform, the heels of the subjects were 310mm below the top surface of the uncompressed seat cushion. For each subject, the distance between the seat and footrest was adjusted so that the thighs were just touching the leading edge of the seat cushion.

Table B.2 Characteristics of 12 male subjects

Subject	1	2	3	4	5	6	7	8	9	10	11	12
Age, years	37	46	26	25	33	25	41	42	29	50	26	24
Weight, kg	88	83	70	70	75	74	86	68	88	90	100	68
Height, m	1.81	1.86	1.75	1.76	1.78	1.85	1.68	1.67	1.75	1.73	1.85	1.91

Each of the 12 subjects was tested with all 10 backrest conditions in a single session, to minimize effects due to any fluctuation in environmental conditions. The order in which the backrest conditions were tested was randomised for each subject. A subject occupied the seat for 5 minutes prior to the start of each set of tests, to allow the properties of the seat cushion to stabilize.

B.3 RESULTS

B.3.1 Influence of backrest bulk properties

Figure B.2 shows the mean vertical transmissibilities measured between the platform and the SAE pad on the seat squab, with a soft-foam backrest, a hard foam backrest and the stuck-to-rigid backrest. The frequency of the primary resonance in each case is around 3.5 Hz. Motions up to around 5.0 Hz were amplified relative to the platform (transmissibility greater than one); higher frequency motions were progressively attenuated with increasing frequency. The differences were not statistically significant; in the figure, the mean transmissibility at resonance with the soft-foam backrest is slightly less than that measured with the hard foam backrest ($p = 0.433$; Wilcoxon) and the rigid backrest ($p = 0.158$).

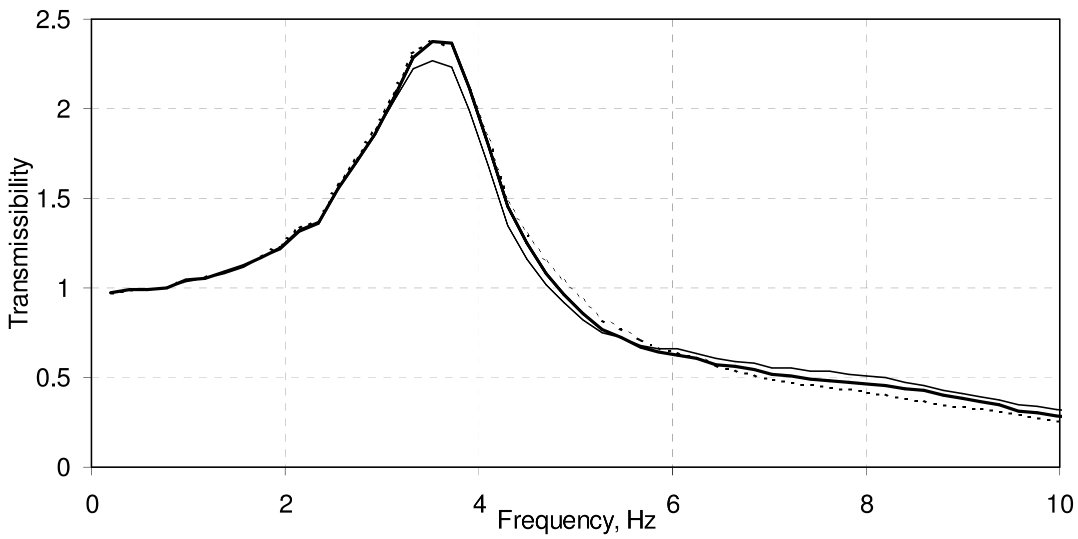

Figure B.2 Comparison of mean vertical transmissibilities, from the vibrator platform to the seat squab. Each graph shows the mean transmissibility of 12 subjects with a vertical backrest.
Hard foam backrest ——— Soft-foam backrest ———
Stuck- to-rigid backrest - - - - - - -

B.3.2 Influence of surface properties of the back and backrest

In Figure B.3 the mean vertical transmissibilities measured with four different backrest contact conditions are compared. The mean cushion transmissibilities at the resonance frequencies with the foam and 'stuck- to-backrest' conditions were similar. The transmissibility at resonance with the back 'stuck-to-backrest' was only slightly higher than in the condition in which the backrest was lubricated, however this difference was found to be significant (p = 0.015). When no contact was made with the backrest, the transmissibility around the primary resonance was significantly lower than with the other three backrest conditions ($p < 0.01$). The frequency at which the primary resonance occurred was also reduced without the backrest ($p < 0.05$).

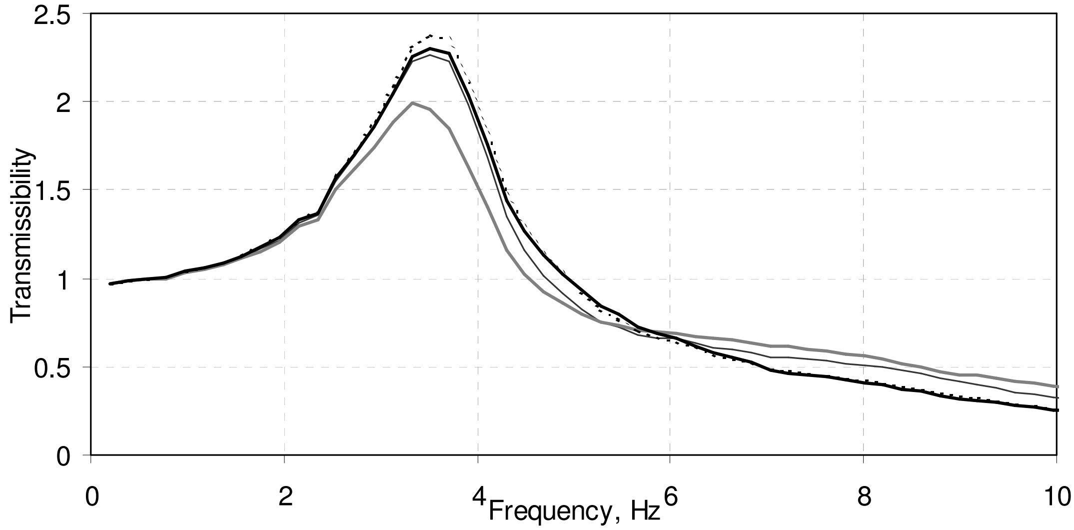

Figure B.3 Comparison of mean vertical transmissibilities, from the vibrator platform to the seat squab. Each graph shows the mean transmissibility of 12 subjects.
Soft-foam backrest ——— No backrest contact ———
'Stuck' to rigid backrest - - - - - - - Lubricated backrest ———

Figure B.4 shows the mean vertical transmissibility between the platform and the seat surface, measured with the soft-foam backrest, with and without the fabric cover over the backrest. For frequencies up to 10 Hz the transmissibilities are very similar.

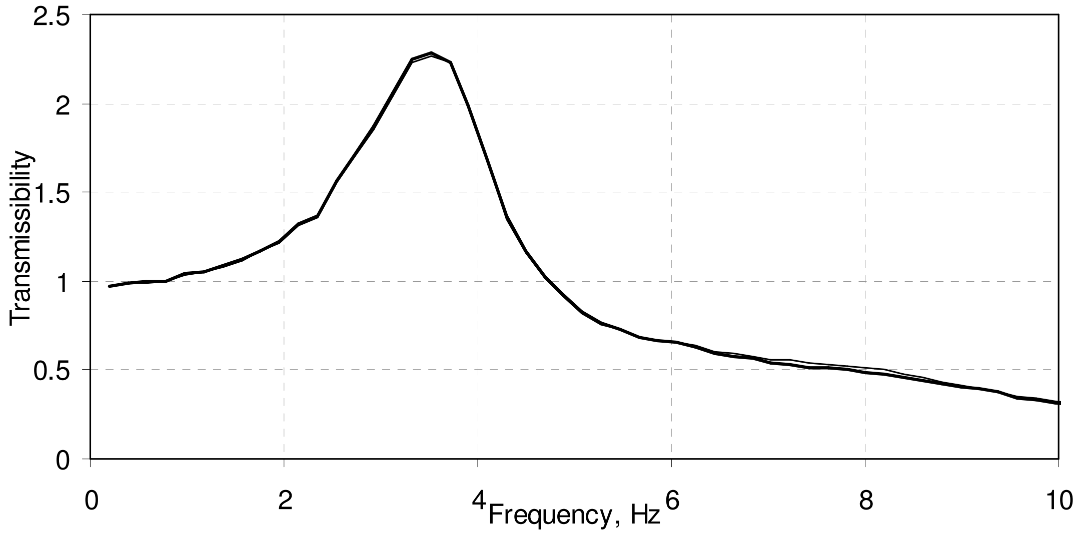

Figure B.4 Comparison of mean vertical transmissibilities, from the vibrator platform to the seat squab. Each graph shows the mean transmissibility of 12 subjects.
Soft-foam backrest ——— Covered soft-foam backrest ———

B.3.3 Influence of backrest inclination

Figure B.5 compares the mean vertical transmissibilities of the seat cushion measured with the rigid and soft-foam backrests at three angles of inclination: 90°, 100° and 110°. The level of significance of the differences in transmissibility, between pairs of backrest conditions, at the primary resonance and at 5 Hz are given in Table B.3 and Table B.4 respectively (Wilcoxon matched-pairs signed ranks test).

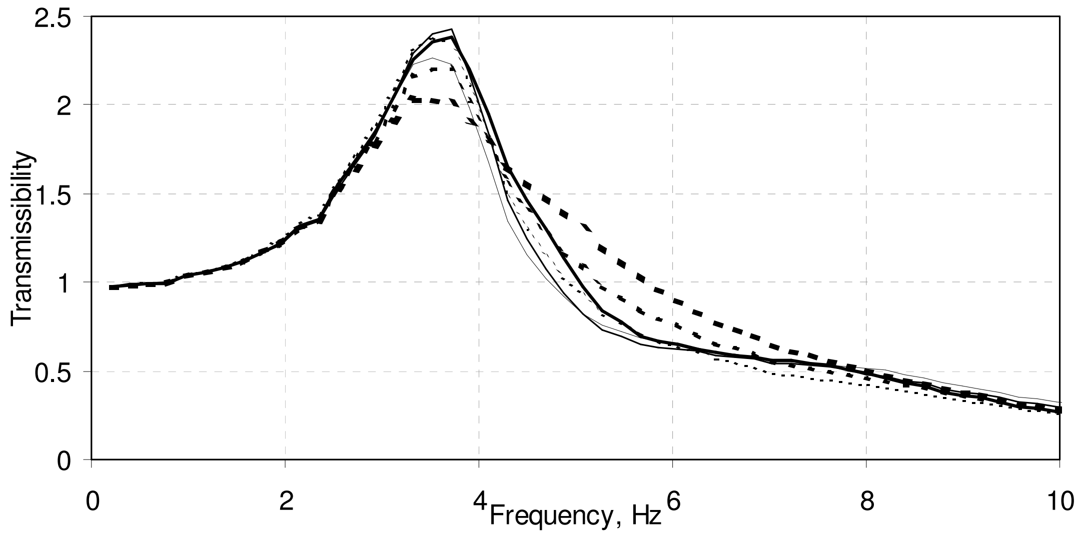

Figure B.5 Comparison of mean vertical transmissibilities, from the vibrator platform to the seat squab. Each graph shows the mean transmissibility of 12 subjects.

Soft-foam backrest 90° — Soft-foam backrest 100°

Soft-foam backrest 110° — 'Stuck' to rigid backrest 90°

'Stuck' to rigid backrest 100° — 'Stuck' to rigid backrest 110°

With the soft-foam backrest, the frequency of the primary resonance was unaffected by backrest angle. However, the transmissibility at resonance and also the transmissibility between approximately 4.5 and 5.5 Hz was affected by the backrest angle. At resonance, there was a significant difference in transmissibility with the backrest set to 100 and 110 degrees. At 5.0 Hz, the transmissibilities with backrest angles of 90 and 110 degrees, and 100 and 110 degrees were also significantly different.

When using the rigid backrest, the transmissibility at resonance decreased with increasing backrest angle. However, the transmissibility over the frequency range 4.5 Hz to 7.0 Hz increased with increasing backrest angle. Similar, although less pronounced, trends can be seen in the transmissibilities measured with the foam backrest. With the rigid backrest, significant differences in transmissibility were found between all pairs of backrest angles, both at resonance and also at 5Hz.

Table B.3 Differences in transmissibility at resonance between pairs of backrest conditions (Wilcoxon matched-pairs signed ranks test).

Condition A		Condition B		Significance, *p*
Backrest condition	backrest angle, degrees	Backrest condition	backrest angle, degrees	†$p < 0.1$ *$p < 0.05$ **$p < 0.01$
Soft foam	90	Soft foam	100	0.071†
Soft foam	90	Soft foam	110	0.754
Soft foam	100	Soft foam	110	0.028*
‘Stuck’ to, rigid	90	‘Stuck’ to, rigid	100	0.012*
‘Stuck’ to, rigid	90	‘Stuck’ to, rigid	110	0.004**
‘Stuck’ to, rigid	100	‘Stuck’ to, rigid	110	0.006**
Soft foam	90	‘Stuck’ to, rigid	90	0.158
Soft foam	100	‘Stuck’ to, rigid	100	0.002**
Soft foam	110	‘Stuck’ to, rigid	110	0.002**

Table B.4 Differences in transmissibility at 5 Hz between pairs of backrest conditions (Wilcoxon matched-pairs signed ranks test).

Condition A		Condition B		Significance, *p*
Backrest condition	Backrest angle, degrees	backrest condition	backrest angle, degrees	†$p < 0.1$ *$p < 0.05$ **$p < 0.01$
Soft foam	90	soft foam	100	0.695
Soft foam	90	soft foam	110	0.002**
Soft foam	100	soft foam	110	0.005**
‘Stuck’ to, rigid	90	‘stuck’ to, rigid	100	0.004**
‘Stuck’ to, rigid	90	‘stuck’ to, rigid	110	0.004**
‘Stuck’ to, rigid	100	‘stuck’ to, rigid	110	0.005**
Soft foam	90	‘stuck’ to, rigid	90	0.019*
Soft foam	100	‘stuck’ to, rigid	100	0.005**
Soft foam	110	‘stuck’ to, rigid	110	0.003**

B.4 DISCUSSION

B.4.1 Influence of backrest bulk properties

The results show no clear differences between transmissibility measurements with either the soft-foam backrest, the hard-foam backrest or the rigid backrest. This could indicate that all three backrest conditions present the back with a surface that is effectively rigid in shear, when compared to the soft tissues of the back.

B.4.2 Influence of surface properties of the back and backrest

When the back was in contact with the backrest there was a significant increase in seat cushion transmissibility at frequencies in the region 3.0 Hz to 5.5 Hz. The resonance frequency, and the transmissibility at resonance also increased slightly with increased backrest contact. These effects are consistent with an increase in the stiffness of the seat-body system when the seat back is fixed. It could be hypothesised that these changes occur because the presence of the backrest acts to constrain the motion of the upper body. With the lubricated backrest condition, similar although less pronounced effects on transmissibility were found. Subject's commented that they could feel their backs move relative to the lubricated backrest, particularly with the higher magnitude motions. These measurements suggest that with the lubricated backrest condition, the subjects' backs were less impeded than with the 'stuck-to-backrest' or the soft-foam backrest conditions. Lewis and Griffin (1996) found similar results using a seat with a freely suspended sliding backrest. Transmissibilities measured using this seat were found to be more similar to results with the 'back off' condition than the rigid backrest condition, although it was noted that there were postural differences between the conditions.

There were no significant differences in transmissibilities measured with the soft foam backrest, the 'stuck-to-rigid backrest' and the covered soft-foam backrest. This could indicate that in all of these conditions the back was effectively stuck to the backrest and there was no relative motion between the back and either the backrest surface, the fabric-covering or the foam cushion.

B.4.3 Influence of the backrest inclination

As the backrest angle of the seat increased, the proportion of a subject's weight supported by the seat backrest also increased and a corresponding proportion of the weight supported by the seat cushion decreased. This probably accounts for the decrease in transmissibility at resonance, with increasing backrest angle. Using a single subject, Fairley (1986) showed that the primary resonance was generally unaffected by backrest angle. However, in this study the lower legs were vertical, so that with increasing backrest angle the weight supported by a subject's feet decreased and the weight supported by the seat increased.

In the region 4.5 Hz to 7.0 Hz, the vertical transmissibility increased with increasing inclination of the backrest; this was particularly apparent with the 'stuck-to-rigid backrest' condition. As there was no corresponding increase in transmissibility below the resonance frequency, it is likely that this increase in transmissibility with increasing backrest angle was due to the second resonance, seen more distinctly in some subjects; this is consistent with the findings of Fairley (1986).

The effects of backrest inclination were more pronounced with the rigid backrest than the foam backrest. As the backrest angle is increased, the dynamic force acting in compression on the backrest surface will have increased. The difference in transmissibility between these two backrest conditions at 100° and 110° could be a result of the compliance of the foam in compression compared to the rigid backrest.

B.5 CONCLUSIONS

There were no significant differences between seat transmissibilities measured with either of the foam backrests or the rigid backrest, when the seat back was vertical (i.e. at 90°). This would suggest that the compliance of each backrest in shear was negligible when compared to that of the soft tissue of the back.

The effect of lubricating the backrest was to reduce the transmissibility at resonance. Transmissibility at resonance was also reduced when there was no contact between the subject and the backrest, but transmissibility at higher frequencies was greater with the back-off condition than when the back was 'stuck' to the backrest. A similar effect upon vibration transmitted to the seat surface could be achieved by increasing the inherent damping of the seat cushion.

The transmissibility at resonance tended to decrease with increasing backrest inclination, this was particularly apparent when using the rigid backrest. This effect may be a result of changes in weight distribution at different backrest angles. In the frequency range 4.5 Hz to 7.0 Hz, transmissibility tended to increase with increasing backrest angle; again this trend was more significant with the rigid backrest condition, and may have been a result of a second resonance in some subjects becoming more distinct.

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