UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Institute of Sound and Vibration Research

EFFECTS OF VERTICAL MECHANICAL SHOCKS AND BODY POSTURE ON DISCOMFORT

by

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ABSTRACT

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The discomfort caused by vertical vibration depends on the magnitude and frequency of vibration, but little is known about how discomfort depends on the magnitude and frequency of mechanical shocks or on body posture. The main objectives of this thesis were to advance understanding: (i) of how the discomfort caused by a vertical mechanical shock depends on the nominal frequency, magnitude, and direction of the shock and seating dynamics, and (ii) of the effects of body posture on vibration comfort when sitting and standing.

Three of the four experiments presented in this thesis investigate the discomfort caused by mechanical shocks in an upright sitting posture. The first experiment compared the frequency-dependence of discomfort caused by shocks and sinusoidal vibration in the range 0.5 to 16 Hz at vibration magnitudes less than ±9.4 ms^{-2}. A different frequency-dependence was found for shocks and for vibration, with shocks being less uncomfortable than vibration at frequencies greater than 4 Hz. The difference is explained by shocks containing energy at frequencies other than their fundamental frequency. The rates of growth of discomfort depended on frequency, indicating an effect of magnitude on the frequency-dependence of discomfort caused by shocks and vibration. A second experiment investigated the effect of shock direction (i.e., up or down) on discomfort in the range 2 to 5 Hz with peak accelerations from 7 to 11 ms^{-2}. Upward displacements at frequencies from 2 to 4 Hz were more uncomfortable than downward displacements when the peak acceleration approached or exceeded 1 g. This was explained by the human body leaving, and subsequently impacting with, the seat. A third experiment found that a three degree-of-freedom model is able to predict SEAT values of blocks of polyurethane foam when people are exposed to shocks in the range 1 to 16 Hz. Predicted and measured SEAT values were consistent with subjective responses at most frequencies and magnitudes investigated.

A fourth experiment investigated how the discomfort caused by vertical vibration depends on the frequency and magnitude of vertical vibration (0.5 to 16 Hz at 0.3 to 3.2 ms^{-2} r.m.s.) in four postures. The frequency-dependence of discomfort was equivalent to the standardised frequency weighting W_b when sitting upright, sitting leaning forward, and standing with straight legs. When standing, bending the legs increased discomfort in the range 2 to 4 Hz but reduced discomfort at frequencies greater than 5 Hz, consistent with the effects of bending the legs on biodynamic responses.

There are four main findings from the research reported in this thesis: (i) The same methods can be used to predict the discomfort caused by shocks and vibration but the optimum frequency weighting for evaluating shocks depends on the shock magnitude; (ii) Shocks with fundamental frequencies in the range 4 to 16 Hz cause less discomfort than vibration of the same frequency and magnitude; (iii)The SEAT value is a useful predictor of seat comfort and a three degree-of-freedom model can be used to predict SEAT values of occupied foam cushions during exposures to vertical shocks in the range 1 to 16 Hz with peak accelerations less than 1g; (iv) The frequency-dependence of discomfort caused by vertical vibration is similar in normal standing and when sitting upright or sitting leaning forward, but differs when standing with bent legs.

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DECLARATION OF AUTHORSHIP

I, GIULIA PATELLI ....

declare that the thesis entitled

Effects of vertical mechanical shocks and body posture on discomfort

and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
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7. Parts of this work have been published as:

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Patelli G., Morioka M. and Griffin M.J.(2013). A review of how the discomfort caused by vertical mechanical shocks depends on the shock waveform. 48th UK Conference on Human Response to Vibration, Stihll Ltd., Ascot.

Signed: ....

Date:...

Acknowledgements

After having written more than 60000 words, I have not many words left but I certainly have some sincere gratitude to express.

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Chapter 1: INTRODUCTION

In environments where people are exposed to whole-body vibration and mechanical shocks, the assessment of vibration and mechanical shocks in relation to the risks to health and comfort can assist the safeguarding of their health and their comfort.

The evaluation of vibration exposures should take into account the axis, the duration, and input location of the motions and should conform to standardised guidance for assessing vibration and mechanical shocks, as presented in either British Standard BS 6841:1987 or International Standard ISO 2631-1:1997. Although the Standards provide useful guidance, they assume that the discomfort caused by vertical continuous vibration and the discomfort caused by vertical mechanical shocks have the same frequency-dependence within the range 0.5 Hz to 80 Hz and they do not allow for any effects of different sitting postures or different standing postures.

The frequency weightings advocated in the standards for evaluating vibration and mechanical shocks have been influenced by studies of vibration discomfort caused by sinusoidal vibration (e.g., Griffin et al., 1982; Corbridge and Griffin 1986). Recent studies have shown the effect of frequency on the discomfort caused by vertical shocks (Ahn and Griffin, 2008; Zhou and Griffin, 2016a). These studies have also found that the frequency-dependence of the equivalent comfort contours changed with the magnitude of the shocks. However, there are no known studies that made a direct comparison of the discomfort caused by vertical continuous vibration and the discomfort caused by vertical shocks. Consequently, it is not clear whether the frequency-dependence of the discomfort caused by vibration is equivalent to the frequency-dependence of the discomfort caused by shocks and whether it is possible to apply the same frequency weighting to both types of motion.

Previous studies have found that changes in body posture affect both the biodynamic responses of the body (e.g. Paddan and Griffin, 1993; Matsumoto and Griffin, 2000a; Mansfield and Griffin, 2002; Subashi *et al.*, 2006) and the subjective responses of seated and standing people exposed to vertical vibration (e.g. Thuong and Griffin, 2011; Basri and Griffin, 2012, 2013). In relation to changes in standing postures a note in Section 4 of British Standard 6841:1987 warns that the methods applied when standing with a normal posture might not be appropriate when standing with the legs bent. Due to limitations in past research and uncertainty in the standards, it is not yet clear the extent to which the discomfort caused by vibration depends on posture when sitting and standing.

The main objectives of this work are (i) to advance understanding of how frequency, magnitude, direction (i.e. up or down) and seat dynamics influence the discomfort caused by vertical mechanical shocks, and (ii) to advance understanding of the effects of sitting and standing posture on the discomfort caused by vertical vibration.

This thesis is structured into 9 Chapters.

Chapter 1 introduces the scope of the research and the advance in understanding that is desired.

Chapter 2 reviews studies that have investigated the effects of body posture, and the magnitude, frequency, and direction of vertical motions on subjective and biodynamic responses of people. It shows why this research is needed and gives a critical point of view of what is known and what is not known yet about human response to vertical vibration and mechanical shocks.

Chapter 3 describes the research methods and the equipment used for experimental work.

Chapter 4 is an experimental chapter. It investigates and compares the discomfort caused by vertical vibration and the discomfort caused by vertical mechanical shocks.

Chapter 5 is an experimental chapter. It investigates the effect of direction and magnitude of vertical mechanical shocks on discomfort.

Chapter 6 is an experimental chapter. It investigates the discomfort caused by vertical mechanical shocks when a soft seat is used. It proposes a method for predicting the effects of a seat on motion discomfort from measurements and predictions of SEAT values.

Chapter 7 is an experimental chapter. It focuses on the effect that variations in sitting and standing postures have on vibration comfort.

Chapter 8 discusses the results obtained during the experimental work presented in this thesis.

Chapter 9 presents the main conclusions of this thesis and proposes future research.

Chapter 2: LITERATURE REVIEW

2.1 Introduction

This chapter will introduce previous literature about the main topics of this thesis. The scope of this chapter is to give to the reader a clear picture of what it is known about the effects of posture on human responses to vibration and of what it is known about exposure to vertical high magnitude mechanical shocks. At the same time it will underline the gaps in present research and will justify the need for the work described in the thesis.

2.2 Vibration discomfort

2.2.1 Introduction, context and definitions

There are many environments in daily life where people are exposed to vibration: buildings, roads, vehicles or work environments. The frequent exposure to vibration leads to questions about whether vibration might be harmful to people and how the severity of a motion can be evaluated.

Epidemiological studies suggest that vibration exposure may cause the occurrence of long term injuries in humans (e.g., Bovenzi and Hulshof, 1999). However, the nature of the consequences on human health due to a prolonged exposure to vibration makes judging the severity of a motion a challenging task. In order to predict the human response to vibration, one area of research has focused on modelling and predicting the forces along the spine and another area tries to relate the physical characteristics of a motion to the subjective perception of that motion.

Before starting to discuss details about the effects that vibration might have on humans it is relevant to give some basic notions of what vibration is and how it is measured.

Vibration can be defined ”*mechanical oscillation about an equilibrium point”* (BS ISO 2041:2009). Vibration can be categorized into deterministic vibration (periodic or non-periodic), where the future variation in time of the motion can be precisely predicted from past history, or random vibration, where the future variation in time of the motion can only be estimated through statistical approaches. A simple example of deterministic and periodic motion is the sinusoidal vibration, which is characterized by a single frequency component. A mechanical shock can also be a deterministic motion and can be defined as a “*non-periodic excitation of a mechanical system that is* *characterized by suddenness and severity and usually causes significant relative displacements in the system*“(Harris and Piersol, 2001).

Besides any terminology, a motion is defined by its frequency content and magnitude. The magnitude of a motion can be expressed in many ways: in terms of displacement, velocity, acceleration, or jerk. Having chosen displacement or velocity or acceleration or jerk, the magnitude could be expressed in terms of root-mean-square (r.m.s., definition in Section 2.6), peak, peak-to-peak or vibration dose value (VDV, definition in Section 2.6). The choice of one of these ‘quantities’ depends on the motion itself, since the magnitude should be representative of the motion. If, for example, 60 seconds of acceleration recording contain 5 short shocks with peak acceleration greater than 2g and duration less than 1 second, calculating the r.m.s. over the whole period could underestimate the intensity of the shocks. On the other hand, if 60 s of acceleration recording contains 60s of Gaussian broadband random vibration, calculating the peak acceleration over the whole period won’t reflect the accumulation of its characteristics over time. The crest factor is defined as:

$$\text{Crest factor} = \frac{\text{peak acceleration}}{\text{r.m.s.acceleration}}$$

For crest factors greater than 6 (BS 6841:1987) or 9 (ISO 2631-1) the standards recommend the used of the vibration dose value, VDV.

When assessing vibration in relation to effects on health and comfort, acceleration should be used as the primary quantity to express the magnitude of the vibration, and the choice of using r.m.s. or VDV may be decided on the basis of the crest factor.

The evaluation of discomfort is the subject of this study and the main method to investigate human response to mechanical shocks and vibration. The following paragraphs discuss and describe possible factors that affect the discomfort caused by mechanical vibration and shocks.

2.2.2 Rating the vibration discomfort: scales and methods

2.2.2.1 Scaling methods and psychophysical laws

The study of vibration discomfort belongs to the branch of psychology’s known as psychophysics. Psychophysics is the science that studies the relations between perception and external stimuli. The central issue of Psychophysics has always been the measurement of the sensory magnitude and the definition of a psychophysical law that expressed the mathematical relationship between the subjective sensation and the intensity of a stimulus. The most important progress in this field was achieved in the early 1850's by the physicist Gustav Fechner, who proposed methods to measure the subjective sensation experimentally and the first psychophysical law. He proposed indirect scaling methods based on the discrimination between slightly different intensities of a stimulus (just noticeable difference, JND). From his experimental results he proposed a linear relationship between the subjective magnitude, Ψ, and the logarithm of the physical magnitude, φ, of a stimulus, through a constant *k:*

$$\Psi = k \log \varphi \qquad (1)$$

Besides indirect scaling methods, direct scaling methods are based on direct measurements of the sensation of an input stimulus through the observers' judgements (Gescheider G. A, 1997). Ratio scaling methods are a subcategory of direct scaling methods and are based on ratio relationships between different magnitudes of sensation, such as the method of magnitude estimation refined by Stanley Smith Stevens (1956) and the method of magnitude production. That means, for example, that if a motion produces twice the discomfort of another motion, the ratio between the two sensations will be 2:1 and the rating (i.e. the number) given to the first motion will be two times the rating given to the second motion. Experiments measuring brightness and loudness proved the inadequacy of Fechner's law and led to the formulation of Stevens' power law in the late 1957 (Stevens, 1957). Stevens' power law is expressed in equation (2) and assumes that the sensation (i.e. subjective) magnitude, ψ, of a stimulus is proportional to the n^{th} power of the physical magnitude of the stimulus, φ, through a constant *k.*

$$\Psi = k \varphi^n \qquad (2)$$

In equation 2 the exponent, n, is called the 'rate of growth' of sensation (e.g. discomfort) and k is a constant.

The validity of Stevens' power law was demonstrated also in vibration discomfort (e.g. Shoenberger and Harris, 1971; Jones and Saunders, 1974). In Jones and Saunders' (1974) study 60 subjects sat on a hard wooden seat and were exposed to pairs of sinusoidal vibration (one reference and one test stimulus) in the range 5 to 80 Hz. They were asked to judge how many times the test motion was more intense than the reference. The same experiment but with ten subjects and frequencies in the range 5 to 40 Hz was repeated with a standing posture. When plotting the sensation magnitudes as a function of the vibration magnitude on a logarithm scale they produced straight line growth functions with high correlation coefficients (average of about 0.8 across frequencies) with both postures indicating the validity of Stevens' power law.

2.2.2.2 Psychophysical methods for assessing vibration perception

Below, the application of Steven's power law and other methods to quantify the magnitude of sensation will be explained for measuring the discomfort due to exposure to vibration. Advantages and disadvantages of the different methods will be discussed.

The first studies that attempted to quantify the perception of vibration are dated around 1930-40 (Reiher and Meister, 1931; Jacklin and Liddell, 1933; Helberg and Sperling 1941; Goldman, 1948). In many of these early studies observers used semantic labels to judge the discomfort caused by a motion (e.g. 'perceptible', 'unpleasant', 'intolerable'). Commonly, the choice of semantic labels is different between different studies and this may lead to two main problems. First, subjects can interpret differently the meaning of each label and this could generate a large individual variability (Fothergill and Griffin, 1977a). Second, different studies can use different attributes. This would make it difficult to compare the results from different studies. Figure 2.1 is extracted from Hanes (1970) and shows the equivalent comfort contours obtained by several investigators, in both sitting and standing postures.

Some divergence between findings can be noticed even when similar labels are used. For example, the curves obtained by Olley (1934) and Jacklin and Liddel (1933, early) refer to the same attribute of discomfort (i.e. 'uncomfortable'), although they show quite different patterns. Furthermore, in semantic scales it is not possible to establish a quantitative relationship between the points of the scale (for example how much "noticeable" differs from "unpleasant"). On the other hand, there are practical advantages in using semantic scales. They can be easily understood by subjects, they are less time-consuming and for this they are often used in surveys or questionnaires.

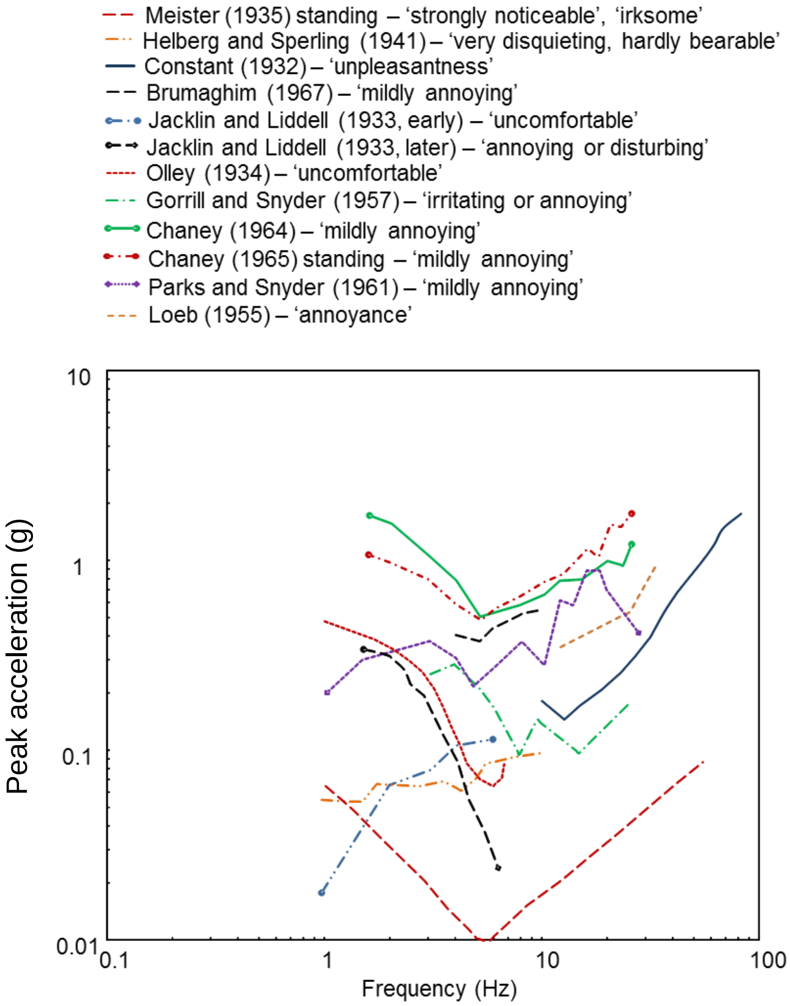


Figure 2.1 The graph shows the equivalent comfort contours obtained in different studies where semantic labels where used to judge the discomfort. Figure extracted by Hanes (1970).

The method of magnitude estimation has been broadly used to evaluate vibration discomfort. Magnitude estimation is a scaling method where the observer gives a direct numerical estimation of the psychological magnitude of series of stimuli (Stevens, 1956). Two main approaches of this method are: absolute and relative magnitude estimation. In relative method of magnitude estimation (RME), subjects experience pairs of stimuli (reference-test, or vice versa). The subjects are asked to judge the discomfort caused by a test vibration relatively to the discomfort caused by a reference vibration. Therefore, if a subject assigns a rating of 100 to the reference and perceives the test vibration to be half as uncomfortable as the reference, its subjective rating is probably going to be 50. Magnitudes and frequencies of test stimuli are usually presented in a random order among subjects. In absolute magnitude estimation (AME), subjects are exposed to a random sequence of test stimuli, separated by a short time interval, during which the subject gives a judgment. This method is said to be fairly free of biases such as those due to the order or the number of stimuli (Zwislocki and Goodman, 1980). Recently, Huang and Griffin (2014) designed a study to test whether the two methods (i.e. RME and AME) gave similar responses to noise and vibration. The study was structured into two sessions. In each session the two methods were applied alternatively to judge noise and vibration. After finishing the whole experiment each subject was asked to indicate the preferred method, depending on whether the stimulus was noise or vibration. Both the relative magnitude estimation and the absolute magnitude estimation were repeatable. Absolute magnitude estimation produced less inter-subject variability in the rate of growth of discomfort during exposure to vibration, whereas it produced a greater inter-subject variability in the rate of growth during exposure to noise. However, the two methods lead to similar results, leaving the option of choosing either one or the other method, although the majority of the subjects found it easier to use RME than AME.

Other techniques for rating discomfort caused by vibration were developed, such as the ‘method of magnitude adjustment’ and the ‘method of constant stimuli’. In the method of adjustment, subjects are usually presented with pairs of reference-test stimuli and asked to adjust the amplitude level of the test vibration in order to produce similar discomfort caused by the reference. This method has been demonstrated to produce less variability than semantic scales (Fothergill and Griffin, 1977a) but subjects may find it more difficult to rate the discomfort using the method of adjustment rather than using semantic scales. Sometimes, the experimenter can adjust the magnitude of vibration depending on the response of the subject, as in the ‘method of limits’. The ‘method of constant stimuli’ (Griffin *et al.,* 1982, Parsons and Griffin, 1982), adopts a single standard reference motion and all the test stimuli are judged in relation to it.

Taking into account the validity of Stevens’ power law in vibration discomfort, the repeatability of the method and its quickness (e.g. Huang and Griffin, 2014) when considering a large set of stimuli, this research mainly used the method of absolute magnitude estimation.

2.3 Effect of vibration magnitude on human response to vibration

2.3.1 Effect of vibration magnitude on discomfort caused by shocks and vibration

The relation between the physical magnitude, φ, of a motion and the subjective response, ψ, to the same motion can be expressed by Stevens' power law (Section 2.2). From equation 2 using a logarithmic transformation, the following equation is obtained:

$$\log_{10}\psi = n\log_{10}\varphi + \log_{10}k \qquad (3)$$

In equation 3, n and k represent, respectively, the slope and the intercept of the linear regression between $\log_{10}\psi$ and $\log_{10}\varphi$. The exponent n is therefore representative of the rate of increase in discomfort with increasing magnitude.

If the frequency dependence of the acceleration required to get similar discomfort across frequencies did not depend on the level of vibration magnitude, the exponent n should be constant across a frequency range.

In early studies, the exponent n appeared to be independent of the frequency of vibration and to be about unity, with sinusoidal vertical vibration (Jones and Saunders, 1974; Fothergill and Griffin, 1977b) and vertical mechanical shocks (Howarth and Griffin, 1991). These studies used the method of magnitude estimation to obtain discomfort judgements, although Fothergill and Griffin also used the method of magnitude production.

More recently, Morioka and Griffin (2006 a, b) found that the rate of growth of discomfort was not constant over the range of frequencies from 2 to 315 Hz during fore-and-aft, lateral, or vertical whole-body vibration. During whole-body vertical vibration, twelve subjects judged the discomfort caused by 2-s duration sinusoidal stimuli at the preferred one-third octave centre frequencies between 2 and 315 Hz relative to the discomfort caused by a 2 s reference motion at 20 Hz with a magnitude of 0.5 ms^{-2} r.m.s. The psychophysical relationship used by the authors to obtain the rate of growth of discomfort and the equivalent comfort contours is described in equation 4 and is a modified version of Stevens' power law in equation 3.

$$\log_{10}\psi = n\log_{10}(\varphi - \varphi_0) + \log_{10}k \qquad (4)$$

In equation 4, φ_0 is the sensation threshold at each frequency obtained in the same study and it represents the magnitude below which vibration is not perceived. The rate of growth of discomfort and equivalent comfort contours for vertical vibration are shown in Figure 2.2. The frequency-dependence of the rate of growth caused the variation in the ‘shape’ of the equivalent comfort contours shown in the figure with increasing magnitude. At frequencies with lower values of *n*, the vibration magnitude must be increased more to produce the same increase in discomfort (Figure 2.3) than at frequencies with greater values of *n*. As a consequence, equivalent contours will be further apart at these frequencies. At frequencies with higher values of *n*, a smaller increment in magnitude is sufficient to produce the same increase in discomfort (Figure 2.3) than at frequencies with lower values of *n*. As a consequence, the equivalent contours will be closer together at these frequencies. In Figure 2.2 it seems that the area of greatest sensitivity shifts to lower frequencies when increasing the magnitudes (e.g. from 4 to 10 Hz with low magnitudes but 2 to 5 Hz at high magnitudes.

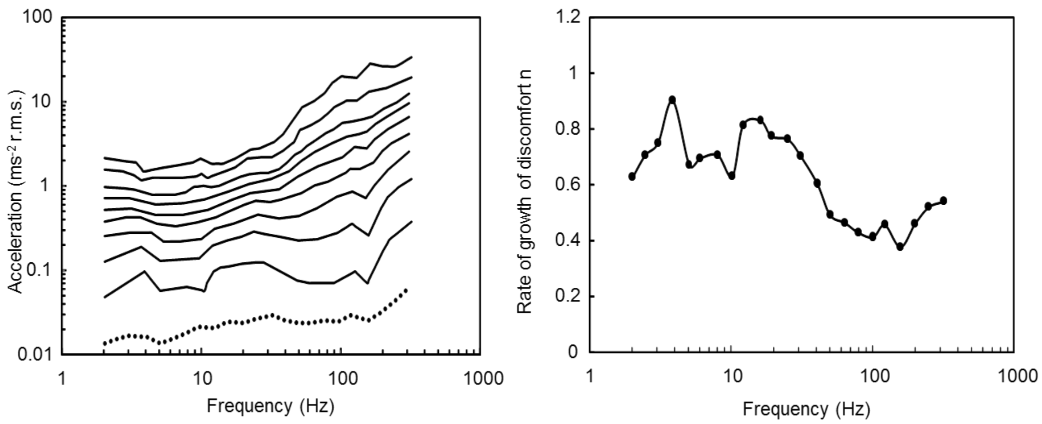


Figure 2.2 Equivalent comfort contours and rate of growth of discomfort obtained in the vertical direction in Morioka and Griffin (2006a).

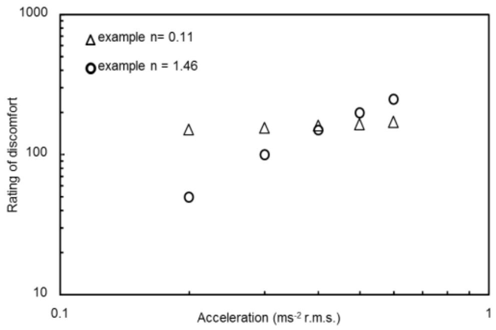


Figure 2.3 Example of the effect of having a different value of the exponent n on vibration discomfort with increasing magnitude.

The effect of vibration magnitude on the shape of equivalent comfort contours, often referred as ‘non-linearity’ in subjective response, was confirmed by studies with mechanical shocks (e.g. Ahn and Griffin, 2008; Zhou and Griffin, 2016a), a lower range of frequencies (e.g. Zhou and Griffin, 2014a), different postures (e.g. standing in Thoung and Griffin, 2011) different backrest inclinations (Basri and Griffin 2012, 2013) and roll and pitch oscillation (e.g. Wyllie and Griffin, 2009).

The effect of magnitude of vibration cannot be overlooked since it means that changing the magnitude can change the frequency of greatest severity in relation to discomfort. Although in many conditions the frequency-dependence of equivalent comfort contours changes with the magnitude of vibration, all current standards for evaluating vibration provide a single frequency weighting for all magnitudes.

2.3.2 Effect of vibration magnitude on the dynamic response of the body to vibration and shocks

Biodynamics studies the dynamic behaviour of the body exposed to vibration. An effect of the magnitude of vibration has also been observed in the dynamic behaviour of the body exposed to vibration, although this is not thought to be the prime cause of the subjective non-linearity.

Transmissibility and apparent mass are transfer functions that express the transmission of vibration through and to the body, respectively (for mathematical definitions see Section 2.7) and are thus often used in biodynamics. The non-linearity in the biodynamic response corresponds to a change of the frequency response function with a change in the magnitude of vibration.

Fairley and Griffin (1989), Mansfield and Griffin (2000), Matsumoto and Griffin (2005) found that the resonance frequency of the apparent mass for seated subjects exposed to vertical random vibration decreased from about 6 Hz to about 4 Hz when increasing the magnitude of vibration within the range 0.125 to 2.5 ms^{-2} r.m.s (Figure 2.4). Toward and Griffin (2011a) found that the mean resonance frequency of the apparent mass decreased from 5.2 to 4.7 Hz when the magnitude increased from 0.5 to 1.5 ms^{-2} r.m.s. Similar outcomes are found analysing the transmissibility from the seat to the head when a hard seat with no backrest is used. Matsumoto and Griffin (2002a) found that the resonance frequency of the median transmissibilities from vertical seat vibration to vertical vibration decreased with increasing magnitude at all locations (Head, T1, T5, T10, L1, L3, L5, pelvis). Particularly, for transmissibility from the seat to L3 it decreased from 6.25 to 4.75 Hz when the vibration magnitude increased from 0.125 and 2.0 ms^{-2} r.m.s.

Non-linearities of the apparent mass and vertical transmissibility to the head during vertical vibration were also found when a reclined rigid backrest is used (Toward and Griffin, 2011a) and in other postures, such as standing with three different upper-body postures and two different lower limb postures (Subashi *et al.*, 2006).

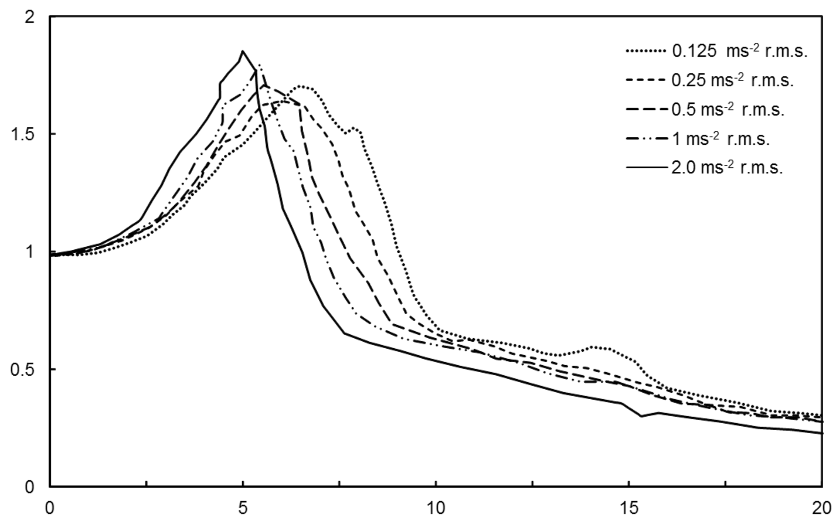


Figure 2.4 Effect of magnitude on the vertical apparent mass during vertical random vibration in the range 0.5 to 20 Hz (Matsumoto and Griffin, 2002a).

2.3.3 High magnitude vibration

It is now clear that a change in the magnitude of vibration has a non-negligible effect on the frequency-dependence of human responses to vibration, both subjective and dynamic responses. The effect of magnitude should not be overlooked when evaluating the effects of vibration on human health or comfort.

Not many studies have investigated the effect of magnitudes greater than 1 g on the discomfort caused by vertical mechanical shocks. However, oscillatory motions were investigated in early studies to understand the tolerance of people to high magnitudes (e.g., Ziegenruecker and Magid, 1959; Mandel and Lowry, 1962; Chaney 1964).

Ziegenruecker and Magid (1959) exposed 10 members of the United States Air Force (weight 65 to 95 kg; height 175 to 195 cm) to sinusoidal vibration at 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 and 15 Hz. The objective of the study was to find tolerance limits to vertical vibration. Subjects sat on a jet aircraft seat, with their arms resting on an armrest, hands gripping the extended armrest, full contact with the backrest but no contact with the headrest. Their bodies and feet were fully restrained so as not to minimise motion of the body in the vertical or horizontal directions. At each frequency, acceleration started from zero and gradually increased. Subjects were asked to stop the vibration when “they thought that actual body harm would occur”. Subjects attended 11 runs in total (one for each frequency), with two runs per day. After each exposure, subjects were also asked to indicate their symptoms and the reasons why they stopped the vibration, including: ‘abdominal pain’, ‘chest pain’, ‘testicular pain’, ‘head symptoms’, ‘dyspnea’, ‘anxiety’, and ‘general discomfort’. The median tolerance limits obtained at each frequency were about 4 g at 1 Hz, 3.5 g about at 2 Hz, 3 g at 3 Hz, 2 g from 4 to 6 Hz, 1.5 g at 7 and 8 Hz, 2.5 g at 9 and 10 Hz and about 6.5 g at 15 Hz (Figure 2.5). The median exposure duration lasted from a minimum of 18 s at 8 Hz to a maximum of 208 s at 3 Hz. The most of the subjects reported that the tolerance limit was reached well after one of the symptoms first occurred. At frequencies from 1 to 4 Hz, the most frequent symptoms were dyspnea or general discomfort, where the general discomfort was described as ‘sensation of muscles, joints, thorax and abdomen being torn or falling apart’. Increases in heart rate and blood pressure were also found after each run.

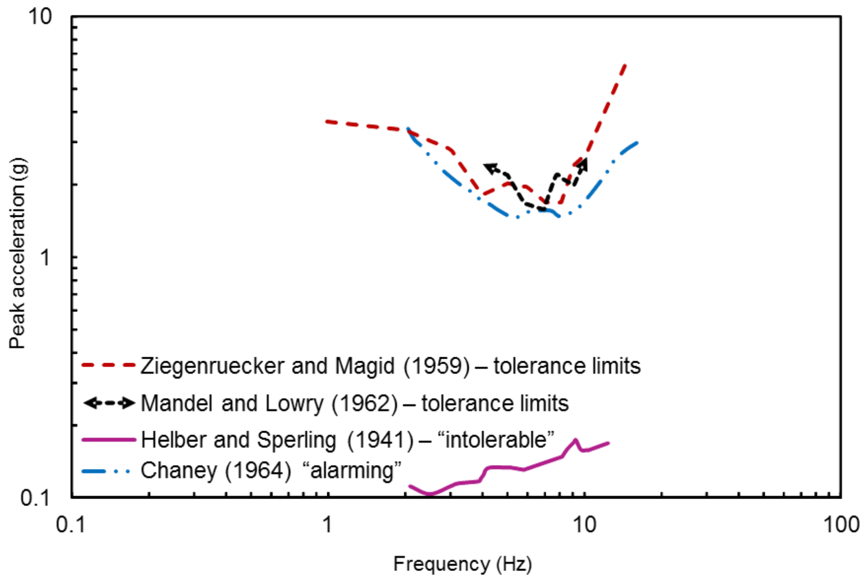


Figure 2.5 Equivalent comfort contours in terms of peak acceleration from previous studies.

Tolerance limits similar to the levels found by Ziegenruecker and Magid (1959) were also produced by Mandel and Lowry (1962) and Chaney (1964). Mandel and Lowry (1962) exposed 22 male subjects (weight 63 to 105 kg, 165 to 188 cm) to vertical sinusoidal vibration at 4, 5, 6 , 7 ,8, 9, and 10 Hz. Subjects sat comfortably with full contact with the backrest and their arms resting on an armrest. Their bodies and feet were fully restrained. At each frequency, acceleration started from zero and gradually increased until subjects reached their tolerance level and stopped the vibration. Tolerance levels ranged from about 3 g to about 1.5 g in the range of frequencies from 4 Hz to 10 Hz (Figure 2.5).

Chaney (1964) carried out subjective tests with ten male employees (weight 68 to 98 kg; height 165 to 190 cm) of the airplane division of an airplane company. Subjects were exposed to vertical vibration at 1, 1.5, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 23, 27 Hz. Subjects sat on a soft seat cushion, their backs were supported by a low backrest at the height of the first lumbar vertebra and they were restrained by a single lap belt. Subjects sat in front of a display and they were asked to adjust the vibration amplitude in order to reproduce the sensation indicated by a label on the display screen (i.e. perceptible, mildly annoying, extremely annoying, and alarming). They were asked to give judgements with regard to vibration as a sensation and not with regard to their experience. The sensation ‘alarming’ was described as the intensity at which subjects started to ‘experience concern for their physical well-being’, with no necessity to feel any pain. Alarming sensations were reached at levels of about 2.5 g to 1.5 g from 2 to 8 Hz and from 1.5 g to 3 g from 10 to 20 Hz (Figure 2.5). At these magnitudes levels participants experienced various physical symptoms such chest pain, abdomen pain, dyspnea, etc.

Extremely different results were obtained by Helberg and Sperling (1941). Their study aimed to investigate the sensitivity of passengers to railway vibration. Twenty-five subjects sat on a wooden bench and were exposed to either horizontal or vertical oscillatory motions in the range 2 to 12 Hz. Levels of discomfort described as ‘vibration unbearable’ were encountered at vibration magnitudes ranging from 0.1 to 0.2 g in the range 2 to 12 Hz. These levels are noticeably lower than the levels found in the previous studies.

Although different psychophysical methods were used in the studies mentioned above, other observations can be made about the differences between the studies. In studies with high levels of tolerability to vibration, the participants worked in environments characterised by high levels of acceleration (e.g. pilots, air force employees). It can be expected that common railway passengers may have tolerance limits lower than military officers. Although in some studies the participants were explicitly asked to judge the vibration based only on their sensations, it is unlikely that people who are daily exposed to high magnitudes and trained for such situations would not be ‘biased’ by their experience. Furthermore, it is evident that high thresholds were found in extreme conditions where physical symptoms also occurred.

The above studies used sinusoidal vibration. Because there was no study showing a difference in sensation between shocks and vibration, the response of passengers to shocks with peak accelerations greater than 1 g in different directions (i.e. 'up' or 'down') is unclear.

2.4 Effect of frequency on human response to vibration

As explained in the introduction, one oscillatory motion differs from others by its magnitude (e.g. the r.m.s. of the acceleration calculated over a period of time *T*) and by its frequency content. The frequency content could be found by computing, for example, the power spectral density of the acceleration. The reaction of the body to vibration depends on the frequency of the vibration and it is therefore important to know the extent to which frequency affects human response to vibration for each direction of vibration. Regarding to the effect on health and discomfort, whole-body vibration is often restricted to the frequency range 0.5 Hz to 80 Hz, excluding the very low frequencies that cause motion sickness (i.e. below 0.5 Hz) since they are beyond the scope of this thesis. Because each frequency produces more or less discomfort and a greater or lesser biodynamic response, unweighted spectra of acceleration are not enough to judge the severity of vibration.

2.4.1 Equivalent comfort contours

A simple way to show the effect of frequency of vibration on discomfort is to expose people to a series of sinusoidal motions (i.e. single frequency vibration) of various frequencies and magnitudes and compare their sensations with the sensation caused by a reference motion of fixed magnitude and frequency (Miwa., 1967; Shoenberger and Harris, 1971; Jones and Saunders, 1972). With a constant magnitude of acceleration, different frequencies induce different discomfort, so in order to obtain the same discomfort across frequencies the acceleration must change (Figure 2.3). Equivalent comfort contours are curves that express the magnitude of vibration as a function of frequency for a constant level of discomfort. They can be constructed by making assumptions about the relationship between the subjective magnitudes (i.e. subject's feedback) and objective magnitudes (i.e. measured magnitude of vibration). It means that psychophysical laws are used to predict the vibration magnitude that causes a certain level of discomfort at each frequency (e.g. Stevens' power law). Equivalent comfort contours represent an intuitive tool to show experimental results and are often used not only to show the effect of frequency, but also to show the combined effect of other factors such as magnitude and posture (see Sections 2.2 and

2.5) since other factors may change their frequency-dependence (i.e. the ‘shapes’ of the contours).

2.4.2 Frequency-dependence for vertical whole-body vibration

Figure 2.6 shows equivalent comfort contours obtained with sinusoidal, random, and shock-type vibration in earlier and more recent studies (Dupuis *et.al.*, 1972; Griffin *et. al*, 1982; Corbridge and Griffin, 1986; Morioka and Griffin, 2006; Zhou and Griffin 2014a, 2016a). All contours were obtained with subjects in an upright sitting posture on a hard rigid seat and clearly show that the frequencies of greatest sensitivity to vertical vibration are within the range 5 to 10 Hz. Greater sensitivity corresponds to lower acceleration, since a lower acceleration is needed to produce the same discomfort as that at other frequencies. The contours rise again at frequencies greater than about 10 Hz, showing a lower sensitivity of the human body to higher frequencies in the vertical direction. This change in sensitivity makes necessary to give a specific ‘weight’ to each frequency that reflects the effect that each frequency has on discomfort and led to the idea of “frequency weightings”. Particular attention needs to be paid to the contours produced by the studies Griffin *et al.* (1982) and Corbridge and Griffin (1986) since these contributed to the implementation of the frequency weightings suggested in current standards for assessing vertical vibration and mechanical shocks (e.g. BS 6841:1987). Consequently, at frequencies where sensitivity is greater the ‘weighting factor’ must be greater (i.e. from 5 to 16 Hz).

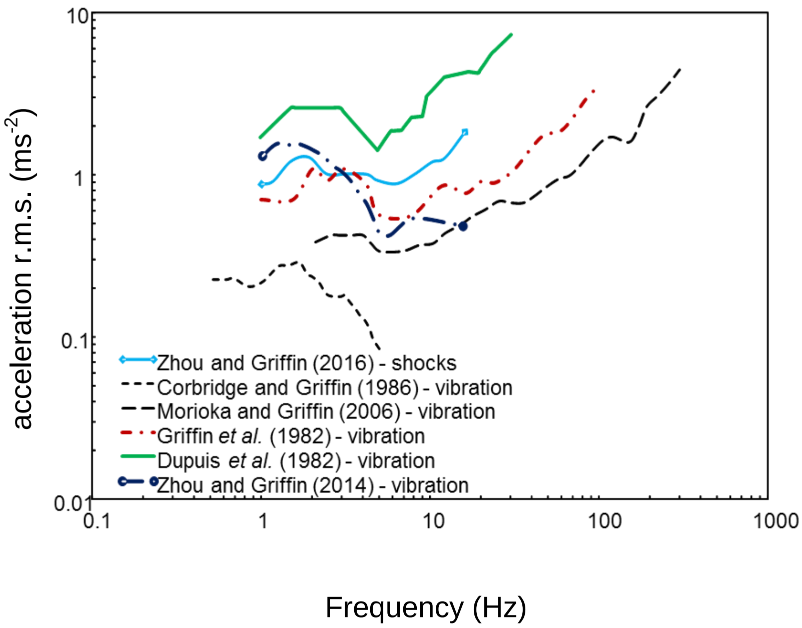


Figure 2.6 Equivalent comfort contours obtained in previous studies in terms of r.m.s. acceleration.

Research attempted to investigate whether there was a link between the discomfort and the dynamic behaviour of the body exposed to whole-body vibration. Measurements of both vertical transmissibility from seat to head and vertical apparent mass showed that they are frequency-dependent, they present a resonance peak between 4 and 8 Hz and decrease in modulus at frequencies greater than about 10 Hz (Figure 2.9; Hinz and Seidel, 1987; Fairley and Griffin, 1989; Paddan and Griffin, 1998; Mansfield and Griffin, 2000; Matsumoto and Griffin, 2002a, 2005; Toward and Griffin, 2011a; Zhou and Griffin, 2014b). In Figure 2.7 all the apparent masses were obtained by using a vibration magnitude of 1.0 ms^{-2} r.m.s., except in Zhou and Griffin (2014b) where the magnitude of vibration was 0.8 ms^{-2} r.m.s. that may explain a slightly higher resonance frequency of the apparent mass consistent to what has been discussed in paragraph 2.2. Table 2.1 presents in more detail the excitations and methods used by the different authors to obtain biodynamic responses. The range of frequencies where resonance frequencies fall seem to be in accordance with the range of frequency where people are more sensitive to vibration.

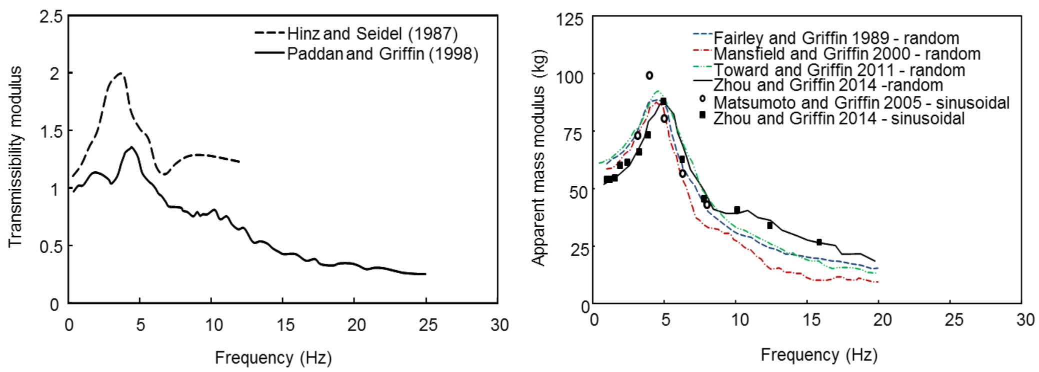


Figure 2.7 On the left measurements of median vertical transmissibilities from the seat to the head from different studies. On the right, measurements of median vertical apparent mass (modulus) from different studies. Details of magnitudes, types of excitation and postures used in the studies are summarized in Table 2.1.

Recently, statistically significant associations were found between biodynamic responses and subjective responses during exposure to vertical sinusoidal vibration (Zhou and Griffin, 2014b) in the $^{1}/_{3}{}^{rd}$ octave range 1-16 Hz and vertical sinusoidal vibration and mechanical shocks in the range 3.15–8.0 Hz (Matsumoto and Griffin, 2005). Matsumoto and Griffin (2005) found that the median normalised apparent masses (i.e. the apparent masses divided by their values at 5 Hz) were significantly correlated with the median magnitude estimates of the discomfort caused by shocks with peak acceleration 1.4 and 2.8 ms^{-2}. The median normalised mechanical impedances were significantly correlated with the median magnitude estimates of the discomfort caused by vertical continuous vibration at 0.5 ms^{-2} r.m.s. (Zhou and Griffin, 2014a) calculated the correlations between the ratio of normalised apparent masses at two frequencies and the ratio of the subjective responses between the same two frequencies for all possible pairs of frequencies investigated in the study. They found, for example, that the ratio of the apparent mass at 4 Hz to the apparent mass obtained at higher frequencies was correlated with the ratio of the magnitude estimate of discomfort at 4 Hz to the magnitude estimate of discomfort at the same higher frequencies, meaning that people who had a proportionally greater apparent mass at 4 Hz relative to their apparent mass at higher frequencies were more sensitive to 4 Hz vibration. These results suggested a link between the biodynamic response of the body and the perception of discomfort with both sinusoidal and shock-type whole-body vibration.

Exposure to sinusoidal and random vibration led to similar results characterized by a pronounced drop in equivalent comfort contours around 5 Hz. Also in terms of biodynamic responses no significant differences in the vertical apparent mass in terms of either modulus and phase have been found between sinusoidal and random vibration (Figures 2.8 and 2.9; Mansfield and Maeda, 2005a; Zhou and Griffin, 2014b).

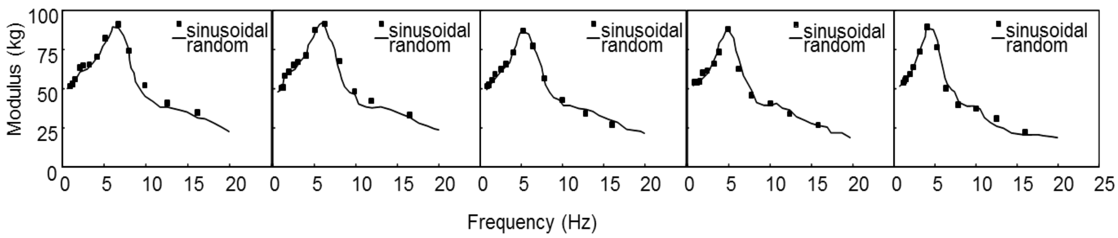


Figure 2.8 Modulus of the apparent mass obtained by Zhou and Griffin (2014b) with random vibration (▬) and sinusoidal vibration (■) at five different magnitudes 0.1, 0.2, 0.4, 0.8 and 1 ms^{-2} r.m.s. acceleration (from left to right). Random vibration had duration of 60 s and flat constant bandwidth spectrum band limited by Butterworth filter cut-off frequencies of 0.5 and 18 Hz with 24 dB/octave attenuation rate. Vertical sinusoidal motions lasted 6 s and were presented at the centre frequencies of the 1/3 octave frequency band 1 to 16 Hz. The same magnitudes were used for random and sinusoidal vibration.

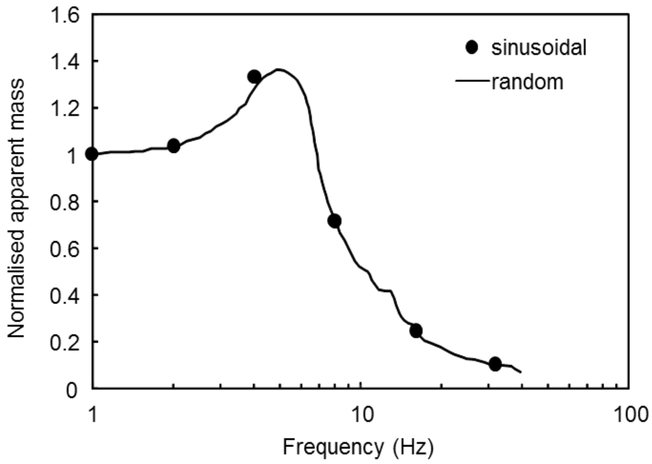


Figure 2.9 Modulus of the normalised apparent mass obtained by Mansfield and Maeda (2005) with random vibration (—) and sinusoidal vibration (●). Random vibration lasted 60 s, was characterized by a magnitude of 1.0 ms^{-2} r.m.s. (unweighted) and had equal energy at all frequencies in the range 1 to 40 Hz. Vertical sinusoidal motions were presented at the centre frequencies of the octave frequency band 1 to 32 Hz and were presented at the magnitudes listed in Table 2.1.

Table 2.1 Specification of methods and experimental setup of previous biodynamic studies. This table lists the biodynamic studies mentioned either in Section 2.2 or Section 2.3 of this Chapter 2.

Paper	Type of stimuli	Direction of vibration	Frequency range	Magnitude Range	Posture and number of subjects	Transfer function used	Type of seat	Results
Hinz and Seidel (1987)	Sinusoidal vibration	vertical	2 Hz to 12 Hz	1.5 ms^{-2} and 3 ms^{-2} r.m.s.	Erect sitting posture	Seat to head transmissibility and vertical apparent mass 4 subjects	hard shaped seat	Individual resonance frequencies of apparent mass and transmissibility occurred from 3.5 to 5 Hz and presented lower values of the modulus at the highest magnitude of vibration.
Paddan and Griffin (1988a)	60 s random vibration	vertical	0.2 Hz to 31.5 Hz	1.75 ms^{-2} r.m.s.	comfortable upright sitting posture with and without backrest contact 12 subjects	Seat to head transmissibility in all translational and rotational axes (CSD method**)	Rigid flat seat	With and without backrest the vertical axis showed a main resonance peak around 6 Hz. However, the backrest caused the increase of transmissibility in the fore-and-aft axis over the all range of frequency and almost a doubling in modulus around 7 Hz.
Fairley and Griffin (1989)	60 s random vibration	vertical	0.25 Hz to 20 Hz*	0.25 to 2.0 ms^{-2} r.m.s. * (6 dB steps)	comfortable upright sitting posture * no contact with backrest * 8 subjects *	vertical apparent mass (CSD method**)	rigid steel surface	The mean resonance frequencies decreased from 6 Hz to 4 Hz when increasing the magnitude from 0.25 to 2.0 ms^{-2} r.m.s.
Mansfield and Griffin (2000)	60 s random vibration	vertical	0.20 Hz to 20 Hz	0.25, 0.5, 1.0, 1.5, 2.0 and 2.5	comfortable upright sitting posture	vertical apparent mass	flat rigid surface	The resonance frequency of the median normalised apparent

				m s^{-2} r.m.s.	no contact with backrest 12 subjects	vertical and fore-and-aft transmissibility seat to abdomen, seat to upper abdomen, seat to lumbar spine, seat to seat to posterior superior iliac spine, and seat to iliac crest. (CSD method**)		mass decreased with each increase in vibration magnitude from about 6 Hz to about 4 Hz. Transmissibilities seat to lower abdomen showed non-linearity.
Matsumoto and Griffin (2002a)	60 s random vibration	vertical	0.5 Hz to 20 Hz	0.125 to 2.0 ms^{-2} r.m.s. (6 dB steps)	comfortable and upright posture no contact with backrest 8 subjects	Vertical apparent mass (CSD method**) Vertical, fore-and-aft and pitch transmissibilities to the head to six points along the spine (T1, T5, T10, L1, L3, L5 vertebrae) and to the pelvis.	flat rigid seat	Individual vertical apparent masses showed a main peak between 4.75 and 5.75 Hz. The resonance frequency of both apparent masses and transmissibility decreased with increasing magnitude of vibration.
Mansfield and Maeda (2005)	4 s sinusoidal vibration and 60 s random vibration	vertical	Random vibration: 1 Hz to 40 Hz Sinusoidal vibration: 1,2, 4, 8, 16 and 32 Hz	Random vibration: 1.0 ms^{-2} r.m.s. Sinusoidal vibration 1 Hz: 0.2 ms^{-2} r.m.s. Sinusoidal vibration 2 Hz: 0.4 ms^{-2} r.m.s. Sinusoidal	comfortable and upright posture 12 subjects	Vertical apparent mass (CSD method**)	rigid hard seat	For random vibration the individual apparent masses showed resonance frequencies between 4.5 Hz and 6.0 Hz, with median resonance frequency around 5 Hz. For sinusoidal vibration the most of subjects had a maximum apparent mass at 4 Hz.

				vibration from 4 to 32 Hz: 0.5 ms^{-2} r.m.s.				They found negligible differences between the modulus of the apparent mass obtained with the two types of stimulus, showing equivalence of the two methods for calculating apparent mass.
Subashi *et al.*(2006)	60 s random vibration	vertical	2 Hz to 20 Hz	0.125, 0.25 and 0.5 ms^{-2} r.m.s.	Five standing postures: Upright Lordotic Anterior lean Knees bent Knees more bent 12 subjects	Vertical and cross-axis apparent mass (CSD method**)	ridig steel platform	The vertical apparent mass resonance frequency decreased with increasing vibration magnitude in all postures.

*In the experiment where authors investigated also the effect of magnitude.

** Cross spectrum density (CSD) method. For details about the method see Section 2.7.

Above observations are consistent with the use of the same frequency weighting for both random and sinusoidal vibration (i.e. same frequency dependence).

Equivalent contours obtained in studies with shocks do not show the same characteristics found for vibration and appear flatter (Figure 2.6). Spectral densities of sinusoidal vibration are ideally characterized by single spectral lines, while for broadband random vibration the energy can be considered to be distributed over a range of frequencies (Figure 2.10). In the case of mechanical shocks neither of these requirements is satisfied. As shown in Figure 2.10, the energy in a shock is distributed over the neighbourhood of the fundamental frequency of the shock. This characteristic makes it difficult to study the dynamic response of the body during exposure to mechanical shocks by using a frequency analysis approach (e.g. apparent mass and transmissibility). The flatness of contours obtained with mechanical shocks may be due to the shocks containing energy at frequencies other than their fundamental frequency. For example a shock with a fundamental frequency where the sensitivity to vibration is greatest contains also adjacent frequency components where sensitivity to vibration is lower. The discomfort caused by the shock will depend on the combined effect of several frequencies. Because equivalent comfort contours for shocks appear to show different frequency dependence, this leads to questioning whether it is appropriate to use the same frequency weightings used for random and sinusoidal vibration. However, there are no studies yet that compare directly the subjective responses obtained with shocks and vibration, using the same experimental conditions. Since no obvious evidence is currently available, it is not possible yet to judge the suitability of standards when assessing mechanical shocks.

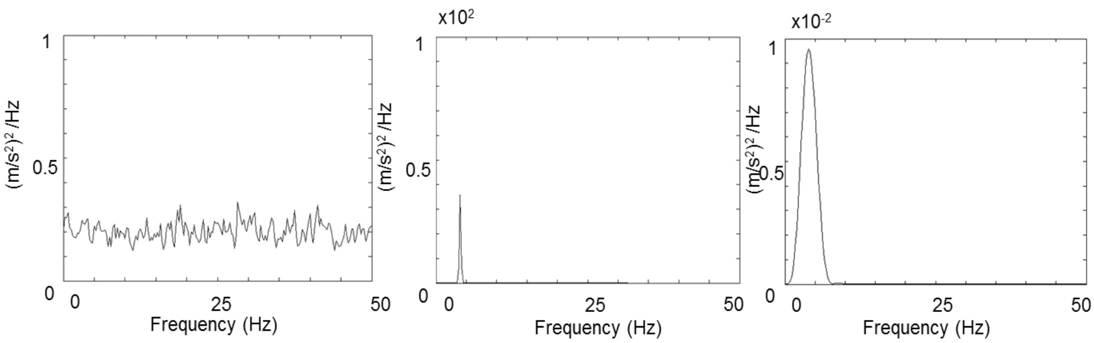


Figure 2.10 On the left, spectral density of a 60 seconds random acceleration of 3.5 m/s^2 of r.m.s and frequency band 0 to 50 Hz. At the centre, spectral density of a 6 seconds sinusoidal acceleration of 3.5 m/s^2 of r.m.s and frequency 4 Hz. On the right,

spectral density of a 1.5 cycles sinusoidal shock of 7 m/s^2 peak acceleration (around 3.5 m/s^2 of r.m.s) and fundamental frequency of 4 Hz.

2.5 Effect of duration on human response to vibration

Differences between vibrations may be characterized by different durations. Vibration could extend for a long period of time (e.g. turbulence in aircraft) or could be single short events, such as mechanical shocks (e.g. in tractors).

There has been an attempt to find the most suitable mathematical relationship between the magnitude of vibration and the duration of vibration in respect of the discomfort caused by the vibration.

Miwa (1968) used vertical and horizontal pulsed sinusoidal vibrations of durations between 0.005 to 6 s and in the frequency range 2-300 Hz, to investigate the dependence of discomfort on duration. He found the perceived intensity of vibration tended to increase, increasing the duration of the input up to a certain maximum level, at each frequency. He identified a *critical time limit,* defined as the time corresponding to this maximum value. The estimated critical time limits were about 2 s in the range 2-60 Hz, 0.8 s in the range 60-200 Hz and 0.5 s between 200 and 300 Hz. These critical times were thought to be useful to relate discomfort with time. Despite that, very few data points showed support for such a critical time (Howarth, 1986).

For many years standards to evaluate exposure to whole-body vibration suggested the use of the root-mean-square to represent the magnitude of vibration (e.g. ISO, 1978). The root-mean-square implicitly corresponds to a second power time dependency, since a^2t=constant.

It has been shown r.m.s. values are not adequate for predicting discomfort when motions present high crest factors or very short durations. Griffin and Whitham (1980 a, b) proposed a fourth power relationship, in which discomfort increased in proportion to the magnitude of vibration and the fourth root of the duration of the vibration. This is reflected by the vibration dose value:

$$\text{Vibration dose value (VDV)=}\ \left\{\int_0^T [a_w(t)]^4 dt\right\}^{1/4}$$

where $a_w(t)$ is the frequency-weighted acceleration and T is the exposure duration.

2.6 Effect of posture on human response to whole-body vibration

A change of posture presumably corresponds to a change of the mechanical properties of the body, consequently it can be expected to affect the discomfort experienced during vibration.

Some studies have focused on the effect of backrest inclination on human response to vibration, due to its broad application in automotive industry and in transports. When the body is in contact with the backrest, the angle of inclination of the backrest influences the components along the three orthogonal axes (i.e. vertical, fore-and-aft, and lateral) of the acceleration measured at the backrest. For example, when a subject is exposed to vertical vibration, the inclination of the backrest may increase the fore-and-aft component at the back and affect the comfort. During fore-and-aft vibration in the range 2 to 80 Hz, subjective responses showed that with an inclined backrest at 20° and 40° sensitivity was greater than when a vertical backrest was used (Kato and Hanai, 1998). Consistent results were found in the range 2.5 to 25 Hz, with angles of backrest of 0°, 30°, 60°, and 90° from the vertical axis (Basri and Griffin, 2011). Also during vertical vibration in the range 1 to 20 Hz, the discomfort at frequencies greater than 8 Hz increased when inclining the backrest from the vertical to up to 30°, 60°, and 90° (Basri and Griffin, 2013).

In addition to backrest inclination, the effect on human health, discomfort and dynamic response of the body to vibration with other postures, such as sitting leaning forward, twisting (Wikström, 1993) and standing (Thuong and Griffin, 2011), have been investigated.

Current standards provide methods for assessing the whole-body vibration experienced by standing, sitting, and recumbent people but do not define these postures precisely or indicate the effects of variations in these postures (British Standards Institution, 1987; International Organization for Standardisation, 1997). It is not clear for example whether they are suitable for assessing situations where people stand with their legs bent, such as high speed marine craft operators. Both biodynamic research and research on vibration discomfort is required to clarify these issues.

During 60 s of vertical Gaussian random vibration in the frequency range 0.25 to 25 Hz with a magnitude of 1.75 r.m.s. ms^{-2}, the resonance frequency of the vertical transmissibility from the floor to the head was about 5 Hz when either standing with straight legs or sitting upright with no backrest but decreased to about 3 Hz when standing with bent legs (Figure 2.11, Paddan and Griffin, 1988a, 1993). On the other hand at high frequencies, the modulus of transmissibility obtained with a 'standing with straight legs' posture was found to be greater than the modulus of transmissibility obtained with a 'standing with bent legs' posture for frequencies greater than 8 Hz (Paddan and Griffin 1993).

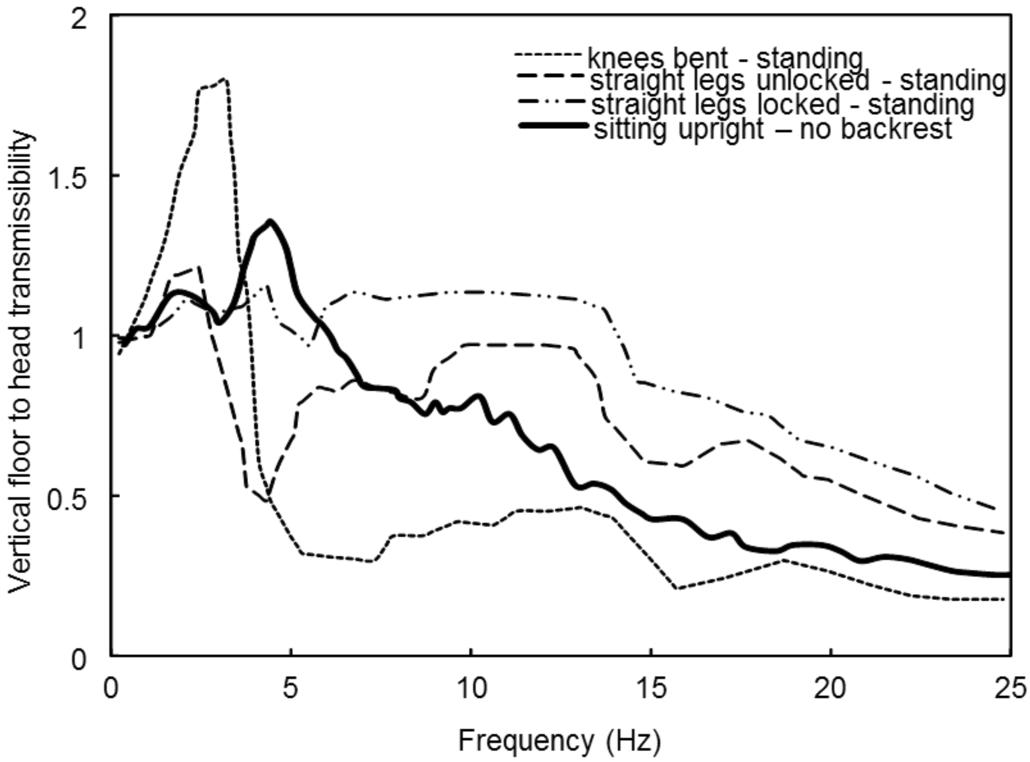


Figure 2.11 Transmissibility from seat to the head (Paddan and Griffin, 1988a) and from the floor to the head (Paddan and Griffin, 1993) with standing with straight and bent legs.

Similarly, the resonance frequency of the vertical apparent mass decreased from about 6 Hz to about 3 Hz when changing the posture from standing with straight legs to standing with knees bent (Coermann, 1962; Matsumoto and Griffin, 1998). Matsumoto and Griffin (1998) also found that transmissibilities to the knees in the fore-and-aft direction showed a main peak around the resonance frequency of the apparent mass (i.e. 2.75 Hz) when the subjects stood with their knees bent. The authors suggested that a bending motion of the knees may occur and contribute to the resonance of the entire body in this posture.

Subashi *et al.* (2006) investigated the vertical and fore-and-aft cross-axis apparent mass of twelve subjects exposed to vertical random vibration in the range 2 to 20 Hz at three magnitudes of vibration (0.125, 0.25 and 0.5 ms^{-2}) for five different standing postures: upright (comfortable standing with straight legs), lordotic (straight legs, back slightly bent backward), anterior lean (straight legs, back slightly bent forward), knees bent (upright upper body, 120° between lower legs and upper legs) and knees more bent (upright upper body, 110° between lower legs and upper legs). They found that the greatest differences in the resonance frequency of the vertical in-line apparent mass occurred between standing postures with straight legs and standing postures with knees bent (Figure 2.12), where the resonance frequencies halved from about 6 Hz to about 3 Hz (almost the half). A significant difference was also found between the postures 'knees bent' and 'knees more bent' where the main resonance frequency changed from 3.1 Hz to 2.6 Hz, confirming the bending of the knees contributed to a 'softening' effect. No differences were found between the results obtained with the postures where only the upper body position changed.

Consistent with this finding, Mansfield and Griffin (2002) did not find any significant difference in the resonance frequency of the vertical apparent mass between sitting upright and sitting leaning forward (Figure 2.12). These findings suggest that there is not much contribution of the upper body to the biodynamic response to vertical vibration when either standing or sitting. However, this does not necessarily mean that changes in the upper body will not affect the subjective response to vertical vibration. Since there is a lack of studies of discomfort around this topic, further investigation is needed.

There is a lack of evidence whether bending the knees when standing affects the discomfort caused by vibration. Several studies of vibration discomfort have been conducted with standing subjects (e.g., Chaney, 1965; Ashley, 1970; Jones and Saunders, 1972; Oborne and Clarke, 1974; Thoung and Griffin, 2011; Figure 2.13). Although there is variability, when standing with straight legs these studies suggest greatest sensitivity to acceleration in the frequency range 4 to 16 Hz, consistent with the frequency weightings advocated in current standards. However, the rate of growth of discomfort depends on the frequency of vibration, so the frequency-dependence of equivalent comfort contours varies with the magnitude of vibration, and a single frequency weighting is not optimum for all magnitudes of vibration (Thuong and Griffin, 2011).

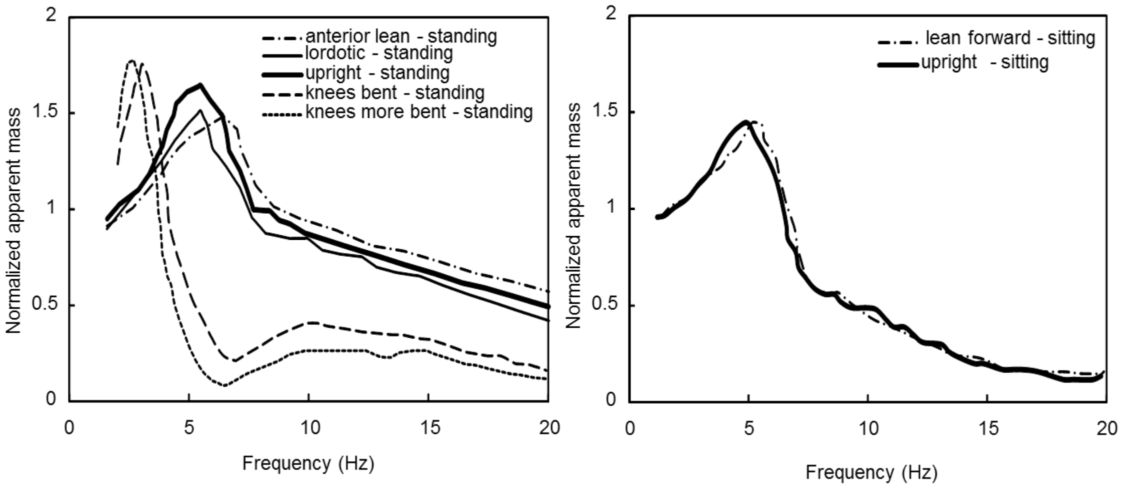


Figure 2.12 On the left, median normalized apparent mass obtained by Subashi *et al.* (2006) with five standing postures at magnitude 0.5 ms^{-2} r.m.s. of vertical random vibration in the range 2 to 20 Hz. On the right, median normalized apparent mass obtained by Mansfield and Griffin (2002) with two of the sitting postures analysed in the study at magnitude 1.0 ms^{-2} r.m.s. of vertical random vibration in the range 1 to 20 Hz.

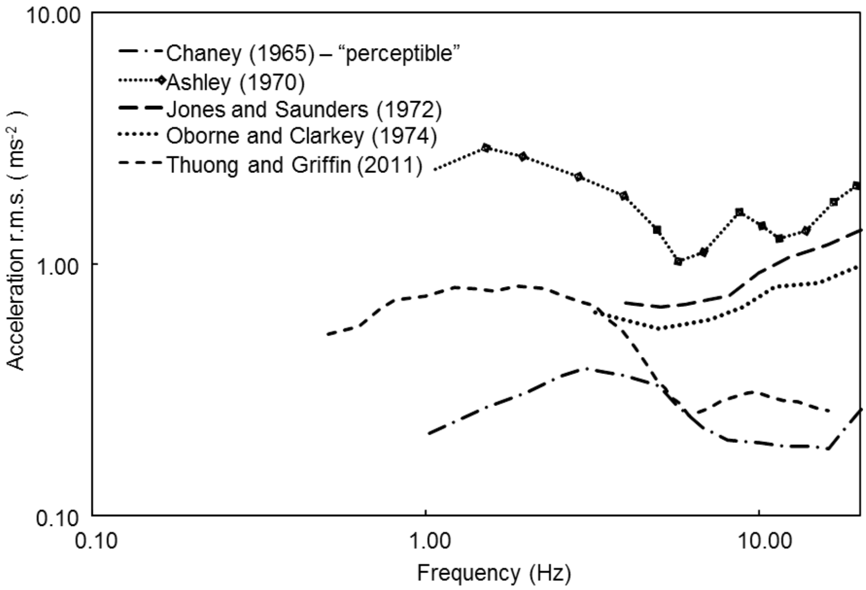


Figure 2.13 Equivalent comfort contours obtained by different studies that investigated the discomfort caused by vertical vibration with standing subjects (Chaney, 1965; Ashley, 1970; Jones and Saunders, 1972; Oborne and Clarke, 1974; Thoung and Griffin, 2011).

2.7 Whole-body vibration and shock assessment: standards and methods

The methods used to evaluate whole-body vibration and mechanical shocks are mainly stated and suggested in British Standard BS 6841 (1987) and International Standard ISO 2631 (1997). ISO 2631 (1997) and BS 6841 (1987) give a useful guidance on assessing whole-body vibration, including some mechanical shocks.

2.7.1 Frequency weightings

Section 2.3 explained the meaning of equivalent comfort contours and the importance of giving to each frequency the 'weight' that it has on discomfort for each direction of vibration. Current standards take into account the direction of vibration, the input location of vibration, and the effect of frequency on discomfort. ISO 2631-1 (1997) and BS 6841 (1987) were influenced by studies of discomfort caused by sinusoidal vibration (e.g. Dupuis *et al*. 1972; Griffin *et al*. 1982; Corbridge and Griffin, 1986; Parsons and Griffin, 1978, 1988), which contributed to the implementation of frequency weightings.

Although the two standards present some differences, they provide similar frequency weightings. The frequency weightings in BS 6841:1987 are W_b for vertical vibration at the seat pan, W_c for fore-and-aft vibration of the backrest, W_d for horizontal vibration at the seat pan, W_e for rotational vibration and W_f for vertical vibration in the range 0.1 Hz to 0.5 Hz causing motion sickness. Frequency weightings in ISO 2631-1 (1997) are W_k for vertical vibration, W_c for fore-and-aft vibration of the backrest, W_d for horizontal vibration, W_e for rotational vibration and W_f for vertical vibration in the range 0.1 Hz to 0.5 Hz causing motion sickness. Differences between W_k and W_b include W_b giving 20% less weight than W_k at frequencies lower than 3.15 Hz and W_b giving 25% greater weight than W_k at frequencies greater than 50 Hz (Griffin, 1998). Except for W_f, all the frequency weightings are defined over the range 0.5 to 80 Hz.

Each frequency weighting is a cascade of band limiting and band pass filters. The transfer function of the frequency weightings provides the corresponding phase response. This is given by the product of the transfer functions of a high-pass and low-pass second-order Butterworth filters, an a-v transition filter and an upward-step filter. The cut frequencies of the high pass and low pass filters are 0.4 Hz and 100 Hz, respectively. The a-v transition filter is proportional to acceleration at lower frequencies and to velocity at higher frequencies, while the upward-step filter is proportional to jerk. More details about filter specifications can be found in ISO 8041 (2005).

2.7.2 Risk assessment of whole-body vibration

The standards provide vibration exposure values to assess the severity of a motion. These values must take into account the properties of the motions that are to be evaluated.

Each method considers a different time dependency of the input acceleration. Methods based on r.m.s. use a second power time-dependency (in which a^2t=constant).

$$\text{root-mean-square (r.m.s.)} = \{\frac{1}{T}\int_0^T [a_w(t)]^2 dt\}^{1/2}$$

The vibration dose value (VDV) is based on a fourth power time dependency (in which a^4t=constant). This averaging technique will give more weight to peaks than to the r.m.s. method.

$$\text{vibration dose value (VDV)} = \{\int_0^T [a_w(t)]^4 dt\}^{1/4}$$

The use of VDV is currently preferred. It is also especially recommended in the case of motions with a high crest factor, greater than 6 in BS 6841:1987 and greater than 9 in ISO 2631:1997.

For motions having crest factors lower than the above limits the vibration dose value may be estimated using the following equation

$$\text{estimated vibration dose value (eVDV)} = [(1.4 \times a^4) \times b]^{1/4}$$

where a is the r.m.s. of the frequency-weighted acceleration and b is the duration in seconds of the short period accelerations.

The limits not to exceed correspond to a vibration dose value of 15 $ms^{-1.75}$ in BS 6841 and 17 $ms^{-1.75}$ in ISO 2631-1 during an entire day.

Adding to the above methods, ISO 2631-1:1997 introduces also the use of the maximum running r.m.s. (MTVV) as an alternative to the use of VDV, in case of high crest factors, occasional shocks or transient motions. This method is based on the evaluation of the r.m.s. acceleration for a short integration time. The running r.m.s. is defined by the equation:

$$\text{running r.m.s. } a_w(t_0) = \left\{\frac{1}{\tau}\int_{t_0-\tau}^{t_0}[a_w(t)]^2 dt\right\}^{1/2}$$

where τ is the integration time for running averaging, $a_w(t)$ is the instantaneous frequency weighted acceleration and t_0 is the instantaneous time of observation. The MTVV will be the maximum of the running r.m.s.

$$\text{MTVV} = \max[a_w(t_0)]$$

It is recommended to use $\tau = 1$ when calculating the MTVV.

The r.m.s. and VDV tend to be the most used averaging techniques when evaluating exposure to vibration.

2.6.3 Whole-body vibration evaluation and postures

For exposures to vertical vibration, W_b must be applied to the acceleration time history measured at the interface seat-human body with sitting postures and to the acceleration time history measured at the floor with standing postures.

In BS 6841:1987 it is stated that standing refers to an ‘erect’ standing posture and that bending the knees may affect the transmission of vibration through the body and so it may affect the discomfort.

2.7.3 Weak points in the standards

The issues discussed in Sections 2.3, 2.4 and 2.5 and the information given in this section indicate some weak points of the standards.

For each direction of vibration, posture and vibration waveform a single frequency weighting is provided, neglecting the effect that magnitude has on the frequency-dependence of human responses to vibration.

Only a few postures are taken into account: standing with straight legs, sitting upright, recumbent. No variations in standing (e.g. knees bent) and sitting (e.g. leaning forward) are considered.

The frequency weightings recommended in the standards are based on research with sinusoidal vibration and therefore might overlook the spectral characteristics of shock-type vibration. Also, the band-limiting filters used to implement the frequency weightings (whole-body vibration) have lower and upper cut-off frequencies of 0.4 to 100 Hz respectively. For shocks having fundamental frequencies close to the very low frequencies, filters will cut some components and distort the input signal.

In respect of exposure to shocks, research still has not investigated directly whether there are significant differences in discomfort compared to the situation where people are exposed to continuous vibration. In addition, rarely has it been considered having peak acceleration greater than 1 g, which could cause the body to be lifted up and may increase therefore the risk to health.

In respect of posture, little research has been done on the effect of bending the knees in standing subjects on their discomfort. From the standards it is still unclear how vibration should be assessed in these conditions. Similarly, some environments bring people to assume sitting postures far from the simple upright posture, for example people might have to lean their upper body forward (e.g. on motorcycles). There is the need to compare these two postures (i.e. standing with knees bent and sitting leaning forward) with the basic postures considered in the standards to see whether they may have a significant effect on discomfort.

Before criticizing these two aspects of the standards, research should be undertaken to obtain more evidence of possible effects of posture and high magnitude shocks on human responses to vibration.

2.8 Biodynamic response to vertical vibration

2.8.1 Transfer function to analyse the dynamic response of the body

Some studies of the dynamic responses of the human body to vibration use a similar approach to the study of the dynamic behaviour of mechanical structures, by analysing the characteristics of transfer functions in the frequency domain. Transfer functions can be extracted from the ratio between measurements at different points, for example the acceleration at the base of a seat and the top of the seat (e.g. seat transmissibility) or between measurements at the same location, for example between the force and the velocity measured at the same point (e.g. mechanical impedance).

Transmissibility describes the transmission of vibration through a body and it is defined as:

$$TR(f) = \frac{X(f)_{output}}{X(f)_{input}}$$

where $X(f)$ is the same physical magnitude, such as acceleration or force, measured at an input and at an output location.

In the case of the human body, transmissibility may be challenging to measure since it might be difficult to fix the transducers on the body surfaces. For example to determine the transmissibility from seat to head from acceleration measurements it is necessary to attach the accelerometers to some support. Bite bars (Paddan and Griffin, 1988a) have been used in past studies for this purpose to overcome the problem, although the experimental setup and procedure can still be complicated and time consuming.

The mechanical impedance $Z(f)$ is the ratio between the force applied at a point and the resulting velocity at the same point:

$$Z(f) = \frac{F(f)}{v(f)}$$

The apparent mass (AM) has been widely used to study the dynamic response of the body during vibration compared to transmissibility and mechanical impedance, thanks to the ease of performing measurements of force and acceleration. The definition of apparent mass comes from second Newton's law:

$$F(t)=m*a(t)$$

where $F(t)$ is the force applied at one point and the resulting acceleration $a(t)$ at the same point, both functions of time t.

For rigid bodies m is a constant, while for non-rigid bodies m depends on the frequency of the excitation:

$$AM(f) = \frac{F(f)}{a(f)}$$

Because transmissibility gives the information about the vibration transmission properties of the structure that is being studied, its use would be preferred to the apparent mass, that on the contrary only gives information around one point.

There are several techniques that have been developed to calculate transfer functions, either in the case of transmissibility or apparent mass or mechanical impedance.

In the case of a single input, the cross-spectral density method (CSD) can be used. The transfer function $H(f)$ is obtained as the ratio between the cross-spectral density $G_{io}(f)$ of the input and the output and the power spectral density of the input $G_{ii}(f)$:

$$H(f) = \frac{G_{io}(f)}{G_{ii}(f)}$$

Each transfer function is then a complex quantity characterized by a modulus $| H(f) |$ and a phase $\Phi(f)$:

$$| H(f) | = [\{(\mathrm{Re}[H(f)])^2+(\mathrm{Im}[H(f)])^2\}]^{1/2}$$

$$\Phi(f) = \tan^{-1}\left\{\frac{\mathrm{Im}\,[H(f)]}{\mathrm{Re}\,[H(f)]}\right\}$$

However, dynamic analysis in the frequency domain is possible when the input vibration is either sinusoidal or broadband random vibration.

When the input is a shock the study of the dynamic behaviour of the body becomes more complicated.

Recently a model has been developed to predict the equivalent apparent mass of the body when people are exposed to shocks, and it was demonstrated to work accurately for peak accelerations less than 1 g (Zhou and Griffin, 2016b). In this study 20 subjects were exposed to vertical shocks of the waveforms shown in Figure 2.14, presented at the 13 preferred one-third octave centre frequencies in the range 1 to 16 Hz and at nine magnitudes. They were also exposed to 60 s of random vertical vibration with a flat constant bandwidth acceleration power spectrum in the range 1 to 16 Hz, at five magnitudes (0.1, 0.2, 0.4, 0.8 and 1.6 ms^{-2} r.m.s.). The biodynamic response of the human body exposed to mechanical shocks was predicted using a single-degree-of-freedom model or a second-degree-of-freedom model. The values of stiffness and damping were extracted using an optimization routine that minimized the error between the acceleration predicted by the model and the acceleration measured at the seat. For shocks, the equations of motion were solved in the time domain through the numerical fourth order method of Runge-Kutta. In addition, from each model, the mathematical expression of the equivalent apparent mass was derived and calculated using the optimum parameters for each nominal frequency of the shocks in the range 1 to 16 Hz. Single degree-of-freedom and two-degree-of-freedom models were also used with random vibration but were solved in the frequency domain. In the case of random vibration, the optimum parameters were found by minimizing the error between the predicted apparent mass and the apparent mass calculated by the CSD method from measured accelerations and forces. Results showed that the acceleration waveforms of shocks obtained with either a single degree-of-freedom or a two-degree-of-freedom model well fitted the measured accelerations at almost every frequency and every magnitude of the shocks with a median error less than 20% (Figure 2.15). Greater percentages of error (up to about 40%) were obtained in the case of low frequencies and peak magnitudes approaching 1 g (upward displacements), probably due to subjects slightly leaving the seat, and in the case of high frequencies, where a difference in the phase between the measured and predicted acceleration led to greater errors. The accelerations predicted by a two-degree-of-freedom model fitted the measured time histories with a smaller error than a single-degree-of-freedom model. Optimum stiffness and optimum damping obtained with a time-domain model of response to shocks varied with the magnitude and frequency of the shocks and also correlated with the optimum parameters obtained with a frequency-domain model of response to random vibration. When using the parameters obtained with a frequency-domain model of response to random vibration in order to predict the shock-type accelerations, the errors between predictions and measurements were greater (median error of 50%) compared to the errors obtained when using the parameters extracted with a time-domain model. However, for practical applications the use of only one set of parameters obtained with a frequency analysis approach and random vibration is reasonable, instead of calculating parameters for each frequency and each magnitude of the shocks.

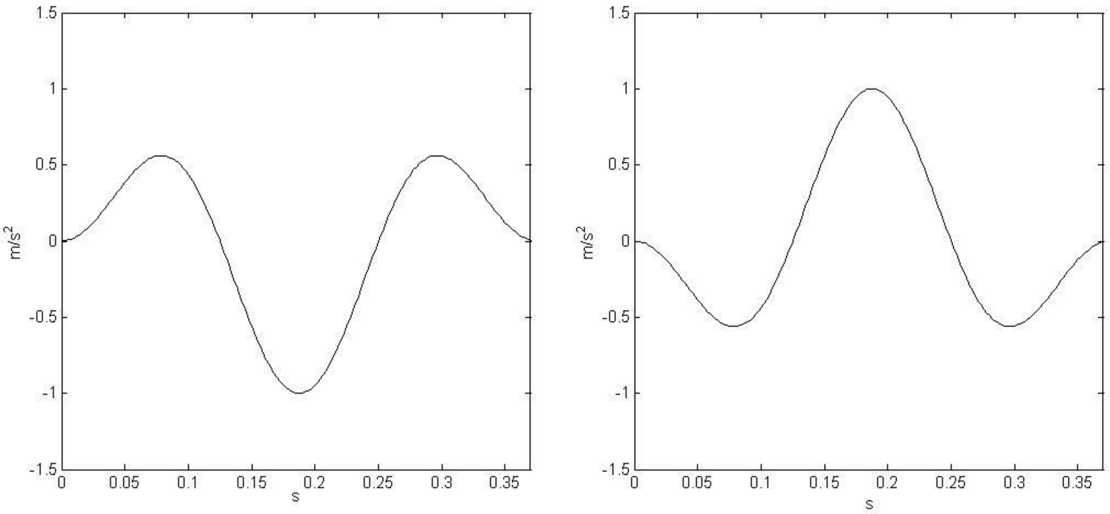


Figure 2.14 Shock-type vibration used in Zhou and Griffin (2016b). On the left side, example of acceleration waveform of a shock with fundamental frequency of 4 Hz corresponding to upward displacement. On the right side, example of acceleration waveform of a shock with fundamental frequency of 4 Hz corresponding to downward displacement.

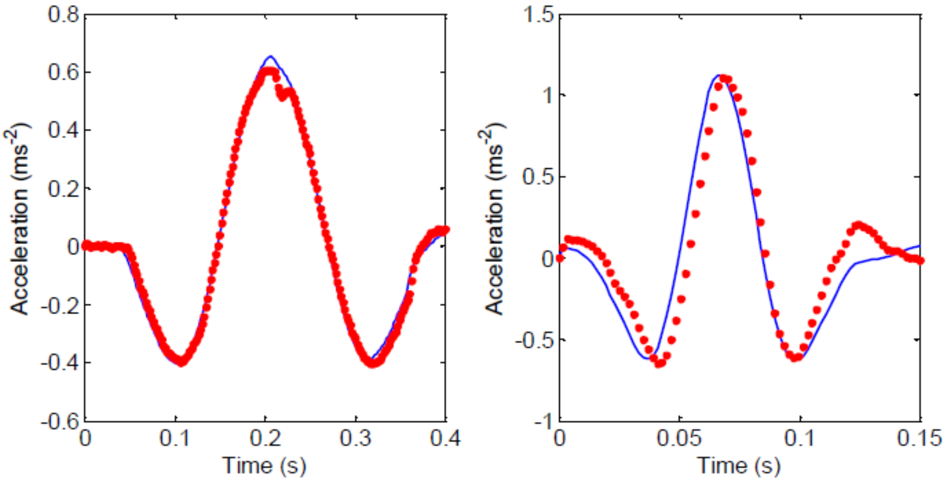


Figure 2.15 Figure taken by Zhou and Griffin (2016b). It shows the measured (—) and the predicted (●●●) acceleration waveform of a shock of 4 Hz (left side) and a shock of 16 Hz (right side) obtained for one subject during the low magnitude session

2.8.2 Seat dynamics and dynamic comfort of soft seats

Seats used in vehicles are commonly made of open-cell polyurethane foam.

Either the static or the dynamic comfort of polyurethane foam seats has been widely investigated. Thickness, hardness, seat stiffness, and force-deflection curves have been demonstrated to affect the static comfort of a soft seat, where an increase of the stiffness caused a non-linear decrease of static comfort (Ebe and Griffin, 2000a). The static comfort is not sufficient when the seat is exposed to vibration. In another study, Ebe and Griffin (2000b) proposed a qualitative model that included both the static and the dynamic discomfort to predict the overall discomfort caused by vibration when using soft seats of different hardness and thickness. However, a quantitative model that could predict the discomfort taking into account both seat and human body characteristics under dynamic conditions would be of more aid to the design of seats.

Soft seats and human body cannot be studied separately. The coupled system of the seated human body plus a seat must be taken into account. As shown by Wei and Griffin (1998b), Toward and Griffin (2011b), and Tufano and Griffin (2013) the dynamic response of a soft cushion (e.g. seat transmissibility) during vertical vibration is influenced by the dynamic response and the characteristics of the subject who sits on it, such as the sitting weight, the hip width and the body mass index. When designing a seat it is therefore necessary to consider also the response of the human body to vibration. Measurements of seat dynamics using human subjects represent a useful and indicative tool for this purpose. However, the seat transmissibility measured with human subjects could be expensive and time consuming.

After the introduction of an active anthropodynamic dummy that simulated the human body in dynamic conditions (Lewis and Griffin, 2002), mathematical models have been proposed to predict seat transmissibility without using subjects. It has been demonstrated that it is possible to predict seat transmissibility from the mechanical impedance of the seat and the mechanical impedance of the human body, predicted with either a one-degree-of-freedom model or a two-degree-of-freedom model (Wei and Griffin, 1998b). The stiffness and the damping of a block of foam and a real car seat were extracted by using an indenter rig. Seat stiffness and damping were then used to predict the seat transmissibility together with a single degree-of-freedom or a two-degree-of-freedom model that represented the human body (Figure 2.16). Predicted transmissibilities fitted accurately the transmissibilities obtained with eight subjects exposed to 100-s of random vibration at 0.5 ms^{-2} r.m.s. (Figure 2.17) with a flat acceleration power spectral density in the range 1 to 30 Hz.

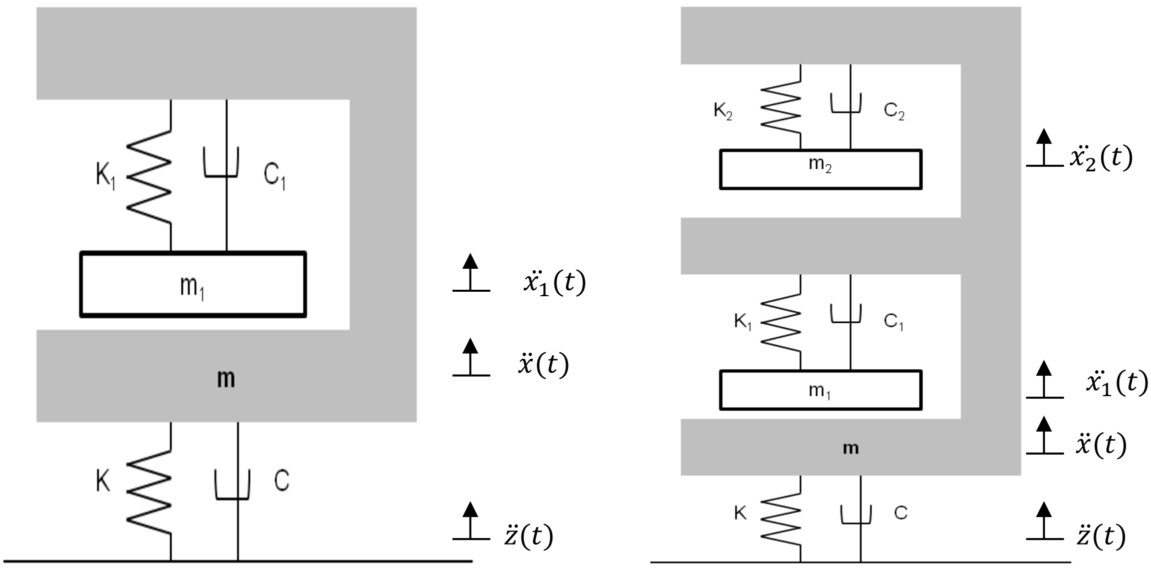


Figure 2.16 On the left, the body is modelled as a single-degree-of-freedom system with total mass M= m + m_1, stiffness K_1 and damping C_1, while K and C are the seat stiffness and the seat damping. On the right, the body is modelled as a two-degrees-of-freedom system with total mass M= m + m_1+ m_2, stiffnesses K_1, K_2 and dampings C_1, C_2, while K and C are the seat stiffness and the seat damping (Wei and Griffin, 1998b).

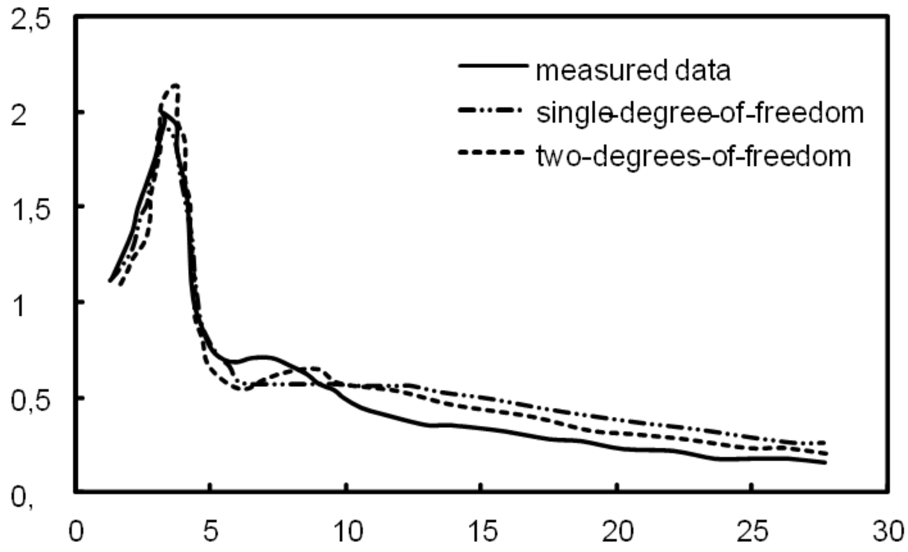


Figure 2.17 Predicted and measured data obtained with eight subjects exposed to 100s vertical random vibration at 0.5 ms^{-2} r.m.s with a flat acceleration power spectral density in the range 1 to 30 Hz.

The magnitude of vibration is a non-negligible factor when evaluating the dynamic response of a seat, since it greatly affects the dynamic stiffness of the seat and the seat transmissibility. The resonance frequency of the median vertical transmissibility of a sprung cushion decreased from about 5 Hz to about 3 Hz as the magnitude of vibration increased from 0.2 to 2.5 ms^{-2} r.m.s. (Fairley and Griffin, 1986). In addition to a decrease in the resonance frequency of the vertical seat transmissibility with increasing magnitude of vibration, Tufano and Griffin (2013) found that also the measured dynamic stiffness of three blocks of foam decreased with the increasing of magnitude of vibration from 0.25–1.6 ms^{-2} r.m.s. of vertical random vibration in the range 0.25 to 25 Hz. This showed a simultaneous softening behaviour of the foam and of the human body.

Other parameters affecting seat transmissibility can be related to the physical and geometric characteristics of the seat used, such as the density of the seat material or the thickness of the cushion.

Using an indenter rig and an electro-dynamic vibrator, it was found that the dynamic stiffness of three blocks of polyurethane foam (of the same density) but thicknesses of 60, 80 and 100 mm increased between 14% and 19% when the thickness decreased from 100 mm to 80 mm, and increased between 31% and 37% when the thickness decreased from 100 mm to 60 mm over the frequency range 1 to 20 Hz (Zhang *et al.,* 2015). A pre-load of 400 N and 600 N was used in the study. The vertical in-line transmissibility was measured in the same study with twelve subjects exposed to 60 s of random vibration of flat power density spectrum in the range 0.5 to 20 Hz and magnitude of 0.8 ms^{-2} r.m.s. The modulus showed a decrease of the principal resonance frequency with increasing thickness of the foam. The decrease in the dynamic stiffness, meaning a 'softening', of the foam, with increasing thickness was considered a factor that could partially explain the change in the resonance frequency of the seat transmissibility.

Although shocks can be common in many environments, there is little research on the dynamic response to mechanical shocks of the coupled system of a soft seat-human body. There has been no study of how of the thickness of polyurethane foam affects the discomfort caused by shocks. During exposure to mechanical shocks, seat transmissibility cannot be measured through the CSD method due to the spectral characteristics of shocks. However, the SEAT value (%) can be measured as a ratio of the weighted VDVs of the impulsive accelerations measured at the base and at the top of the seat. A SEAT value (%) gives an indication on how the extent to which a shock is transmitted through the seat will affect comfort. No investigation has been undertaken about whether the SEAT values are affected by the magnitude of the shocks, the thickness of polyurethane foam and whether they correlate with subjective responses during exposure to shocks.

2.8.3 Biodynamic modelling for exposure to mechanical shocks

As shown and discussed in previous paragraphs, simple models such as a one-degree-of-freedom model or a two degree-of-freedom model seem to predict accurately the dynamic response of the seated body to vertical random and sinusoidal vibration when either sitting on a rigid seat (Fairley and Griffin, 1989; Wei and Griffin, 1998a) or on a soft seat with no backrest (Wei and Griffin, 1998b; Toward and Griffin, 2011b).

Since it has been proven that a simple model of the human body seated on a rigid surface works accurately also in the case of exposure to shocks (Zhou and Griffin, 2016b) and simple models can also be used to model blocks of polyurethane foam (Tufano and Griffin, 2013), it could be hypothesized that similar simple models could be used to predict the response of the coupled seat-human body system exposed to mechanical shocks. As discussed in Section 2.7.1., the optimum parameters of a potential time-domain model of response to mechanical shocks may be extracted from a frequency-domain model of response to random vibration. There is not a systematic study yet that proposes a model and tests the possibility to predict the biodynamic response to mechanical shocks when a soft seat is used. If a simple model could predict the response of the 'seat-human body' system, predictions could also be used to correlate and predict the seat comfort under dynamic conditions in the presence of shocks. Positive correlations between objective and subjective measurements (Niekerk *et al.,* 2006; Basri and Griffin, 2014) suggest that if the predictions of the model fitted measured data and if objective measurements correlated with subjective feedback, the model could also be used to assess the discomfort in such conditions. Successful achievement could aid and simplify the planning and design process of a seat for environments where mechanical shocks are common, taking into account simultaneously the frequency content and the magnitude of the shocks, the subjective and objective responses of the human body to shocks and the dynamic response of a soft seat.

2.9 Vibration evaluation in high speed craft

This PhD project was undertaken with the support of the Institute of Naval Medicine (INM, Minister of Defence, UK). Because the research focuses on exposure to high magnitude vertical mechanical shocks, an application of the findings may be to the evaluation of vibration in high speed marine craft. To justify the choice of the frequency and magnitude of stimuli chosen in this work and of the postures investigated, a brief description of the vibration and environment in high speed craft is given in the following paragraphs.

2.9.1 Rigid Inflatable Boats

The concept of the rigid inflatable boat (RIB), as a modern lifeboat design, was developed by the Royal National Lifeboat Institution (RNLI) by the end of the 1960s.

The rigid Inflatable boat is a light fast boat characterized by a deep V hull and rubber inflatable tubes around it (Figure 2.18). The material of the hard hull may depend on the manufacturer, for example there could be hulls made of steel, aluminium or glass-reinforced plastic (GRP). The presence of an inflatable tube makes the vessel more stable at rest and at slow speeds (Grant and Wilson, 2005), absorb impacts loadings (Pike, 2003) and reduce the amount of water flooding in the deck.

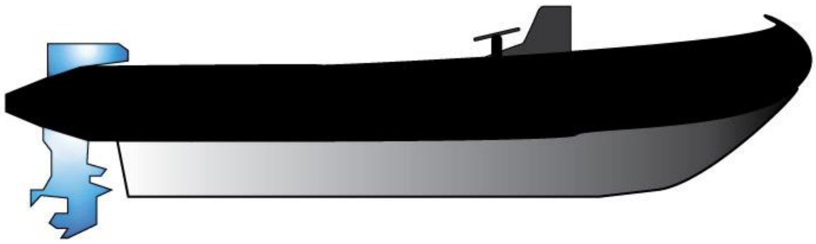


Figure 2.18 Schematic example of rigid inflatable boat.

These vessels are often capable of reaching speeds of 30 or 40 knots, but some can reach 70 knots.

The motions measured on a boat depend strongly on many factors like the location of measurements, the direction of travel (Paddan, 2012) or the speed of the vessel (Townsend *et al.*, 2008, McIlraith *et al.*, 2012). The vibration exposure values are affected by all these variables.

2.9.2 High speed marine craft environment

Personnel working in rigid inflatable boats have to deal with a harsh environment, both psychologically and physically. Ensign *et al.* (2000) carried out a survey of injuries among fast inflatable boat operators. A high percentage of self-reported injuries, which mainly occurred on the job, and most of them localized at the lower back, followed by the knees and the shoulders. Low back pain injuries have been often addressed as the main class of injuries (Bovenzi and Hulshof, 1999) in the context of whole-body vibration.

The motions that crew members are exposed to depend on both extrinsic and intrinsic factors. Intrinsic factors may be the speed of the boat, the design of the seats and of the whole structure of the vessel, the engine vibration, how the boat impacts with waves (direction) but also the posture of the operators. Depending on the position and responsibility of each member of the crew, several postures may be assumed (Figure 2.19). Some extrinsic factors are the changes of weather and sea conditions.

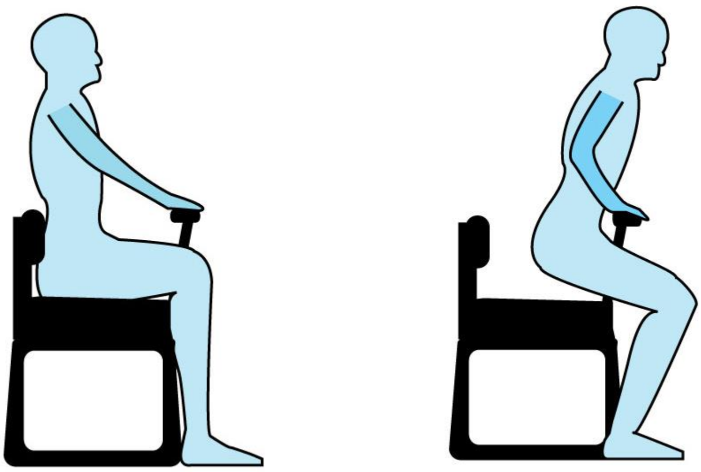


Figure 2.19 Possible postures assumed by the personnel of high speed marine craft.

Although it might be challenging, and sometimes not possible, to control simultaneously all these 'variables', there is a need to understand which are the ranges of magnitude and frequency of vibration operators are usually exposed to and what may be the consequences on the crew. At the same time it might be helpful to investigate whether a change in some of the factors, such as the postures assumed by the operators during specific conditions, would reduce the risks, if any, to health.

Many surveys and studies have questioned how much motion sickness could affect the health and performance of vessel operators (Stevens and Parsons, 2002; Dobie, 2000; Pethybridge, 1982). However, motion sickness has been showed to be mainly due to very low frequency components in the range from slightly below 0.1 Hz to about 0.5 Hz (Griffin,1990) and along the translational (Lawther and Griffin, 1986), rotational (Howarth and Griffin, 2003) and combined directions (Beard and Griffin, 2013; Donohew and Griffin, 2010). Crew members of high speed marine craft are often exposed to impulsive motions with most of the energy in the frequency range 1 to 20 Hz and characterized by severe magnitudes, often exceeding peak acceleration of 1 g.

Townsend *et. al*. (2008) carried out acceleration measurements on a 7.5 m RIB, where the time histories were band limited in the range 0.1592 Hz to 100 Hz through a second-order Butterworth filter. In all vertical (*z*-axis), lateral and fore-and-aft directions very high peaks were recorded. In the *z*-axis both upward and downward shock-type motions were identified and the motion responses showed important frequency components below 5 Hz. Dobbins *et al.* (2008) derived an Impact Count Index to analyse the motions on two high speed craft and found that a high percentage of the vertical accelerations measured at the deck and at the seat pan had peak accelerations greater than 1 g, although this method of measurement has not been standardized.

2.10 Conclusions

From the literature it emerges that it is not clear yet whether low frequency mechanical shocks (e.g. in the range 0.5 to 16 Hz) with magnitudes approaching the gravitational acceleration (g = 9.81 ms^{-2}) provoke discomfort that can be predicted from understanding of the discomfort caused by sinusoidal vibration. This information is relevant to understand whether current standards are suitable to judge vibration conditions found in high speed marine craft.

The common use of soft seats in environments also makes it desirable to test the suitability of the standards when soft seats are used during exposure to shocks. It would be helpful to identify a model that could predict both the dynamic response of the seat-human body system and the effects of a seat on the discomfort caused by shocks.

This thesis proposes to answer the following questions:

1. Do the frequency-dependence and the magnitude-dependence of discomfort caused by shocks differ from the frequency-dependence and the magnitude-dependence of discomfort caused by vibration?
2. Does the magnitude of a vertical shock determine whether the direction of the shock influence discomfort?
3. Can the methods used for evaluating seat transmission and seat comfort during continuous vibration be used also with vertical mechanical shocks?
4. Does the appropriate frequency weighting for discomfort caused by vertical vibration depend on the postures of standing and sitting people?

Chapter 3: METHODS AND MATERIALS

3.1 Introduction

This chapter describes the experimental equipment and the research methods used to complete the work presented in this thesis.

All the experiments involved the participation of human subjects and were approved by the Ethics Committee of the Faculty of Engineering and the Environment of the University of Southampton.

3.2 Experimental equipment

3.2.1 1-m vertical electro-hydraulic simulator

Four experiments are presented in this thesis. The direction of vibration that has been investigated is the vertical direction (*z*-axis, Figure 3.1).

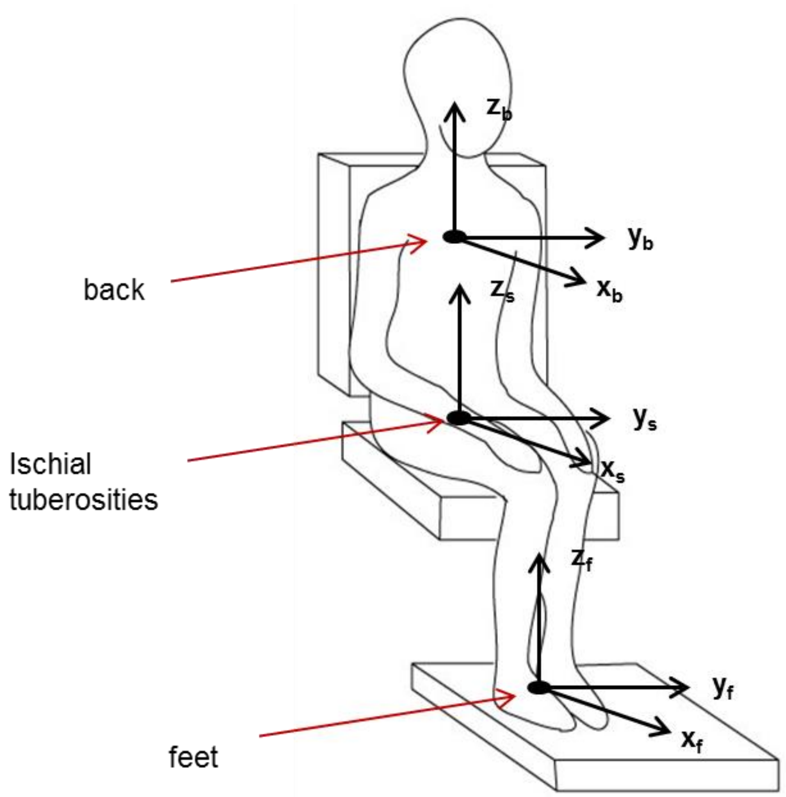


Figure 3.1 Translational orthogonal vibration axes *z* (vertical), *x* (fore-and-aft) and *y* (lateral).

As vertical whole-body vibration was being investigated, a 1-meter electrohydraulic vibrator was used in all the experiments (Figure 3.2).

#

Figure 3.2 Servotest 1-meter vertical electrohydraulic vibrator

The vibrator was manufactured by Servotest (Servotest Testing Systems Ltd., Surrey, U.K.) and driven by dedicated Pulsar software. The vibrator table was made of alloy aluminium and had dimensions of 150 x 890 cm. It was capable of reproducing vertical accelerations up to ±20 ms^{-2}, including transient accelerations. The maximum displacement and velocity were, respectively, ±500 mm (1 meter in total) and ±2.3 ms^{-1}. The nominal range of frequency of operation of the vibrator was 0 to 50 Hz. This covered the range of frequency and magnitude used in this study.

3.2.2 Accelerometers

The accelerations at the rigid seat and at the platform were measured by using a capacitive micromachined accelerometer 2260-002 (Silicon Designs Inc.; Figure 3.3). The specification is summarised in Table 3.1.

The calibration of the accelerometer was performed by giving zero reading when the bottom surface lay on a flat horizontal surface, while by giving -2 g when its top surface was attached to the same flat horizontal surface.

When a soft seat was used, the acceleration at the seat pan was measured using a SIT-pad with a tri-axial accelerometer integrated (Willow Technologies KXD94-2802), as shown in Figure 3.4.

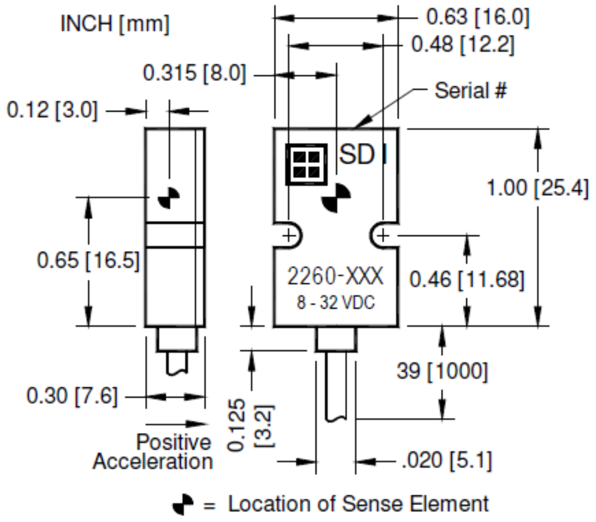


Figure 3.3 Capacitive micromachined accelerometer 2260-002 Silicon Designs Inc.

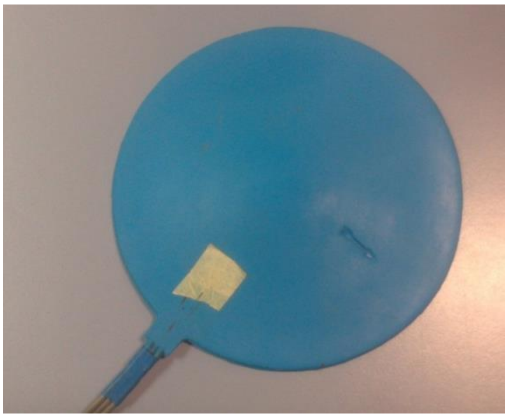


Figure 3.4 SIT-pad with an integrated tri-axial accelerometer (Willow Technologies KXD94-2802).

The calibration was performed in the same way as for the accelerometer Silicon Designs 2260-002. Specifications of the tri-axial embedded accelerometer are summarised in Table 3.2.

The analogue outputs from the transducers were first amplified by a bank of amplifiers and anti-aliasing filters. The anti-aliasing filters had a cut-off frequency of 100 Hz. The amplification gains were set in accordance with the maximum acceleration used in the experiments. The maximum accelerations used went up to about 12.5 ms^{-2} of peak acceleration. For all the experiment the range of measured acceleration was set to approximately 2 g. The analogue outputs were then converted into digital signals by a bus-powered USB M Series multifunction data acquisition (DAQ, National Instruments, NI USB-6211.

All signals were sampled at 512 samples/s and recorded by using the MATLAB toolbox *HVLab* Version 2.0 (ISVR, University of Southampton, UK).

Table 3.1 Specification of the 2260-002 accelerometer (Silicon Designs Inc.).

Model	2260-002 (Silicon Designs)
Sensitivity	2000 mV/g
Range	± 2 g
Frequency Response	0 – 400 Hz

Table 3.2 Specification of the tri-axial embedded accelerometer (Willow Technologies).

Model	KXD94-2802 (Willow Technologies)
Sensitivity	200 mV/g
Range	± 10 g
Frequency Response	0-1000 Hz

3.2.3 Force platform

In the experiment described in Chapter 6 the vertical forces were used to calculate the sitting static weight of subjects from their apparent mass (AM). The procedure for measuring and defining the apparent mass is given in Section 3.3.2.

The contact forces between subjects and the seat surface were measured by using a 12-channel force plate Kistler 9281 B (Kistler Group, Winterthur, Switzerland). The specifications of the platform are listed in Table 3.3. In table 3.3 the symbol 'F_x<->F_y' designates the interference (i.e. cross-talk) between the channel measuring the force component F_x along axis x and the channel measuring the force component F_y along axis y.

The force plate included four quartz piezo-electric force transducers installed at the corners of a rectangular steel frame. Each transducer, numbered *n* (with *n*=1, 2, 3, 4) measured the three orthogonal components $F_{n\text{-}x}$, $F_{n\text{-}y}$ and $F_{n\text{-}z}$ of a dynamic or static force F_n acting in the direction *x*-, *y*- or *z*- respectively. The coordinate system is indicated in Figure 3.5. The outputs from each sensor were summed separately along the three orthogonal axes and conditioned by three charge amplifiers. The force platform supported a rectangular aluminium plate of mass *m* (Figure 3.5).

Table 3.3 Specification of the 12-channels force plate Kistler 9281 B (Kistler Group, Winterthur, Switzerland).

Parameter		Value
Range	$F_{x,}$ F_y	-10 to 10 kN
	F_z	-10 to 20 kN
Overload	$F_{x,}$ F_y	-15/15 kN
	F_z	-10/15 kN
Crosstalk	F_x <-> F_y	<± 1.5 %
	$F_{x,}$ F_y-> F_z	<± 1.5 %
Crosstalk Rigidity	F_z -> $F_{x,}$ F_y	<± 0.5 %
	x-axis	≈ 250 N/μm
	y-axis	≈ 400 N/ μm
Rigidity Natural frequency	*z*-axis	≈ 30 N/ μm
	f_n (x,y)	≈ 1000 Hz
	f_n (z)	≈ 1000 Hz
Operating temperature range		0- 60 ˚C

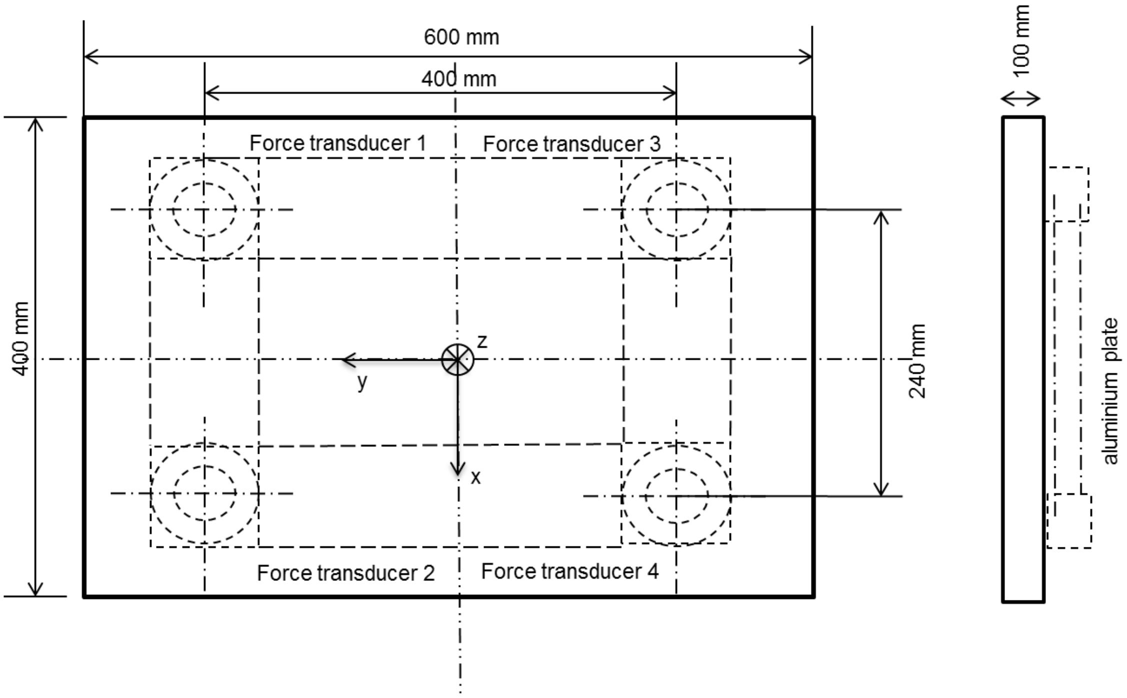


Figure 3.5 Top section and cross section of the force plate.

In this study only the vertical component of the total force was considered. The amplification gains of the amplifiers were set in accordance to the maximum force expected during the experiment. The range was set to ± 1250 N.

Static and dynamic calibrations were performed in the z-direction.

For the static calibration, rigid masses of 5 and 20 kg were used. Before the static calibration, the force signal was set to zero in order to eliminate any contribution of the aluminium plate's weight to the measured forces. The static calibration is necessary in order to set the range of force magnitudes (i.e. ± 1250 N).

The dynamic calibration consisted of measuring the apparent mass of the platform during random vibration (0.2 to 20 Hz, 1.0 ms^{-2} unweighted r.m.s.) with no subject sitting on it. The modulus of the apparent mass, *m*, was constant and equal to 33.2 kg, while the phase was zero over the frequency range 0.2 to 20 Hz (Figure 3.6). Considering that the widest frequency range investigated in this study is 0.5 to 16 Hz, this indicated that the plate behaved as a rigid body within the range of interest. The errors observed in Figure 3.6 for the apparent mass are about ± 4 % for the modulus while the phase varied between -0.06 rad to 0.03 rad in the range 0.2 Hz to 20 Hz . The value of the modulus of the apparent mass at 0.5 Hz was taken as the static weight *m* of the aluminium plate (*m*=33.2 kg). When a subject sat on the force plate and was exposed to vibration, the total output vertical force from the platform included the contribution due to the weight of the aluminium plate. Therefore, to extract the vertical force F_z exerted by the body only, it was necessary to use equation 1, where $a(t)$ is the input acceleration.

$$F(t)_z = F(t)_{z\text{-platform}} - m * a(t) \quad (1)$$

Calibration parameters were used when the forces were acquired.

Signals from the platform were first amplified and filtered by anti-aliasing filters. The anti-aliasing filters had a cut-off frequency of 100 Hz. Subsequently, they were converted into digital signals by a Data Acquisition (DAQ) NI USB-6211 (National Instruments, Texas, U.S.A.).

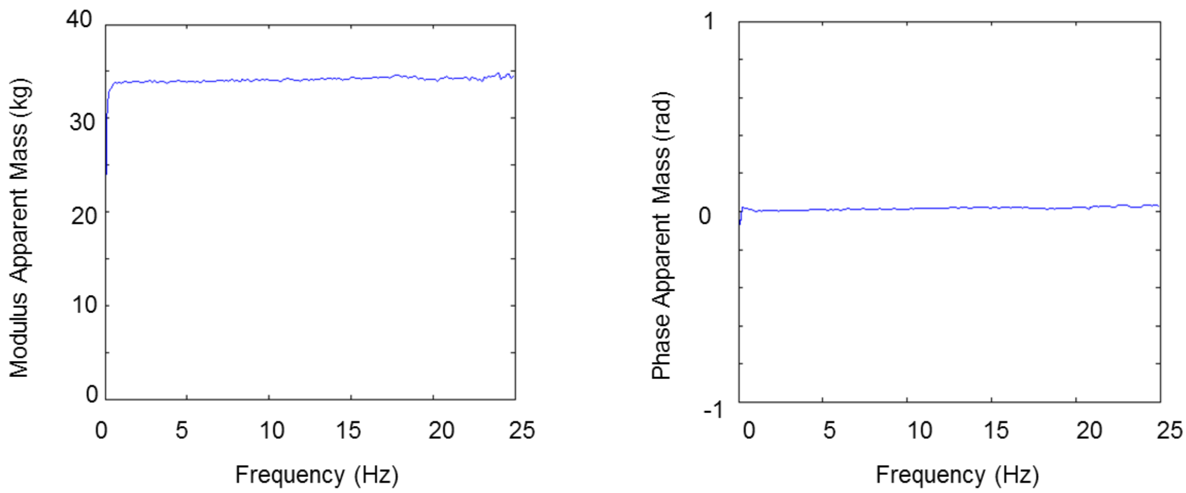


Figure 3.6 Modulus (on the left side of the figure) and phase (on the right side of the figure) of the apparent mass of the aluminium plate above the force platform.

3.2.4 Signal generation

Signals were first generated by using the software MATLAB R2012a (MathWorks Inc., Massachusetts, U.S.) and the toolbox *HVLab* (Institute of Sound and Vibration, University of Southampton, U.K.). They were converted into a format compatible with Pulsar (Servotest Testing Systems Ltd., Surrey, U.K.). To be able to reproduce the motions with the vibrator, it is necessary to go through a process within Pulsar Control System called ‘equalization’.

The equalization enabled the creation of signals to drive the simulator in order to obtain the desired motions.

The equalization process can be divided into two main steps.

The first step consisted in defining the transfer function, called system matrix, between the output and the input. The system matrix was automatically calculated by the software giving as an input a white noise signal to the vibrator. The frequency and amplitude characteristics of the white noise were defined by the operator and were therefore consistent with the range of application. The system matrix was used in the second stage of the process.

The second step of equalization was an iterative process. At the beginning the experimenter uploaded the desired waveform, generated in MATLAB. In each iteration the software generated and replayed a driving signal. The signal measured at the platform by the transducers (e.g. accelerometer) is called 'response signal'. According to the root-mean-square error between the response signal and the desired signal, the software adjusted the driving signal at the next iterations until the error between response and desired signals was below 5%.

A simple scheme summarising the process of equalization is shown in Figure 3.7.

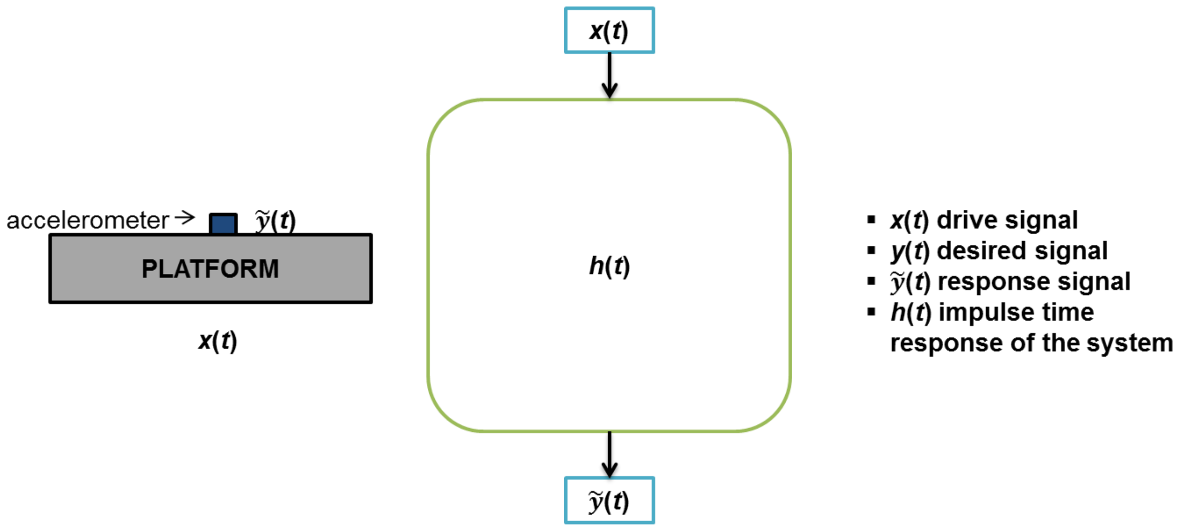


Figure 3.7 Equalization process.

3.2.5 Seats, other equipment and subject safety

Three out of four experiments focused on the exposure to vertical vibration of subjects in a sitting posture. A rigid seat was mounted firmly on the platform (Figure 3.2). The height, width, and depth of the seat surface were 41 cm by 71 cm by 51 cm, respectively. Although it was not used, the seat had a rigid backrest in order to protect the subject from potential falling (e.g. in case of faint).

In one of the experiments a rigid saddle seat was used. The properties and the transmissibility of the saddle seat are reported in Appendix A. In the same experiment also a standing posture was investigated. A metal frame was mounted on the vibrator in order to keep subjects secure. This consisted of an aluminium rectangular structure of dimensions 150 x 890 x 200 cm firmly mounted on the vibrator platform. Subjects wore a full 3-point body harness attached loosely to the metallic frame to prevent them from falling from the platform and hurt themselves if they lost control of their posture. A 105 cm high metal handrail was rigidly mounted on the platform to allow subjects to stabilize their balance (Figure 3.8).

In all sessions and in all conditions, participants were provided with an emergency button. The emergency button stopped the platform when pressed. Subjects were free to use the emergency button at any time for any reason.

All the vibration exposure values were quantified in order to respect the limits recommended in the standards for assessing vibration: British Standard 6841 (1987) and International Standard 2631-1 (1997).

Figure 3.8 Equipment used to secure and protect the subject during the experiment investigating discomfort whilst standing.

3.3 Research methods

The evaluation of discomfort has been chosen in this study as the main method to investigate the human response to mechanical shocks and vibration. The experiment presented in Chapter 6 also included the use of a mathematical model of the seated human body. In this section the research methods used to collect and analyse subjective and objective data will be described.

3.3.1 Perception and discomfort

3.3.1.1 The method of magnitude estimation

In Chapter 2 several psychophysical methods have been listed and discussed. In this section the method of magnitude estimation will be explained more deeply, since it is the method chosen for all the experiments presented in this thesis.

One of the first pioneers of magnitude estimation was S.S. Stevens in the 1950s (Stevens, 1957). The method of magnitude estimation is based on giving a direct numerical rating to the sensation caused by an external stimulus (e.g. a motion). The rating should describe the feeling of the subject who experienced the motion on a ratio scale. By using ratio scaling it is possible to state the ratio between two judgements. For example, if '100' is given to the first stimulus, and the subject feels that the next stimulus is half as uncomfortable the ratio will be 2:1 and they should give it the rating '50'. The rating represents the subjective magnitude, whereas the intensity of the stimulus is the objective magnitude. Subjective and objective magnitudes are assumed to be linked together.

There are two variations of the method: relative magnitude estimation and absolute magnitude estimation. In the first, the observer rates test stimuli relative to the rating given to a reference stimulus. The rating should reflect how much greater/lower the sensation of the test stimulus is compared to the sensation of the reference. In absolute magnitude estimation, the observers decide arbitrarily the value to assign to the test stimulus and they assign it in proportion to the magnitude of the stimulus.

In this study, absolute magnitude estimation was adopted. Absolute magnitude estimation is less time-consuming than relative magnitude estimation. Furthermore, for application to vibration exposures, a recent study found that the two methods yield similar results (Huang and Griffin, 2014).

In the experiments, prior to commencing the real test, the participants started with some practice stimuli in order to become familiar with the method of magnitude estimation. After the practice, a sequence of test stimuli was presented in a random order. The order of the sequence changed subject by subject.

The instructions given to the participants were similar to the following:

"You will be presented with a series of motions in a random order. Your task is to judge the discomfort caused by each of the stimuli using any positive number that appears appropriate – whole numbers, decimals, or fractions. Start giving to the first stimulus any number you wish. We suggest you start with a rating of 100. Rate the successive stimuli in a way that they will reflect your sensation of discomfort. For example, if you assign to the first stimulus '100' and you feel the second stimulus is twice as uncomfortable then its rating should be '200'."

Other instructions about posture, safety and duration of the test were also provided.

3.3.1.2 Equivalent comfort contours

Psychophysical laws describe the relationship between the physical characteristics of a stimulus and the subjective responses to it. The strength of using psychophysical laws is to be able to predict the discomfort caused by vibration knowing the magnitude of the input vibration. The psychophysical law proposed by S.S. Stevens (1957) has been used in this study to relate the vibration magnitude to the subjective magnitude. Stevens' power law is expressed in equation (1)

$$\psi = k \cdot \varphi^{n} \quad (1)$$

where ψ is the subjective magnitude, φ is the stimulus magnitude, k is a constant and n is the power exponent. The value of n is also called the 'rate of growth' of discomfort. Equation (1) can be simplified if it is expressed in a logarithm scale. Logarithm transformation allows obtain the linear relationship expressed in equation (2).

$$\log \psi = \log k + n \log \varphi \quad (2)$$

With N points, that means N levels of vibration magnitude, φ, the slope n of the linear regression in equation 2 and the constant k can be determined from the data and for each fundamental frequency of vibration (Figure 3.9).

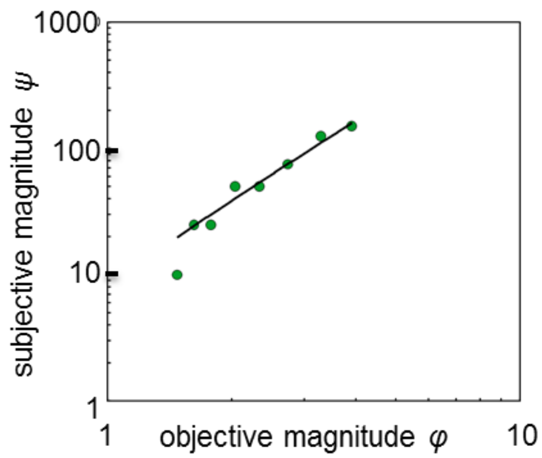


Figure 3.9 Example of linear regression from measured data.

Using the values of n and k, the objective magnitude φ required to produce a sensation magnitude of ψ can be estimated for each frequency of vibration. This predicted value is used to extract the equivalent comfort contours. Consequently the equivalent comfort contours represent the acceleration required to obtain a constant level of comfort across the range of frequency of interest.

3.3.1.3 Body locations of discomfort

Whitham and Griffin (1978) observed that, when changing the frequency of vibration, subjects tended to localise the sensation of discomfort in different parts of the body. In this study, participants were asked to indicate the location of the body where they experienced the greatest discomfort after being exposed to each stimulus. Analysis of the locations of discomfort may help to understand in what part of the body discomfort is felt mostly and the possible causes of discomfort, depending on the frequency and magnitude of vibration.

Body maps were used in order to show to participants what parts of the body they had to consider when indicating the area of greatest discomfort. The body maps used in each experiment depended on the posture. Details of the body maps will be presented in Chapters 4, 5, 6 and 7 dedicated to the experiments performed in this work.

3.3.2 A three degree-of-freedom model of the human seat-body system

In the final experiment, the hypotheses were based on a three degree-of-freedom model that predicted the response to shocks of the human body seated on a soft cushion (Figure 3.10). The mass $m = (m_1+m_2+m_3)$ represented the total sitting mass, k_1, k_2, k_3 and c_1, c_2, c_3 represented, respectively, stiffness and the damping parameters of the three-degree-of-freedom system that represents the whole structure seated human body and seat.

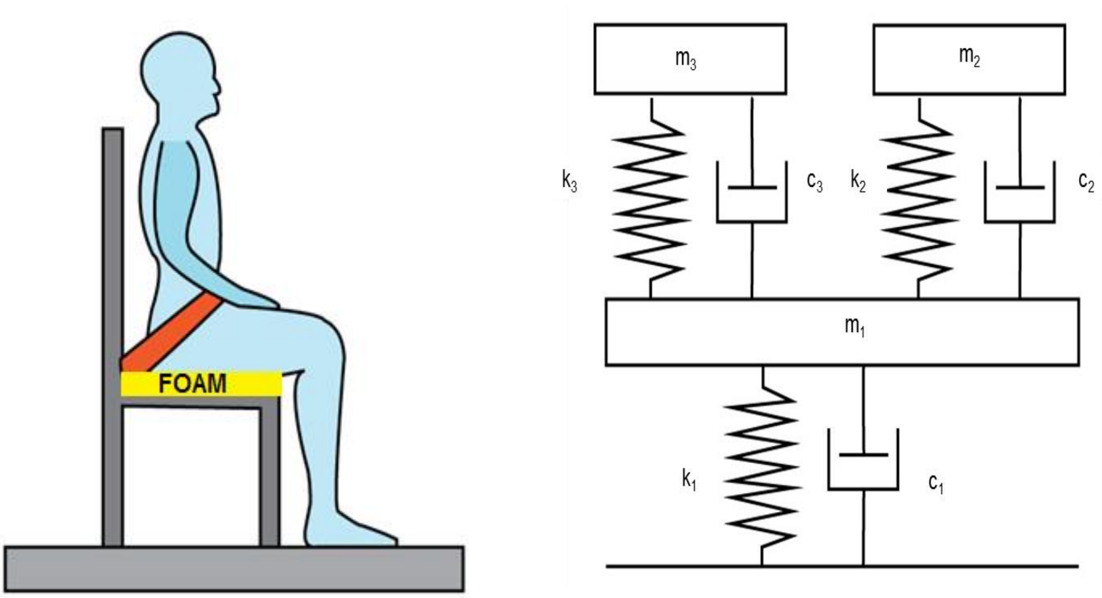


Figure 3.10 Subject seated on a soft cushion attached to a rigid seat (on the left). Three degree-of-freedom model of the human body – seat cushion system (on the right).

The model was implemented in MATLAB R2014a (MathWorks, Massachussets, U.S.A.). The equations of motion of the three masses m_1 (3), m_2 (4) and m_3 (5) were solved using numerical methods in the time domain. Function ‘ode 45’ of MATLAB was used.

$$m_1\ddot{x}_1(t) + k_1(x_1(t) - x_0(t)) + c_1(\dot{x}_1(t) - \dot{x}_0(t)) + k_2(x_1(t) - x_2(t)) + c_2(\dot{x}_1(t) - \dot{x}_2(t)) + k_3(x_1(t) - x_3(t)) + c_3(\dot{x}_1(t) - \dot{x}_3(t)) = 0 \quad (3)$$

$$m_2\ddot{x}_2(t) + k_2(x_2(t) - x_1(t)) + c_2(\dot{x}_2(t) - \dot{x}_1(t)) = 0 \quad (4)$$

$$m_3\ddot{x}_3(t) + k_3(x_3(t) - x_1(t)) + c_3(\dot{x}_3(t) - \dot{x}_1(t)) = 0 \quad (5)$$

In equation 3, x_0 and $\dot{x}_0\dot{x}_0$ are the input displacement and the input velocity of the platform.

The optimum parameters of the model were determined for each subject. The transmissibility of each block of foam was measured and calculated by exposing each subject to random signals of duration 60 seconds, in the frequency band from 0.2 Hz to 30 Hz, and at three magnitudes (0.5, 1.0 and 2.0 ms^{-2} r.m.s.). The parameters were calculated in order to minimize the error expressed in equation 6 between the measured transmissibility and the transmissibility predicted by the mode, in the frequency domain. The parameters obtained from this optimization procedure were used to predict the response of the body to shocks. The function ‘fmincon’ of MATLAB was used.

$$Error = \sqrt[2]{\mathrm{mean}(\sum(\mathrm{Re}\{Z(f)_{predicted}\} - \mathrm{Re}\{Z(f)_{measured}\})^2 + \sum(\mathrm{Im}\{Z(f)_{predicted}\} - \mathrm{Im}\{Z(f)_{measured}\})^2)} \quad (6)$$

In equation 6 $Z(f)_{predicted}$ and $Z(f)_{measured}$ are the complex transfer functions expressing the predicted and the measured transmissibility of the seat for each subject.

The total mass, m (= m_1+m_2+m_3) was constrained to be equal to the sitting weight of each subject.

The sitting weight *m* of the seated body was calculated from the apparent mass (AM) of the subject taking the value at 0.5 Hz.

The apparent mass is a driving point frequency response function. This means that it is the transfer function between two quantities measured at the same point (i.e. at the seat-subject interface). The apparent mass $M(f)$ is defined in the frequency domain as the complex ratio between the output force $F(f)$ and the input acceleration $a(f)$. It is expressed in equation 7, where the variable f is the frequency.

$$M(f) = \frac{F(f)}{a(f)} \tag{7}$$

In this thesis, the apparent mass has been calculated using the cross spectral density (CSD) method expressed in equation 8, where $S_{io}(f)$ is the cross spectral density between the output force and the input acceleration and $S_{ii}(f)$ is the power spectral density of the input acceleration.

$$M(f) = \frac{S_{\mathrm{io}}(f)}{S_{\mathrm{ii}}(f)} \tag{8}$$

3.4 Inter-subject variability

A rigid hard seat was used in all the experiments, except where the effect of foam on discomfort was investigated. This allowed the results of the studies to be independent from the setting used and to be repeatable. However, small differences from other studies may occur due to the small number of subjects used in the experiments, the subjective features (e.g. size), or the postures (e.g. erect or slouched).

As discussed in the literature review, subject variability is a parameter to take into account when analysing and interpreting data. The experimental data were processed for each individual as well as medians over a group of participants were extracted. When calculating the medians, 25 and 75 percentiles have been considered to take into account subject variability.

3.5 Statistical analysis

Non-parametric statistical methods were used to test the hypotheses of all experiments. It was expected that none of the dependent variables investigated had a Gaussian distribution and that their distribution was unknown (Ferguson, 1976; Siegel and Castellan, 1988).

The Friedman two-way analysis of variance was used to test the null hypothesis that *k* related samples belonged to the same population. For example, one application of this statistical method was to test whether the rate of growth of discomfort caused by vibration varied with the frequency of vibration.

The Wilcoxon matched-pairs signed-ranks test was used to test whether two related samples were from the same population. For example, one application of this statistical test was to compare whether the rate of growth of discomfort caused by vibration differed significantly from the rate of growth of discomfort caused by shocks at each frequency of vibration within the frequency range considered.

Chapter 4: THE FREQUENCY-DEPENDENCE OF DISCOMFORT CAUSED BY VIBRATION AND MECHANICAL SHOCKS

4.1 Introduction

The discomfort caused by whole-body oscillatory motion depends on the frequency content of the motion and so ‘frequency weightings’ are used to give more weight to those frequencies causing greater discomfort. Standards give guidance on the use of frequency weightings to evaluate oscillatory motions with respect to discomfort and risk of injury. The frequency weightings have been greatly influenced by studies of vibration discomfort caused by sinusoidal vibration (e.g., Griffin et al., 1982; Corbridge and Griffin 1986), but people are mostly exposed to non-sinusoidal motions.

Many environments expose people to mechanical shocks that vary in their magnitude and their frequency content: two characteristics that influence the waveform of the motion. Whereas a sinusoidal vibration is dominated by a single frequency, mechanical shocks have broad frequency content. It is reasonable to ask whether the standardized frequency weightings are appropriate for evaluating the severity of mechanical shocks.

Experimental studies have revealed a non-linearity in human responses to whole-body vibration, both in terms of subjective responses (e.g. Morioka and Griffin, 2006a, b) and biodynamic responses (e.g. Matsumoto and Griffin, 2005; Zhou and Griffin, 2014b). These findings indicate that a single frequency weighting is not optimum for all magnitudes of vibration.

The standardised frequency weightings have gains that are influenced by human sensitivity to different frequencies of vibration, with band-pass filters (at 0.4 and 100 Hz for whole-body vibration in current standards) to attenuate frequencies outside the frequency range of interest. The weighting filters and the band-pass filters have phase characteristics that arise from convenience rather than evidence. Although the phase characteristics do not affect r.m.s. values, they do affect peak values and vibration dose values recommended for evaluating the severity of shocks and other transients (BS 6841:1987; ISO 2631-1:1997). The effects of phase have received little attention, but the phase between frequency components in a vibration can influence judgements of discomfort (Matsumoto and Griffin, 2002b).

A shock contains many frequency components, with the shock waveform determined by the magnitude of each component and the phase between the components. There will be components at frequencies both greater than and less than the nominal frequency of the shock. This means that the discomfort caused by a shock will depend on sensitivity to vibration at frequencies greater than and less than the fundamental frequency of the shock, not only on sensitivity to the nominal frequency of the shock. A shock with a specific nominal frequency would be expected to cause less discomfort than expected for its magnitude if there is high sensitivity to that frequency, because some of the shock magnitude is at frequencies where there is less sensitivity. Similarly, a shock would be expected to cause greater discomfort than expected for its magnitude if the frequency of greatest sensitivity is at another nearby frequency. These effects would be predicted by a suitable frequency weighting, but there are no known experimental studies to test the expectation.

The discomfort caused by vibration and mechanical shocks in the range 1 to 16 Hz was investigated in two separate studies by Zhou and Griffin (2014a, 2016a). It was found that the frequency-dependence of equivalent comfort contours changed with the magnitude of both types of stimuli and that the greatest sensitivity to acceleration occurred at frequencies between 5 and 10 Hz for vibration and between 5 and 12.5 Hz for shocks. It was not possible to test whether there were differences in the discomfort caused by vibration and shock when they were presented at similar values according to current standards, due to different subjects and settings in the two studies. Furthermore, the discomfort caused by frequencies less than 1 Hz was not investigated, even though the shocks at higher frequencies contained energy at frequencies less than 1 Hz.

This study was designed to investigate whether, for motions having fundamental frequencies in the range 0.5 to 16 Hz, the frequency-dependence of the discomfort caused by 1½-cycle shocks differs from the frequency-dependence of the discomfort caused by sinusoidal vibration having the same fundamental frequency. In addition, the effects of frequency weighting filters and band-pass filters on the evaluation of mechanical shocks having low fundamental frequencies were investigated.

With both sinusoidal vibration and with shocks, it was hypothesized the rate of growth of discomfort would depend on the fundamental frequency of the motion and that the shapes of equivalent comfort contours for vibration and for shock would depend on the magnitude of the motion.

It was hypothesized that for a sinusoidal vibration and a shock having fundamental frequencies that cause greatest discomfort, the shock will cause less discomfort if the vibration and the shock have the same unweighted peak value, or the same unweighted vibration dose value, VDV.

4.2 Method

4.2.1 Subjects

Seventeen male students and office workers at the University of Southampton participated in the study. They were aged 20 to 37 years, stature between 166 and 189 cm, and weight between 59 and 91 kg. The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (Reference number: 8630).

4.2.2 Apparatus

Vertical oscillations were produced by a 1-m stroke vertical electrohydraulic vibrator (Servotest Testing Systems Ltd., Surrey, UK). Mechanical shocks and sinusoidal vibrations were generated by the HVLab Matlab Toolbox (version 2.0, ISVR, University of Southampton, UK), and then equalized and reproduced by a Servotest Pulsar system.

A flat rigid seat was mounted on the platform of the vibrator. The seat had an upright rigid backrest but subjects were asked not to make contact with the backrest. The height, width, and depth of the horizontal supporting seat surface were 41 cm by 71 cm by 51 cm, respectively. There was no backrest and the influence of vibration at the feet was ignored. A noise system (HFRU Noise system 001, ISVR, University of Southampton, UK) produced white noise at 75 dBA via a pair of headphones so as to mask any variations in the noise of the vibrator.

4.2.3 Stimuli

The motions were vertical sinusoidal vibrations and vertical mechanical shocks with fundamental frequencies at the 16 preferred one-third octave centre frequencies in the range 0.5 to 16 Hz.

All ‘sinusoidal’ vibration stimuli had durations of 5 s, with the magnitude of the sinusoid multiplied by the first 5 s of a 0.1-Hz sinusoid. This provided a smooth start and end to the vibrations with maximum magnitude around 2.5 s (Figure 4.1).

The shocks were formed from 1½ cycles of a sinusoid of the required fundamental frequency multiplied by a half cosine over the duration of the 1½-cycle sinusoid (Figure

4.1). The durations of the shocks therefore depended on their fundamental frequency, decreasing from 3 s at 0.5 Hz to 0.09 s at 16 Hz.

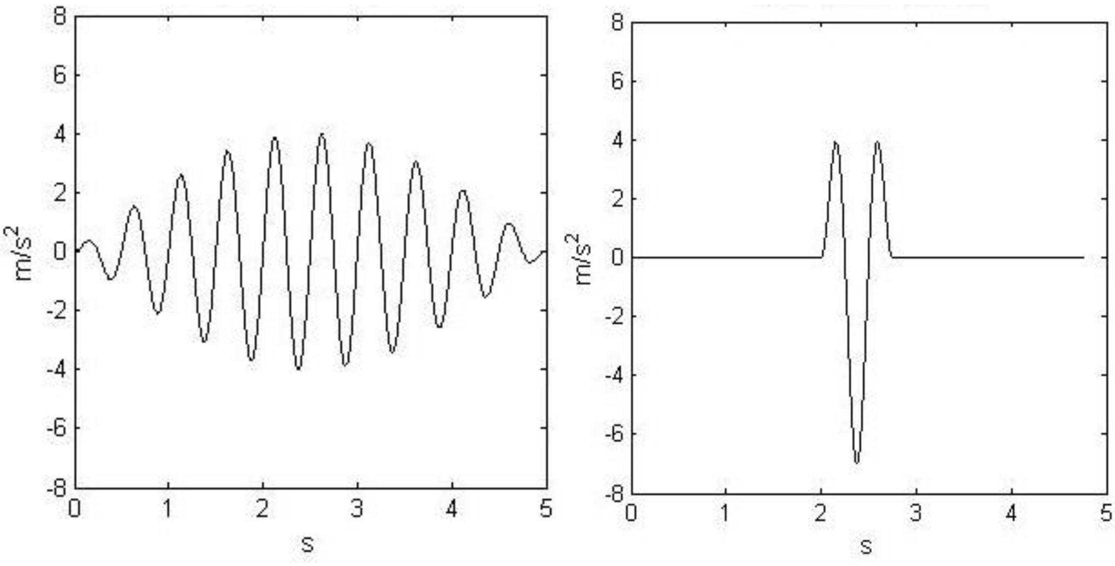


Figure 4.1 Enveloped 2-Hz sinusoidal waveform (left) and 2-Hz shock waveform (right) used in the study.

All motions were quantified in terms of their vibration dose value, VDV, either unweighted or frequency-weighted using weighting W_b in accord with BS 6841:1987 and ISO 8041:2005. This meant that, irrespective of the fundamental frequency, or whether the motion was vibration or shock, motions with similar frequency-weighted VDVs would be expected to produce broadly similar discomfort.

For both vibration and shock, at each fundamental frequency, eight magnitudes of frequency-weighted VDV were presented in 2 dB steps. Present the magnitudes in 2 dB steps means that the magnitudes differ from a multiplying factor of about 1.25, since db= $20\log_{10}\frac{a_1}{a_2}$, where db is the number of decibel and $\frac{a_1}{a_2}$, is the ratio between two amplitudes. The magnitudes varied with the frequency of motion but were always within the range 0.16 to 4.0 $ms^{-1.75}$ (Wb weighted VDV). Table 4.1 shows the magnitudes of all the stimuli in terms of unweighted r.m.s. (for vibration) and unweighted peak acceleration (for shock) (The ranges of magnitude of the stimuli at each frequency are shown for unweighted VDV in Figures 4.4 and 4.5, below, and for peak acceleration in Figure 4.6, below).

Table 4.1 Unweighted r.m.s. accelerations and peak accelerations (ms^{-2}) used at each frequency of vibration

Frequency (Hz)	vibration unweighted r.m.s. acceleration (ms^{-2})									shocks unweighted peak acceleration (ms^{-2})							
0.5	0.2	0.3	0.4	0.5	0.7	0.9	1.1	1.4		0.7	0.8	1.0	1.3	1.6	2.0	2.6	3.2
0.63	0.3	0.4	0.5	0.6	0.8	1.0	1.2	1.5		0.8	1.0	1.2	1.6	2.0	2.4	3.1	3.9
0.8	0.5	0.6	0.7	0.9	1.2	1.4	1.8	2.3		1.2	1.6	2.0	2.5	3.1	3.9	4.9	6.2
1	0.6	0.7	0.9	1.1	1.4	1.8	2.3	2.8		1.6	2.0	2.5	3.2	4.0	5.0	6.4	8.0
1.25	0.6	0.7	0.9	1.1	1.4	1.8	2.3	2.8		1.7	2.1	2.6	3.3	4.1	5.2	6.6	8.2
1.6	0.6	0.7	0.9	1.1	1.4	1.7	2.2	2.8		1.7	2.1	2.6	3.3	4.1	5.2	6.6	8.2
2	0.7	0.8	1.0	1.3	1.6	2.1	2.6	3.3		1.9	2.4	3.1	3.9	4.8	6.2	7.7	8.7
2.5	0.6	0.7	0.9	1.1	1.4	1.8	2.2	2.8		1.7	2.1	2.7	3.4	4.2	5.4	6.8	8.4
3.15	0.5	0.7	0.8	1.0	1.3	1.7	2.1	2.6		1.8	2.3	2.9	3.6	4.6	5.7	7.2	9.0
4	0.4	0.5	0.6	0.8	1.0	1.2	1.5	1.9		1.6	2.0	2.5	3.2	4.1	5.1	6.3	7.9
5	0.4	0.5	0.7	0.9	1.1	1.3	1.7	2.1		1.9	2.4	3.0	3.9	4.8	6.0	7.5	9.4
6.3	0.4	0.5	0.7	0.8	1.0	1.3	1.6	2.0		1.9	2.4	3.0	3.9	4.8	6.1	7.6	9.5
8	0.3	0.4	0.5	0.7	0.9	1.1	1.3	1.7		1.6	2.1	2.6	3.2	4.1	5.1	6.4	8.0
10	0.4	0.5	0.6	0.7	0.9	1.1	1.4	1.8		1.8	2.2	2.8	3.5	4.5	5.6	7.0	8.7
12.5	0.3	0.4	0.5	0.6	0.8	1.0	1.2	1.5		1.6	2.0	2.5	3.1	3.9	5.0	6.3	7.8
16	0.3	0.3	0.4	0.5	0.7	0.9	1.1	1.4		1.5	1.8	2.3	2.9	3.7	4.6	5.9	7.3

4.2.4 Procedure

Subjects attended two sessions. Approximately half of the subjects commenced with a session in which they experienced vibration, and the others commenced with a session in which they experienced shocks.

Subjects sat in comfortable upright postures without touching the backrest and wearing a loose lap belt (Figure 4.2). Their hands rested on their laps and their eyes were closed. The angle between the thighs and the calves was about 90 degrees with the feet parallel and resting on the platform of the vibrator. Subjects wore the headphones presenting 75 dBA of white noise during the whole duration of the experiment.

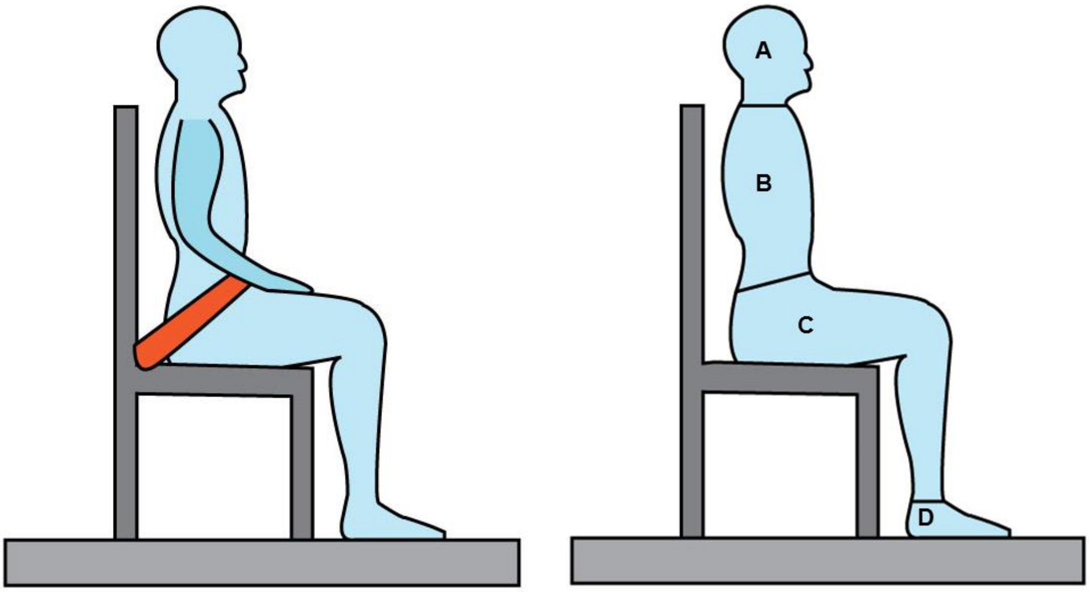


Figure 4.2 Posture adopted by subjects: sitting upright with a loose lap belt for safety and no contact with the backrest (left). Body map used for indicating the locations of major discomfort (right).

Prior to commencing the experiment, subjects were provided training on how to report their judgements of discomfort. The method of magnitude estimation was explained and then subjects practiced by giving a numerical rating of the apparent length of lines of different length. Subjects gave any number for the length of the first line, although 100 was suggested, and then rated subsequent lines so that if a line appeared twice as long it was assigned twice the previous number (e.g., 200), and so on.

Subjects also rated their discomfort caused by each motion using absolute magnitude estimation. In both sessions, the first motion they experienced was a vibration close to the 'middle' frequency and the 'middle' magnitude (i.e., a 5-s motion with a frequency of 2.5 Hz, an unweighted magnitude of 1.1 ms^{-2} r.m.s., unweighted VDV of 2.02 $ms^{-1.75}$, and W_b-weighted VDV of 1.0 $ms^{-1.75}$). They judged the discomfort caused by all other stimuli (either vibrations or shocks) in proportion to the number they provided for the discomfort caused by this sinusoidal motion. If they were unsure of their rating of discomfort, the motion was repeated.

Subjects also indicated the part of the body where they felt most discomfort by referring to the body map shown in Figure 4.2.

Subjects were first exposed to a sequence of 14 practice stimuli, covering the range of magnitudes and frequencies they would judge in the session. They were then exposed to 128 motion stimuli in each session.

4.2.5 Statistical analysis

Non-parametric tests were used in the statistical analysis.

In order to investigate differences between related samples, the Friedman two-way analysis of variance and the Wilcoxon matched-pairs signed ranks were used.

To investigate whether the locations of greatest discomfort changed with the frequency or waveform of vibration, the Cochran Q test and the McNemar test were used.

4.3 Results

4.3.1 Rate of growth of discomfort

The rate of growth of discomfort for each frequency of vibration and shock was obtained for each subject assuming that the subjective magnitude and the physical magnitude are linked through Stevens' power law (equation 1).

Using equation (2), the logarithmic transformation of equation (1), the rate of growth, *n*, was determined by regression for each subject at each frequency of excitation and both waveforms.

$$\psi = k\,\varphi^{n} \qquad (1)$$

$$\log_{10}\psi = n\log_{10}\varphi + \log_{10}k \qquad (2)$$

For both the vibration and the shock, the rate of growth of discomfort, *n*, decreased with increasing fundamental frequency of the motion (Table 4.2; Figure 4.3; $p<0.001$, Friedman).

Wilcoxon analysis showed that the rate of growth of discomfort for shocks was significantly greater than the rate of growth of discomfort for vibration at fundamental frequencies of 0.63, 0.8, 2, 3.15, 5, 6.3, 12.5 Hz ($p<0.012$) and 16 Hz ($p=0.044$).

Table 4.2 Median values of the exponent *n* and the constant *k* obtained in this study.

Frequency (Hz)	Value of exponent *n* (shocks)	Value of exponent *n* (vibration)	Value of constant k (shocks)	Value of constant k (vibration)
0.5	1.43	1.21	65	51.29
0.63	1.34	1.17	47.65	52.99
0.8	1.18	0.82	39.14	60.83
1	0.97	0.73	52.71	63.93
1.25	0.79	0.73	48.93	54.92
1.6	0.68	0.64	48.38	48.81
2	0.82	0.69	57.22	53.55
2.5	0.93	0.74	50.03	48.35
3.15	0.9	0.68	52.5	61.26
4	0.91	0.74	62.09	84.46
5	0.77	0.48	62.6	102.71
6.3	0.81	0.62	56.93	96.24
8	0.71	0.56	67.13	92.99
10	0.77	0.61	61.65	91.98
12.5	0.64	0.47	49.01	101.99
16	0.77	0.39	52.52	95.55

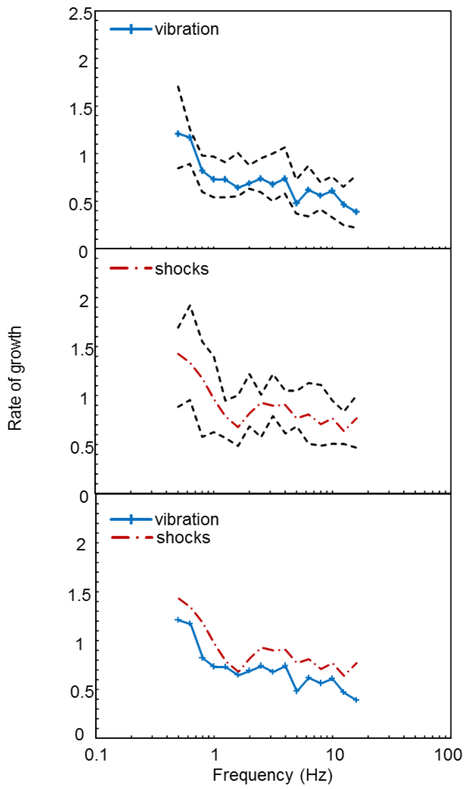


Figure 4.3 Rate of growth of discomfort, *n*, for vibration (—+—) and shocks (▬ ▪) with inter-quartile ranges (**- - - -**). Median values for 17 subjects.

4.3.2 Equivalent comfort contours

4.3.2.1 Equivalent comfort contours in terms of unweighted VDV

From the rate of growth of discomfort, *n*, and the constant, *k*, the vibration magnitudes required by each subject at each frequency to produce subjective magnitudes, ψ, from 63 to 160, were calculated using equation 2. The 'equivalent comfort contours' were calculated in terms of unweighted VDVs, so as to allow comparison of the contours for vibration and shocks.

For both shock and vibration, the shapes of the median equivalent comfort contours changed as the subjective magnitude increased from 63 to 160, a consequence of the frequency-dependence in the rate of growth of discomfort (Figure 4.4).

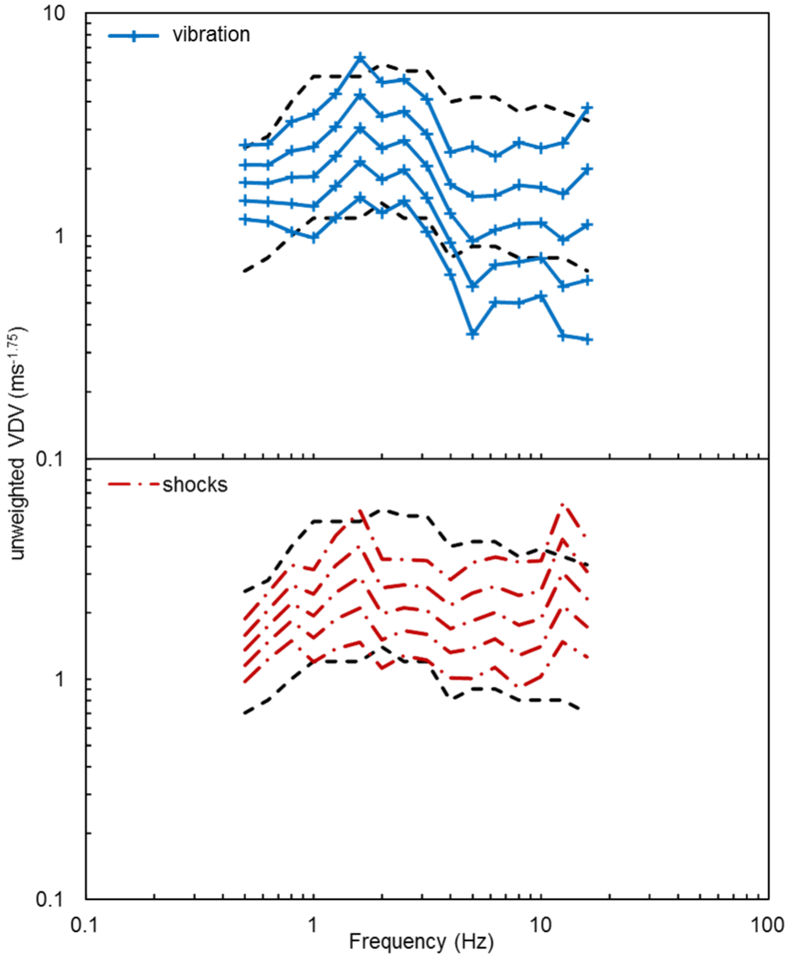


Figure 4.4 Equivalent comfort contours for vibration (—+—) and shocks (▬ ▪) in terms of unweighted vibration dose values, VDV. Contours corresponding to subjective magnitudes: ψ = 63, 80, 100, 125 and 160. Minimum and maximum magnitudes employed in the study (**- - - -**). Medians for 17 subjects.

With both waveforms, the unweighted vibration dose value required for a subjective magnitude of 100 (i.e., ψ = 100) was strongly dependent on the frequency of the vibration (p<0.001, Friedman). With vibration, sensitivity at 5 Hz was greater than all other frequencies in the range 0.5 to 8 Hz (p<0.031, Wilcoxon).

When expressed in terms of the unweighted VDV, the equivalent comfort contours for shocks exhibit a flatter shape than the contours for vibration (Figure 4.5). For a subjective magnitude of 100, the unweighted VDV required for similar discomfort was greater for shocks than for vibration at all frequencies from 4 to 16 Hz (Wilcoxon, p<0.013), except at 12.5 Hz (Wilcoxon, p=0.062).

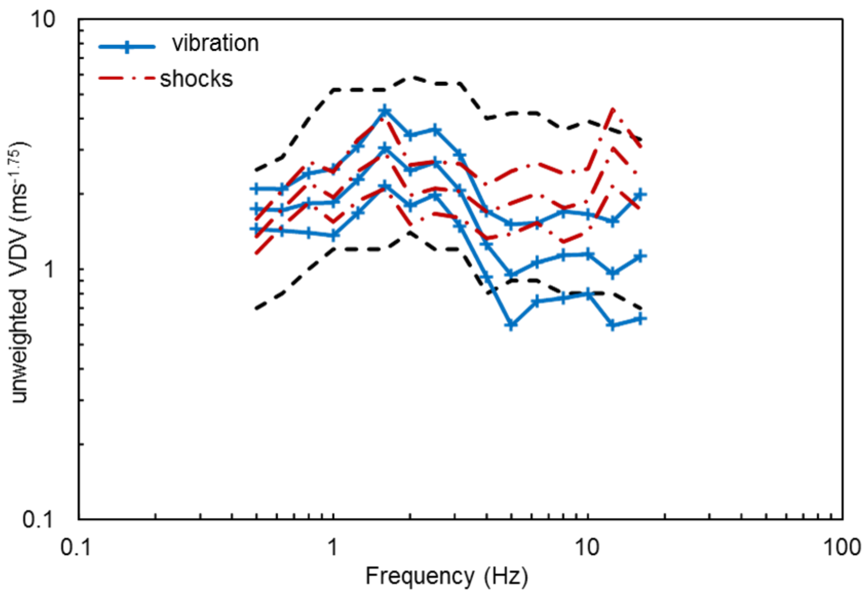


Figure 4.5 Comparison of equivalent comfort contours for vibration (—+—) and for shocks (— ·) in terms of unweighted vibration dose values, VDV. Contours corresponding to subjective magnitudes ψ= 80, 100, and 125 are displayed. Minimum and maximum magnitudes of shock employed in the study (**- - - -**). Medians for 17 subjects.

4.3.2.2 Equivalent comfort contours in terms of unweighted peak acceleration

When expressed in terms of the unweighted peak acceleration, the contours show similar trends but with greater differences between the vibration and the shock at frequencies greater than 5 Hz (Figure 4.6).

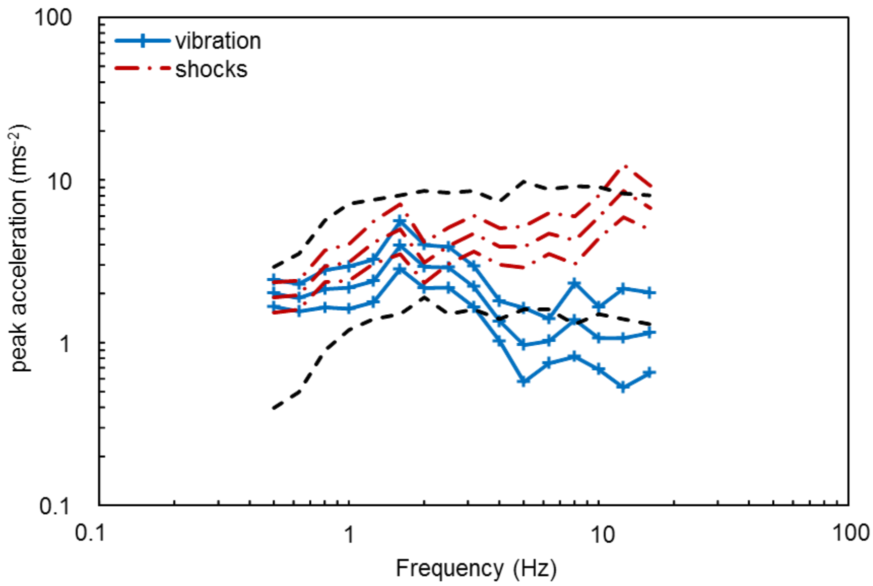


Figure 4.6 Equivalent comfort contours for vibration (—+—) and for shocks (▬ ▪) in terms of unweighted peak acceleration (ms^{-2}). Contours corresponding to subjective magnitudes *ψ*= 80, 100, and 125 are displayed. Minimum and maximum magnitudes of shock employed in the study (**- - - -**). . Medians for 17 subjects.

4.3.2.3 Equivalent comfort contours in terms of weighted VDV

With both waveforms, the weighted vibration dose value required for a subjective magnitude of 100 (i.e., ψ = 100) was strongly dependent on the frequency of the vibration (p<0.001, Friedman).

When expressed in terms of the frequency-weighted VDV, for a subjective magnitude of 100, the weighted VDV required for similar discomfort was greater for shocks than for vibration at all frequencies from 4 to 16 Hz (Wilcoxon, p<0.016; Figure 4.7), except at 12.5 Hz (Wilcoxon, p=0.121). The frequency-weighted VDV was slightly lower for shocks than for vibration at frequencies from 0.5 Hz to 0.8 Hz (p<0.036).

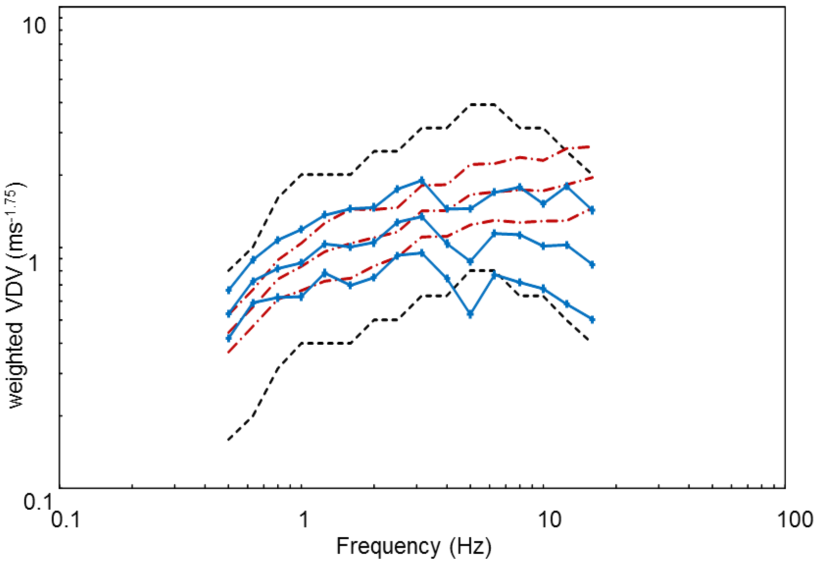


Figure 4.7 Comparisons of equivalent comfort contours for frequency- weighted VDV obtained with vibration (—+—) and shocks (▬ ▪) for three subjective magnitudes: ψ= 80, 100 and 125. The dotted lines (- - -) indicate the range of magnitudes in terms of weighted VDV used in the experiment.

4.3.3 Locations of discomfort

With both waveforms, as the frequency increased from 0.5 to 16 Hz, the location of greatest discomfort tended to fall from the upper body (head and torso) to the lower body (buttocks, tights, calves and feet), as shown in Figure 4.8. In figure 4.8 the ordinates are expressed in terms of percentage where 100 % corresponds to the total number of subjects (i.e. 17 subjects) and so the length of each bar expresses the percentage of subjects who chose one location. At the middle magnitudes and the highest magnitudes of vibration, Cochran tests showed significant variations in the location of greatest discomfort with variations in the frequency of vibration (locations A, $p<0.001$; location B, $p<0.032$; and location C, $p<0.001$). With shocks, there were also significant differences in the location of greatest discomfort (middle magnitudes: location A, $p<0.001$; location C, $p<0.001$; highest magnitudes: location A, $p<0.001$; location B, $p=0.008$; and location C $p<0.001$).

At each frequency, the location of greatest discomfort was similar for vibration and shock, except with the middle magnitudes at 5 Hz (location C more frequent with shock than with vibration, $p= 0.016$; McNemar), and at both 5 and 6.3 Hz (location B (thorax) more frequent with vibration than with shocks, $p<0.016$). With the highest magnitudes at 3.15 Hz, location C (buttocks and legs) was more frequently the location of greatest discomfort during shocks than during vibration ($p=0.004$).

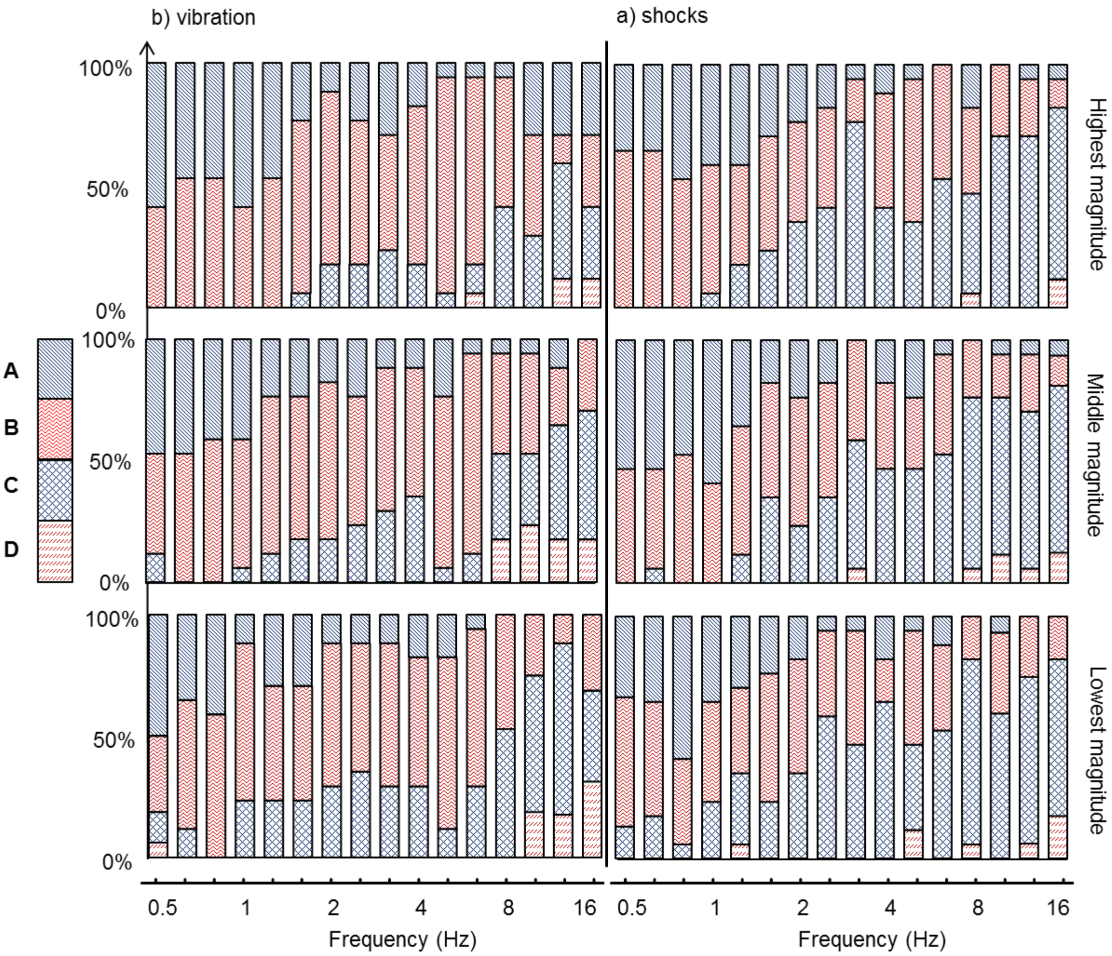


Figure 4.8 Effect of motion frequency and motion magnitude on the location of discomfort during exposure to vertical vibration and vertical shocks. Lowest magnitude (0.5 ms^{-2} unweighted r.m.s. 2.5 Hz reference), middle magnitude (1.1 ms^{-2} unweighted r.m.s. 2.5 Hz reference) and at the highest magnitude of vibration (2.8 ms^{-2} unweighted r.m.s. 2.5 Hz reference). Body locations as in Figure 4.2.

4.4 Discussion

4.4.1 Rate of growth of discomfort

4.4.1.1 Rate of growth of discomfort for vertical vibration

The rate of growth of discomfort caused by vibration depends on the frequency of the vibration (Figure 4.3). As found previously, the rate of growth decreased as the frequency of vibration increased from 0.5 to 2 Hz (e.g., for vertical vibration, Zhou and Griffin, 2014a; for horizontal vibration, Wyllie and Griffin, 2007, 2009). For 1 to 16 Hz sinusoidal vibration over the range 0.1 to 4.0 ms^{-2} r.m.s., Zhou and Griffin (2014a) found that at any frequency in the range 1 to 5 Hz the exponent was greater than at any frequency in the range 6.3 to16 Hz.

4.4.1.2 Rate of growth of discomfort for vertical shocks

The rate of growth of discomfort caused by shock decreases as the fundamental frequency of the shocks increased (Figure 4.3). There have been fewer studies with shock than with vibration, but both Ahn and Griffin (2008) and Zhou and Griffin (2016a) also found the rate of growth decreased as the fundamental frequencies of shocks increased (Figure 4.9). Like the present study, Ahn and Griffin (2008) found that the greatest change in the rate of growth for shocks occurred at frequencies less than about 2 Hz. All three studies found that the rate of growth for shocks is fairly constant with fundamental frequencies greater than about 4 Hz.

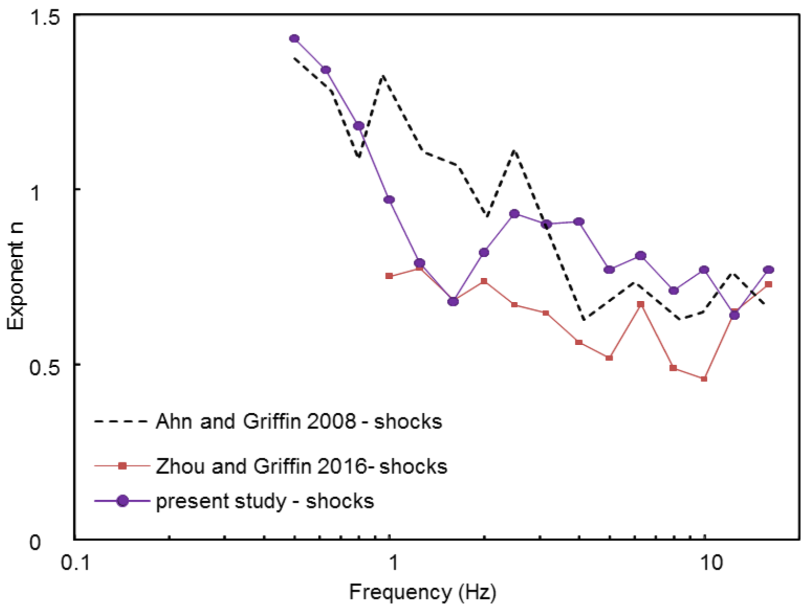


Figure 4.9 Comparison of the rate of growth of discomfort obtained with shocks in the present and previous studies (i.e. Ahn and Griffin,2008, Zhou and Griffin, 2016a).

For shocks with fundamental frequencies from 1 to 16 Hz over a range of magnitudes from ±0.1 to ±7.9 ms^{-2} (corresponding to Wb-weighted vibration dose values of 0.05 to 2.0 ms$^{-1.75}$), Zhou and Griffin (2016a) found no significant difference in the rate of growth of discomfort between upward and downward shocks, or between low magnitude and high magnitude shocks.

4.4.1.3 Comparison between the rate of growth of discomfort for vibration and shock

The present study was designed to allow a direct comparison of the rate of growth of discomfort between vibration and shock, with the same range of W_b-weighted VDVs at each frequency with both waveforms. Previously, separate experiments with sinusoidal vibration (Zhou and Griffin, 2014a) and with shock (Zhou and Griffin, 2016a), were conducted with different ranges of magnitudes. Although the studies of Zhou and Griffin (2014a) suggest the rate of growth of discomfort does not greatly depend on the magnitude of vibration or shock (over the ranges investigated) it may depend on the range of magnitudes of the stimuli being judged. The studies of Zhou and Griffin also employed different subjects (20 males and 20 females with vibration but only 20 males with shock), and were not designed to compare subjective responses to sinusoidal vibration and shock.

The rates of growth of discomfort found in the present study were generally greater for shock than for vibration (Figure 4.3, Table 4.2). A shock with a fundamental frequency f_0 contains components at frequencies less than, and greater than, f_0, so its rate of growth is expected to depend on the rate of growth over a range of frequencies lower and higher than the fundamental frequency of the shock. The frequency distribution of energy in a shock is dependent on the shock waveform, so it is not possible to conclude that the rate of growth of discomfort for shocks is always greater than, or less than, the rate of growth of discomfort for vibration. Although there were greater values of n for shocks than for vibration in this study, the difference may not be important because the frequency of vibration has a far greater effect on the rate of growth of discomfort.

4.4.2 Equivalent comfort contours

4.4.2.1 Equivalent comfort contours in terms of unweighted VDV

The reduction in the rate of growth of discomfort with increasing frequency of vibration means that the frequency-dependence of discomfort caused by vibration depends on the magnitude of motion, with equivalent comfort contours being more widely separated at frequencies greater than about 2 Hz than frequencies less than about 2 Hz (Figure 4.4).

For a subjective magnitude of 100, greatest sensitivity was at 5 Hz, consistent with previous studies using a variety of psychophysical methods for evaluating vibration discomfort (e.g., Dupuis et al., 1972; Jones and Saunders, 1972; Griffin, 1976; Griffin et al., 1982; Corbridge and Griffin, 1986; Morioka and Griffin, 2006a; Zhou and Griffin, 2014a). These studies investigated various ranges of vibration magnitude, vibration frequency, and durations of vibration, but the contours have broadly similar shapes (Figure 4.10).

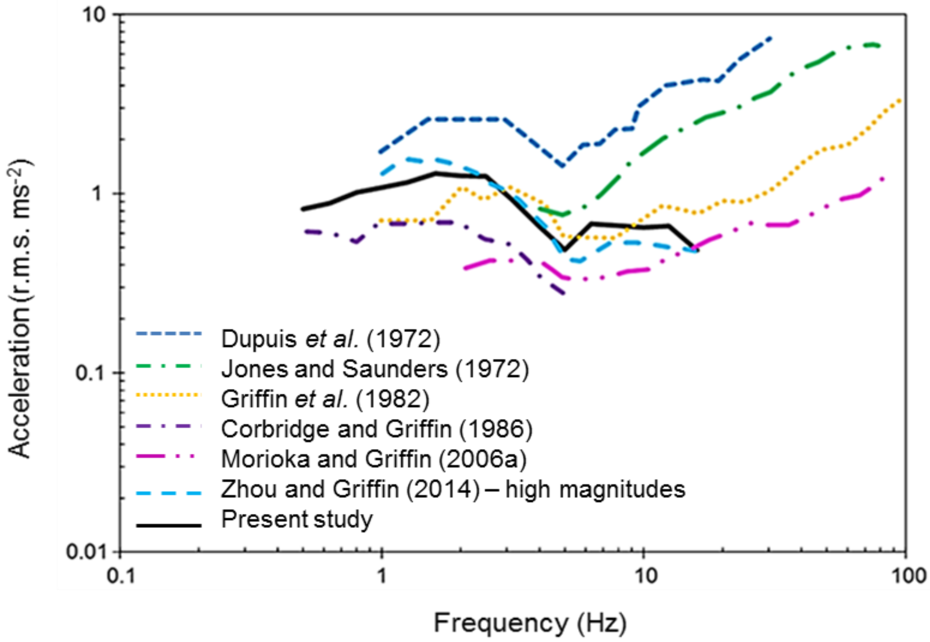


Figure 4.10 Comparison of equivalent comfort contours for sinusoidal vibration obtained in the present and previous studies.

The frequency-dependence in the rate of growth of discomfort also caused the equivalent comfort contours for shock to change shape according to the magnitude of shock (Figure 4.4).

4.4.2.2 Comparisons between equivalent comfort contours for shocks and vibration

For fundamental frequencies greater than about 4 Hz, there was greater sensitivity to unweighted sinusoidal vibration than to unweighted shock (Figure 4.5).

Whereas all the sinusoidal motions had durations of 5 seconds, the duration of each shock was n_c/f_0, where f_0 is the fundamental frequency of the shock and n_c is the number of cycles (1½ cycles for the shocks employed in this study). The durations of the shocks therefore reduced from 3 s (for 0.5-Hz shocks) to 0.09 s (for 16-Hz shocks). The VDV assumes discomfort depends on the 4^{th} root of the duration of motion, and that discomfort is similar if the VDV is similar. The 32-fold reduction in shock duration (from 0.5 to 16 Hz) will have resulted in a 2.38-fold reduction in the VDV for 16-Hz shocks compared to 0.5-Hz shocks. The effect of the time-dependency continues progressively from 0.5 to 16 Hz, whereas the difference between the equivalent comfort contours for vibration and shock is not progressive from 0.5 to 16 Hz. It follows that differences between the equivalent comfort contours for vibration and shock in Figure 4.5 cannot be explained solely by the effect of duration on discomfort being inadequately reflected in the fourth-power vibration dose value.

The method of quantifying the magnitude of the motion (e.g., VDV, r.m.s., or peak) affects the shape of an equivalent comfort contour for shock, but not the shape of an equivalent comfort contour for vibration. When using unweighted peak acceleration (Figure 4.6), there are greater differences between the contours than when using the unweighted VDV (Figure 4.5), showing that the VDV is a better indicator of discomfort than peak acceleration when no frequency weighting is employed. The peak value does not reflect the duration of the motion or even how many times the peak value is reached. Equivalent comfort contours in terms of r.m.s. acceleration are not appropriate because r.m.s. is an average measure that depends on the duration of measurement and cannot be defined in a practically useful way for shocks.

The different frequency-dependence evident in the contours for unweighted vibration and unweighted shock will be due, at least in part, to the shocks containing energy at frequencies other than their fundamental frequency. For shocks having their fundamental frequency where there is greatest sensitivity to vibration (5 to 16 Hz in this study, depending on the magnitude of the motion; Figure 4.4), there will be energy in the shocks at lower and higher frequencies, where sensitivity is less. So, when the fundamental frequency of a shock is at a frequency of greatest sensitivity, a greater unweighted VDV will be required to produce the same discomfort as caused by a sinusoidal motion of that frequency. Although the frequency-dependence of discomfort caused by shocks will depend on the shock waveform, it seems reasonable to conclude that when the fundamental frequency of a shock is a frequency with greatest sensitivity to vibration, the shock will produce less discomfort than a sinusoidal vibration with the same frequency and the same magnitude (e.g., the same unweighted vibration dose value).

The equivalent comfort contours for shock and vibration determined in this study can be compared with similar equivalent comfort contours obtained by Zhou and Griffin (2014a, 2016a) in their ‘high magnitude sessions’ (Figure 4.11). Although the contours are not identical, they show similar characteristics.

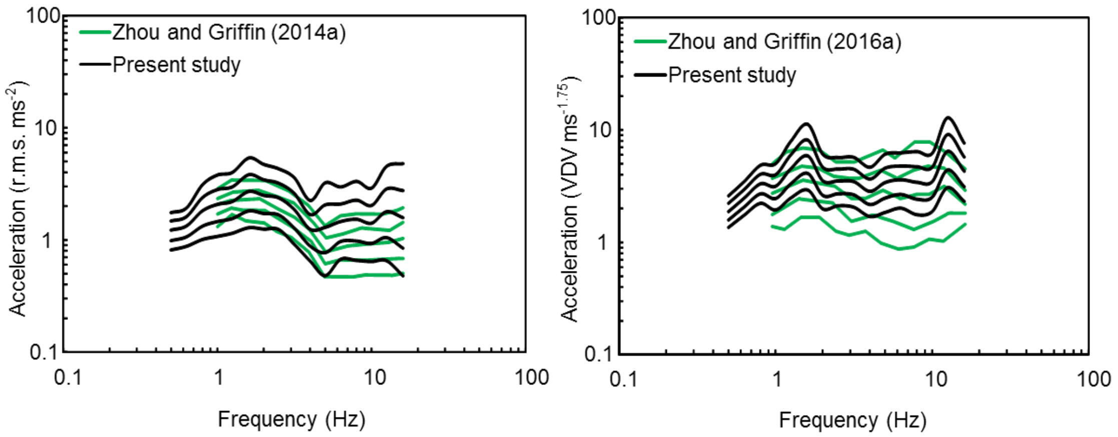


Figure 4.11 Comparison between equivalent comfort contours. Left: sinusoidal vibration in terms of unweighted r.m.s. acceleration from this study and Zhou and Griffin (2014a); right: shock in terms of unweighted VDV from this study and Zhou and Griffin (2016a). Contours are shown for subjective magnitudes of 100, 125, 160, 200, and 250.

4.4.2.3 Comparisons between equivalent comfort contours for vibration and shock in terms of frequency-weighted vibration dose values

When the equivalent comfort contours for vibration and shock are expressed in terms of frequency-weighted VDV, using weighting W_b as shown in Figure 4.7, they should be horizontal if the frequency weighting and time-dependence in the evaluation method are both appropriate.

The equivalent comfort contours in terms of frequency-weighted VDV assume somewhat flatter shapes than the unweighted contours in Figure 4.5 but they are not horizontal. At frequencies greater than 1 Hz, the contours for vibration tend to either increase or decrease with increasing frequency, depending on the vibration magnitude. This is caused by the frequency-dependence of the rate of growth of discomfort and so, although it may be argued that the W_b frequency weighting is a reasonable compromise for the magnitudes of vibration used in this study, it may not be optimum for much higher or much lower magnitudes.

The equivalent comfort contours for shocks show a progressive rise in VDV with increasing frequency, suggesting greater sensitivity at the lower frequencies than predicted by the frequency-weighted VDV. The rise at low frequencies is consistent with the findings of both Zhou and Griffin (2016a) and Ahn and Griffin (2008). Zhou and Griffin (2016a) found that for shocks with a frequency weighted VDV of 2 $ms^{-1.75}$ the magnitude estimates tended to decrease at frequencies from 1 to 4 Hz and tended to remain constant at frequencies greater than 4 Hz (Figure 4.12). Ahn and Griffin (2008) found that shocks with fundamental frequencies less than about 2 Hz and weighted VDVs around 2.9 $ms^{-1.75}$ caused greater than expected discomfort and required greater gain in the frequency weighting than given by frequency weighting W_b (Figure 4.12).

The present and previous studies are consistent in indicating that both the rate of growth of discomfort for shocks is greater at frequencies less than 2 Hz than at higher frequencies and that discomfort caused by the shocks investigated is greater than predicted by frequency weighting W_b (see Section 4.1). In part, the underestimation of discomfort at these low frequencies might be attributed to the relatively high magnitude of the shocks compared to the magnitude of vibration that influenced the shape of the W_b frequency weighting (equivalent to 0.25 and 0.75 ms^{-2} r.m.s. at 2 Hz; Corbridge and Griffin, 1986).

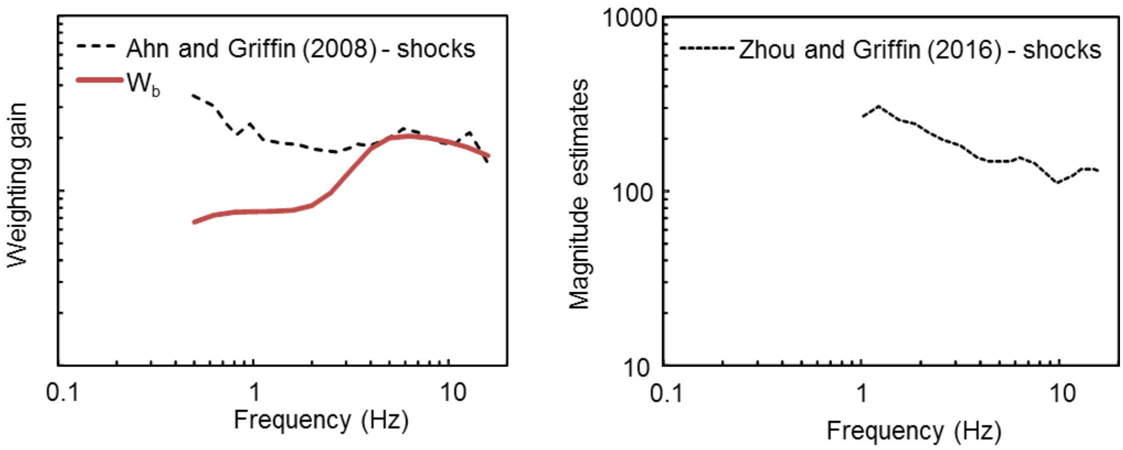


Figure 4.12 Frequency-dependent of discomfort caused by vertical shocks. Left: comparison of frequency weighting W_b with the frequency-dependence of discomfort caused by shocks produced by a one degree-of-freedom model with damping ratio ζ = 0.4 in response to Hanning-windowed half-sine input forces (Ahn and Griffin, 2008). Right: frequency-dependence of magnitude estimates of discomfort caused by shocks with a weighted VDV of 2 $ms^{-1.75}$ (Zhou and Griffin, 2016a).

The present study included greater magnitudes of vibration than Zhou and Griffin (2014a) but both studies found that increasing the magnitude of the vibration decreased the frequency of greatest sensitivity to vibration. Although the shapes of the contours changed with the magnitude of shock, both Zhou and Griffin (2016a) and the present study found flatter equivalent comfort contours for shocks than for vibration. Many frequency components of variable magnitude combine to form a mechanical shock. Since the magnitude of sinusoidal vibration affects the frequency-dependence of response to single frequency motions, it can also be expected to affect the frequency-dependence of responses to shocks. However, the magnitudes of the many frequency components in a shock are lower than the single frequency component in a sinusoidal motion that has the same magnitude as the shock. It is therefore unclear what equivalent comfort contour is likely to be most appropriate for defining a frequency weighting for any shock, let alone all shocks. The previous and the present studies indicate that the use of a single frequency weighting cannot be expected to provide an accurate prediction of the discomfort caused by a different shocks. Shocks with different waveforms have different spectra, so it is not appropriate to derive a frequency weighting for the fundamental frequency of one waveform and apply it to shocks having different waveforms.

4.4.3 Appropriateness of the frequency weighting

Gain of the frequency weighting

Unlike Zhou and Griffin (2014a, 2016a) the present study investigated discomfort caused by frequencies less than 1 Hz (i.e., 0.5, 0.63, and 0.8 Hz). When the contours for a subjective magnitude of 100 were expressed in terms of unweighted VDV, there were no significant differences between the equivalent comfort contours for vibration and shock at these lower frequencies. However, for shocks having fundamental frequencies in this range, the standardised 0.4-Hz high-pass filter used with frequency weighting W_b attenuates some of the low frequencies present in the shock waveform and reduces the frequency-weighted VDV of the shocks. For example, if the fundamental frequency is 0.5 Hz, a sinusoidal vibration and a shock with unweighted VDVs of 2.0 $ms^{-1.75}$ have VDVs of 1.7 and 1.5 $ms^{-1.75}$, respectively, after being filtered solely by the 0.4-Hz high-pass filter required when applying the W_b frequency weighting. After being frequency-weighted using W_b (with the 0.4-Hz high-pas filer in accord with the standards), the VDVs of these two motions are 0.7 and 0.6 $ms^{-1.75}$, respectively. This effect of the high-pass filter on the weighted magnitude of the shocks may explain why, at frequencies less than about 0.8 Hz, the shocks appear to cause more discomfort than vibration with the same frequency-weighted VDV (Figure 4.7). The difference in frequency-weighted VDVs for vibration and shock is somewhat reduced because the 5-s sinusoidal waveforms used in this study also contained some energy at frequencies less 0.4 Hz, and so were also slightly attenuated by the 0.4-Hz high-pass filter.

The approach to predicting the discomfort caused by oscillatory motion has been to define a frequency weighting (from studies of frequencies with more-or-less sinusoidal oscillation) and a duration weighting (from studies with differing durations). The simple combination of the frequency weighting and the duration weighting (e.g., the frequency-weighted vibration dose value) assumes that the frequency weighting is independent of the duration of the motion, and that the duration weighting is independent of the frequency of the motion, and that both weightings are independent of the magnitude of the motion. Such assumptions seem necessary in order to define a simple practical method for evaluating the severity of oscillatory motion. However, the optimum frequency weighting depends on the magnitude of vibration at the moderate magnitudes of motion used in this study and at much lower magnitudes (e.g., Morioka and Griffin, 2006a).

The appropriate weighting may also be expected to change at greater magnitudes than investigated in this study if contact between the seat and the body is lost at times during a cycle of motion. The use of a simple frequency weighting (e.g., W_b) with a simple duration weighting (e.g., VDV) provides a practical method of evaluating shock severity, but the 'non-linearities' in human responses mean no such weightings can provide accurate predictions of the discomfort caused by a wide range of shocks.

Phase of the frequency weighting

When a shock is weighted (by the appropriate frequency weighting and band-pass filters defined in a standard, such as BS 6841:1987 or ISO 2631-1:1997) the waveform of the shock is distorted by the phase responses of all the filters delaying different frequencies by differing amounts. Because the phase response of filters can affect the measured value, it is important that evaluations of vibration are made using filters that have the standardised phase response as well as the standardised gain.

The problem is not confined to defining the appropriate phase for the filter representing the human response (e.g. frequency weighting W_b), it also applies to the band-limiting filters (0.4-Hz high-pass filter and 100-Hz low-pass filter used with W_b). For shocks with the lowest and highest fundamental frequencies used in this study (i.e., 0.5 and 16 Hz), the unweighted waveforms, the weighted waveforms (weighted by frequency-weighting W_b with the designated band-pass filters at 0.4 and 100 Hz), and the waveforms filtered solely by the 0.4-Hz high-pass filter are compared in Figure 4.13. The shock with the 0.5-Hz fundamental frequency is much distorted by the high-pass filter. The phase responses of both the frequency weighting and the high-pass filter also affect the VDV of the waveform and its peak values. The 0.4-Hz high pass filter attenuates 0.5-Hz motion (to 84% of its value) as well as distorting the waveform. The same phenomenon will happen with motions having frequencies close to the low-pass filter at 100 Hz. The effect of the band-limiting filters needs further consideration when evaluating a shock, even if the fundamental frequency of the shock is within the range 0.5 to 80 Hz.

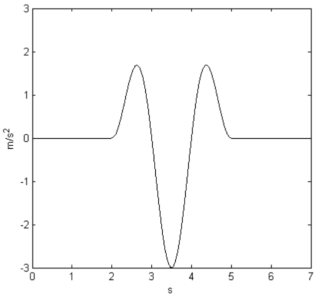
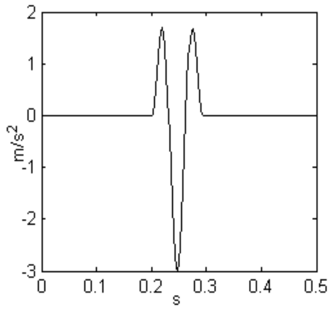
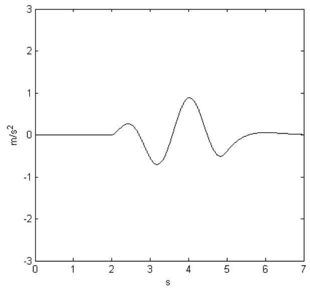
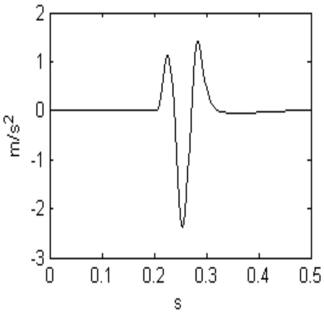
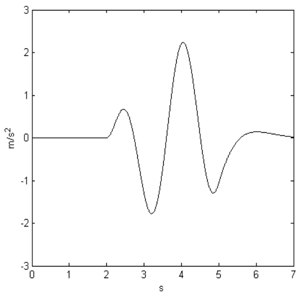
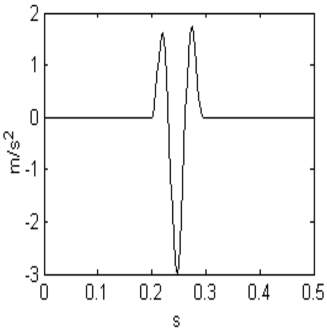
0.5-Hz shock	16-Hz shock
VDV= 2.42 $ms^{-1.75}$  original waveform	VDV= 1.02 $ms^{-1.75}$  original waveform
VDV= 0.74 $ms^{-1.75}$  W_b weighted (including 0.4 Hz high pass filter)	VDV= 0.82 $ms^{-1.75}$  W_b weighted (including 0.4 Hz high pass filter)
VDV=1.87 $ms^{-1.75}$  filtered by the 0.4-Hz high pass filter only	VDV= 1.02 $ms^{-1.75}$  filtered by the 0.4-Hz high pass filter only

Figure 4.13 Effect of frequency weighting W_b and 0.4-Hz high-pass filter on shock waveforms. Left: a shock with fundamental frequency of 0.5 Hz. Right: a shock with fundamental frequency of 16 Hz.

4.5 Conclusions

The rate of growth of discomfort of sinusoidal vibration or mechanical shock depends on the fundamental frequency of the motion and differs between a sinusoidal vibration and a shock of the same fundamental frequency. The frequency-dependence of discomfort caused by both vibration and shock therefore varies according to the magnitude of the motion and differs between sinusoidal vibration and shock. It follows that no single frequency weighting is optimum for all magnitudes or both types of motion.

At frequencies causing greatest discomfort, if a vibration and a shock have the same fundamental frequency and the same unweighted peak value or unweighted vibration dose value, the shock will cause less discomfort. Consequently, when vertical vibration and shocks with fundamental frequencies in the range 0.5 to 16 Hz are evaluated in terms of frequency-weighted vibration dose values using frequency-weighting W_b, shocks with fundamental frequencies greater than 4 Hz are less uncomfortable than sinusoidal motions of the same fundamental frequency.

With fundamental frequencies less than about 1 Hz, shocks cause slightly more discomfort than vibration with the same frequency-weighted VDV, because the high-pass filters employed with the weighting attenuate some low frequency components in the shock waveform more than they attenuate sinusoidal vibration of the same fundamental frequency. The effects of the high-pass filter need consideration if the standardised evaluation method is used to evaluate mechanical shocks containing low frequencies.

Chapter 5: THE EFFECTS ON DISCOMFORT OF THE DIRECTION OF VERTICAL SHOCKS GREATER THAN 1 g

5.1 Introduction

British Standard 6841 (1987) and International Standard 2631-1 (1997) provide guidance on the measurement and evaluation of whole-body vibration and mechanical shocks. A single frequency weighting is provided to allow for the frequency-dependence of the discomfort caused by vertical vibration and shocks, irrespective the waveform and the magnitude of the motion.

In some environments, such as marine craft, military tanks, agricultural vehicles and aircraft, vertical shocks often occur predominantly in one of two directions (i.e. up or down) and the acceleration can exceed 1 g. Few studies have investigated how uncomfortable these motions can be and whether it is necessary to evaluate them differently from lower magnitude vibration.

5.1.1 The effect of direction on the discomfort caused by vertical shocks

Studies that have investigated the effect of the direction of a vertical shock on discomfort have not found that discomfort is different for upward and downward shocks (Howarth and Griffin, 1991; Cameron *et al.*, 1997; Ahn and Griffin, 2008; Zhou and Griffin, 2016a). The peak accelerations of the shocks in these studies were less than 1 g, except in the study of Cameron *et al.* (1997) where in one experiment the vertical shocks in the range 2 to 10 Hz reached 4 g peak. While Howarth and Griffin (1991), Ahn and Griffin (2008), and Zhou and Griffin (2016a) used lower magnitudes and participants were ‘ordinary’ subjects (i.e. students or office employees), Cameron *et al.* (1997) used military operators.

5.1.2 The discomfort caused by vertical high magnitude vibration

Some early studies investigated the discomfort caused by high magnitude sinusoidal vibration with peak accelerations greater than 1 g (e.g., Ziegenruecker and Magid, 1959; Mandel and Lowry, 1962; Chaney 1964, 1965). The main objective of these studies was to find tolerance limits for vertical vibration.

Ziegenruecker and Magid (1959) exposed 10 seated subjects to vertical sinusoidal vibration at frequencies in the range 1 Hz to 15 Hz. They found that a tolerance limit was around 3 g at frequencies in the range 1 to 4 Hz and around 2 g at frequencies in the range 5 to 10 Hz. At these magnitudes of vibration, they also found that subjects experienced symptoms such as chest pain, dyspnea, and increasing heart rate and blood pressure. Thresholds of tolerance at magnitudes between 1g and 4 g were also found by Madel and Lowry (1962) in the frequency range 5 Hz to 10 Hz and by Chaney (1964, 1965), who both reported the occurrence of physical symptoms (such as chest pain, back pain, vision blurring and dyspnea) at the highest magnitudes reached. As discussed in a review by Hanes (1970), their results differ from those of five earlier studies (i.e. Jacklin and Liddell, 1933; Meister, 1935; Gorrill and Snyder, 1957; Parks and Snyder, 1961) where limits of tolerance in terms of peak acceleration ranged from 0.1 to 1 g.

Comparing the frequency dependence of comfort contours obtained by, for example, Helberg and Sperling (1941) with the frequency dependence of the comfort contours obtained by Ziegenruecker and Magid (1959) it seems that while in the first study greatest sensitivity is shown in the region of frequency 2 to 5 Hz, in the second study lower tolerance limits are reached at frequencies from 5 to 10 Hz. Discrepancies among these studies may have been due to the use of different psychophysical methods for judging discomfort, different durations of stimuli, different sitting or standing conditions and different contexts. For example, in Ziegenruecker and Magid (1959) ten seated subjects were restrained tightly with a lap seatbelt and a shoulder harness with the feet strapped down to the platform so that they were not able to move either horizontally or vertically. In studies by Helberg and Sperling (1941) subjects were unrestrained and tolerance limits were found to be about 0.1 to 0.2 g, much lower than in Ziegenruecker and Magid (1959), Mandel and Lowry (1962), and Chaney (1964, 1965).

The participants investigated by Cameron *et al.* (1997), Ziegenruecker and Magid (1959), Mandel and Lowry (1962) and Chaney (1964, 1965) were either members of military forces or worked in environments that are characterized by high magnitude vibration. Although subjects were asked to judge stimuli based on their sensation only, the effect of experience on subjective impressions cannot be excluded. It can be supposed, for example, that for railway passengers or car drivers, where median vibration magnitudes are less than 0.6 ms^{-2} r.m.s. (e.g. Paddan and Griffin, 2002) their sensitivity to high magnitude vibration may be greater than military officers, pilots, or marine craft operators, who are daily exposed to high magnitudes (e.g. Townsend *et al.*, 2008) and have been trained for those environments.

5.1.3 The effect of increasing magnitude on the human response to vibration

Several studies have found that the frequency dependence of the equivalent comfort contours obtained with continuous vibration and shock-type vibration changes with the magnitude of vibration: the region of greatest sensitivity to acceleration shifts to lower frequencies as the magnitude of vibration increases (Morioka and Griffin, 2006a, Ahn and Griffin, 2008, Zhou and Griffin, 2014a, 2016a). The resonance frequencies in the vertical apparent mass and the vertical-in-line seat to head transmissibility decrease as the magnitude of vibration increases (e.g. Fairley and Griffin, 1989, Mansfield and Griffin, 2000, Matsumoto and Griffin, 2002a, Zhou and Griffin, 2014b).

In some situations where the body is not restrained, with upward displacements and peak accelerations greater than 1 g the body will lose contact with the seat. The subsequent impact with the seat would be expected to increase discomfort.

5.1.4 Objective and hypothesis

The main objective of this study was to find at what magnitudes the discomfort caused by vertical shocks with fundamental frequencies in the range 2 Hz to 5 Hz and peak acceleration in the range 7.0 to 10.7 ms^{-2} depends on the direction of the shock (i.e. up or down).

It was hypothesised that upward shocks (where the dominant displacement is upward and the dominant acceleration is downward) would be more uncomfortable than downward shocks (where the dominant displacement is downward and the dominant acceleration is upward) when the peak acceleration of the seat in the downward direction exceeds 1 g. It was also hypothesised that when the downward acceleration of the seat exceeds 1 g, wearing a ‘loose’ seat belt would be more uncomfortable than wearing a ‘tight’ seat belt, because a tight belt would prevent subjects leaving the seat and experiencing a shock when falling back onto the seat.

5.2 Method

5.2.1 Subjects

Sixteen male students and office workers at the University of Southampton participated in the study. They were aged 19 to 37 years, stature between 160 and 185 cm, and weight between 56 and 86 kg. The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (ethics approval number: 13014).

5.2.2 Apparatus

Vertical oscillations were produced by a 1-m stroke vertical electrohydraulic vibrator (Servotest Testing Systems Ltd., Surrey, UK). Mechanical shocks were generated by the *HVLab* Matlab Toolbox (version 2.0, ISVR, University of Southampton, UK), and equalized and reproduced by a Servotest Pulsar system.

A flat rigid seat was mounted on the platform of the vibrator. The seat had an upright rigid backrest but subjects were asked not to make contact with the backrest (Figure 5.1). A noise box (HFRU Noise system 001, ISVR, University of Southampton, UK) produced white noise at approximately 75 dB via a pair of headphones so as to mask other noises in the laboratory.

A lap-belt was used to secure the subjects to the seat. An emergency stop button was provided to subjects.

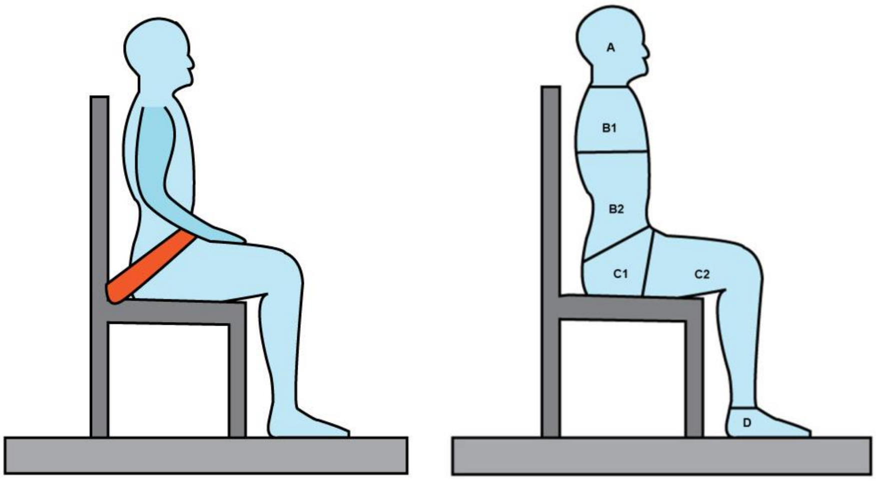


Figure 5.1 Experimental setup and body map used in this study.

5.2.3 Stimuli

The motions were vertical mechanical shocks with fundamental frequencies at the five preferred one-third octave centre frequencies in the range 2 to 5 Hz (i.e., 2.0, 2.5, 3.15, 4 and 5 Hz).

The shocks were formed from 1½ cycles of a sinusoid of the required fundamental frequency multiplied by a half cosine over the duration of the 1½-cycle sinusoid. The duration of the shocks therefore depended on their fundamental frequency, varying from 0.3 s at 5 Hz to 0.75 s at 2 Hz.

At each fundamental frequency, the shocks were presented at five magnitudes of unweighted peak acceleration in the range 7.0 to 10.7 ms^{-2} in 1 dB steps. Each shock was presented in both directions (up and down), where an upward shock had an upward displacement and the specified downward peak acceleration when at the upmost position (see Figure 5.2).

a) upward b) downward

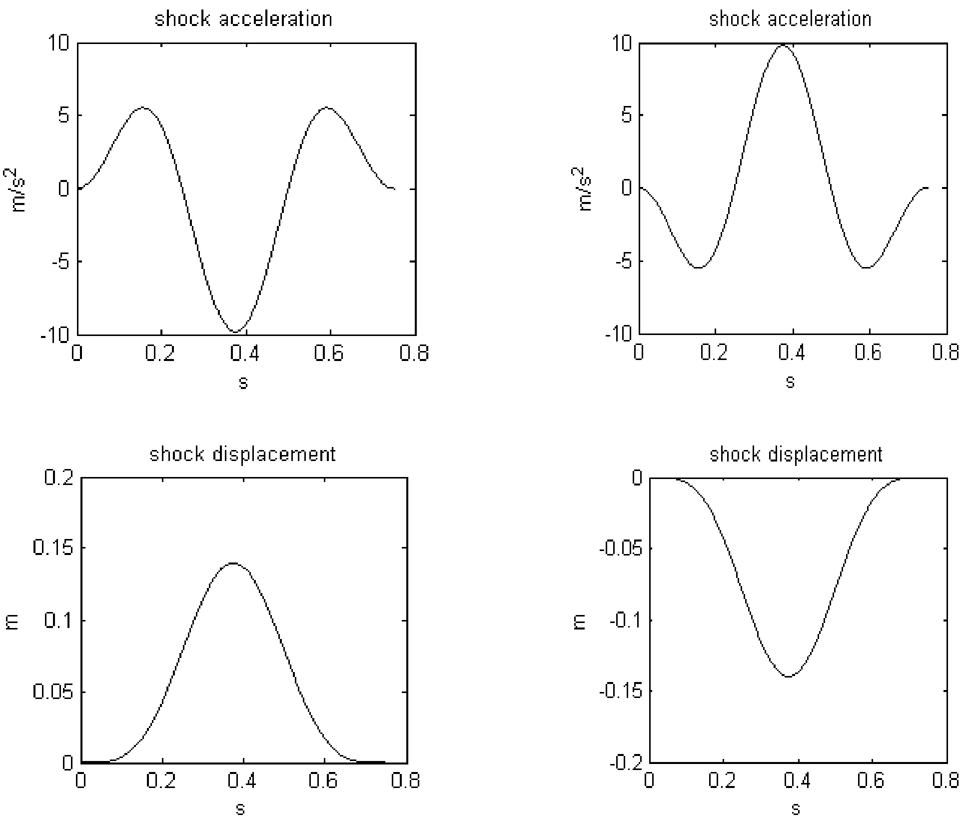


Figure 5.2 Acceleration and displacement of upward (a) and downward (b) shocks.

The upward and downward motions were designed to have the same peak acceleration at each fundamental frequency of the shocks. The desired peak accelerations and the peak accelerations measured on the vibration simulator are shown in Table 5.1. The measured values of the motions were used in the analysis.

5.2.4 Procedure

Subjects attended one session of about 30 minutes duration. They sat upright without touching the backrest with the lap-belt in two conditions: ‘tight belt’ and ‘loose belt’. The experiment was split into two parts, one for each condition with a 5-minute break between parts. Half of the subjects began with the tight belt and half began with the loose belt. The order of presentation of the 50 test stimuli (five magnitudes at five frequencies and in two directions) was randomised for each individual and both sitting conditions.

Table 5.1 Desired and measured peak accelerations of the upward and downward vertical shocks.

Desired peak accelerations (ms^{-2})									
2 Hz		2.5 Hz		3.15 Hz		4Hz		5Hz	
upward	downward	upward	downward	upward	downward	upward	downward	upward	downward
-7.0	7.0	-7.0	7.0	-7.0	7.0	-7.0	7.0	-7.0	7.0
-8.0	8.0	-8.0	8.0	-8.0	8.0	-8.0	8.0	-8.0	8.0
-8.6	8.6	-8.6	8.6	-8.6	8.6	-8.6	8.6	-8.6	8.6
-9.82	9.82	-9.82	9.82	-9.82	9.82	-9.82	9.82	-9.82	9.82
-10.7	10.7	-10.7	10.7	-10.7	10.7	-10.7	10.7	-10.7	10.7
Measured peak acceleration (ms^{-2})									
2 Hz		2.5 Hz		3.15 Hz		4Hz		5Hz	
upward	downward	upward	downward	upward	downward	upward	downward	upward	downward
-7.3	7.4	-7.3	7.0	-7.3	6.8	-7.3	6.5	-7.4	6.5
-8.1	8.0	-8.1	7.7	-8.0	7.4	-7.9	7.3	-8.2	7.2
-8.9	9.1	-8.9	8.5	-8.9	8.2	-8.8	8.0	-8.9	7.8
-9.9	9.9	-9.8	9.3	-9.8	9.1	-9.6	8.8	-9.6	8.7
-10.5	10.6	-10.6	10.1	-10.6	9.8	-10.5	9.6	-10.4	9.5

With the ‘tight belt’, subjects fastened the belt so that the body would always remain in contact with the seat. With the ‘loose belt’, a wooden board (2-cm thick) was put under buttocks, the belt was fastened tight, and then the board was removed before commencing the test.

Participants rated the discomfort caused by each motion using absolute magnitude estimation (Stevens S.S., 1957). Subjects practiced absolute magnitude estimation by giving a numerical rating of the apparent length of several lines.

In addition to rating discomfort, after each motion participants were asked to indicate the body location of most discomfort (using Figure 5.1) and whether the motion caused them to leave the seat.

Subjects practiced with 10 stimuli (encompassing the full range of magnitudes and frequencies in the study), before commencing the experiment. Each session included 100 test stimuli and lasted about 30 minutes.

5.2.5 Statistical analysis

The hypotheses were tested using non-parametric statistical tests. To investigate differences between related samples, the Friedman two-way analysis of variance and Wilcoxon matched-pairs signed ranks were used.

To analyse categorical data (i.e. locations of discomfort) the Cochran Q test and the McNemar's test were employed.

The probabilities shown in this chapter were not adjusted for multiple comparisons.

5.3 Results

The hypotheses of the study were tested by analysing how raw judgments of discomfort varied with the magnitude and the direction of vibration. Within each subject, all magnitude estimates of discomfort (obtained using absolute magnitude estimation) were normalized by dividing by the median of the 100 magnitude estimates and then multiplied by 100. This meant the median magnitude estimate was 100 for every subject.

5.3.1 Effect of shock direction and seat belt tightness

With the 'tight belt', high magnitude upward shocks tended to be more uncomfortable than downward shocks of the same unweighted peak acceleration (Figure 5.3). The difference was statistically significant with 2-Hz shocks greater than 8.2 ms^{-2} (p<0.023), 2.5-Hz shocks greater than 7.3 ms^{-2} (p<0.004), 3.15-Hz shocks greater than 8.0 ms^{-2} (p<0.050), and 4-Hz shocks of 7.2 ms^{-2} (p=0.004) and 8.8 ms^{-2} (p=0.005).

With the 'loose belt', upward shocks were more uncomfortable than downward shocks of the same unweighted peak acceleration (Figure 5.4). The differences were statistically significant with 2-Hz shocks greater than 7.2 ms^{-2} (p<0.002), 2.5-Hz shocks greater than 7.3 ms^{-2} (p<0.002), 3.15-Hz shocks greater than 7.2 ms^{-2} (p<0.012), and 4-Hz shocks of 9.6 ms^{-2} (p=0.004).

There were no statistically significant differences in the discomfort caused by upward and downward shocks at 5 Hz with either a loose or a tight belt.

With all frequencies and magnitudes and both directions of shocks there were no statistically significant differences between the magnitude estimates of discomfort provided with a loose belt and a tight belt (Figure 5.5).

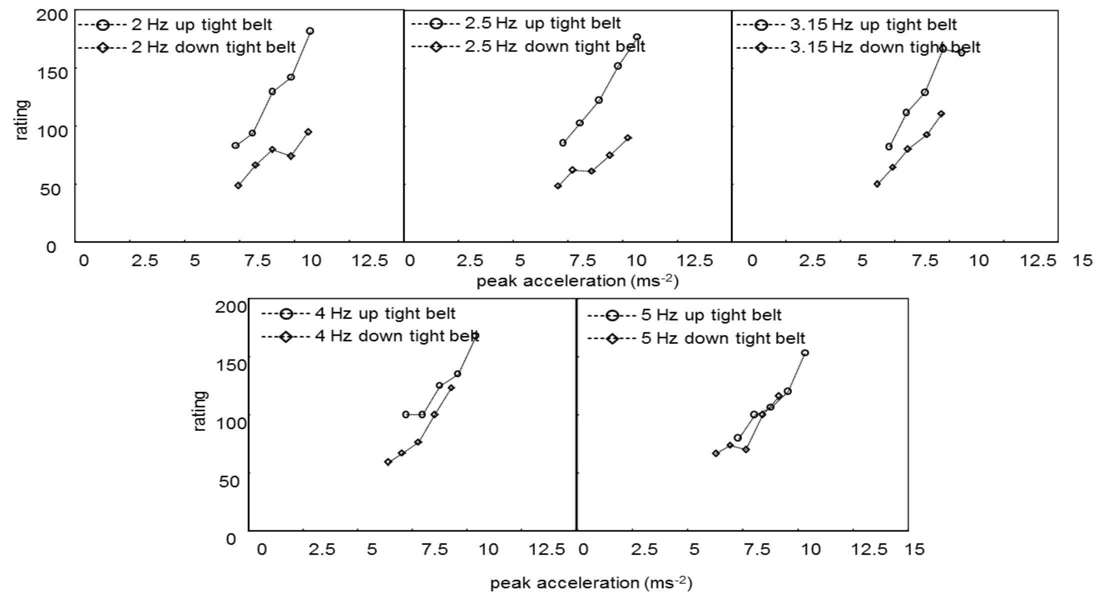


Figure 5.3 Raw ratings of discomfort (normalized) caused by upward (--○--) and downward (--◊--) shocks during the 'tight belt' condition at each frequency of vibration. Median data calculated over 16 subjects.

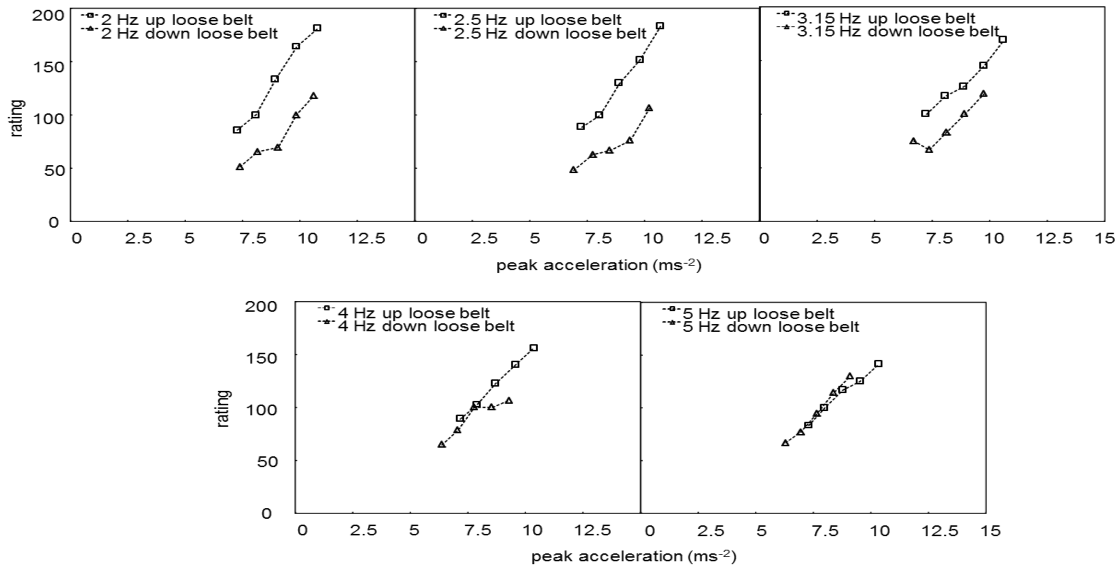


Figure 5.4 Raw ratings of discomfort (normalized) caused by upward (--□--) and downward (--Δ--) shocks during the 'loose belt' condition at each frequency of vibration. Median data calculated over 16 subjects.

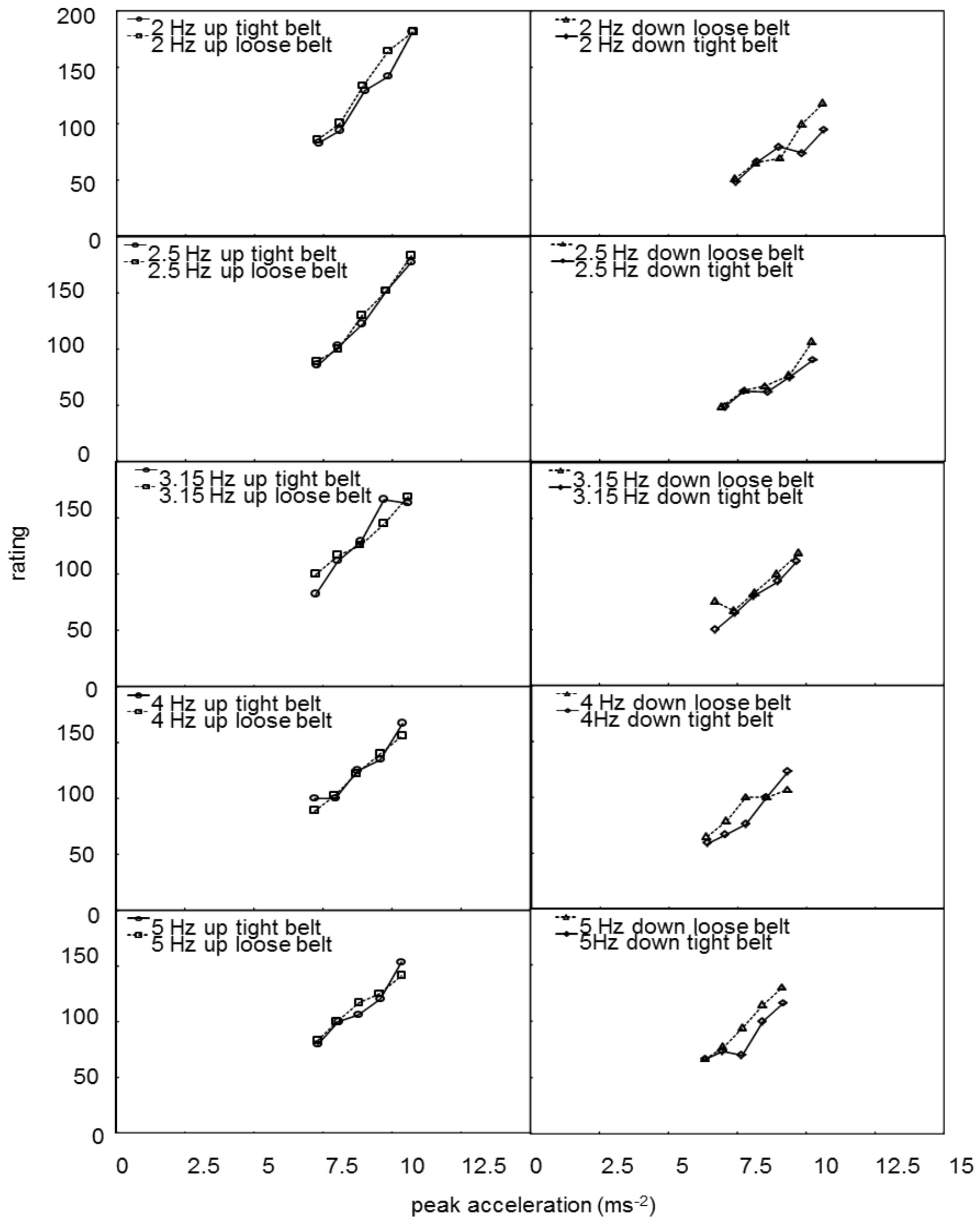


Figure 5.5 On the left, raw ratings of discomfort (normalized) caused by upward shocks in the 'loose belt'(--□--)and 'tight belt' condition (—○—).On the right, raw ratings of discomfort (normalized) caused by upward shocks in the 'loose belt'(--Δ--)and 'tight belt' condition (—◊—). Median data calculated over 16 subjects.

5.3.2 Body locations of discomfort

5.3.2.1 Within belt condition

With the loose belt and upward shocks with fundamental frequencies of 2 and 2.5 Hz, the number of judgements indicating C1 (the buttocks) as the prime location of discomfort depended on the magnitude of vibration (p<0.022, Cochran's Q test; Figure

5.6). As the shock magnitude increased at frequencies less than 3.15 Hz, the number of judgements indicating C1 as the prime cause of discomfort increased (Figure 5.6). With the loose belt and 2.5-Hz shocks, the number of judgements indicating C1 was greater with upward shocks than with downward shocks when the peak acceleration was greater than 9.81 ms^{-2} (p<0.008, McNemar test; Figure 5.6).

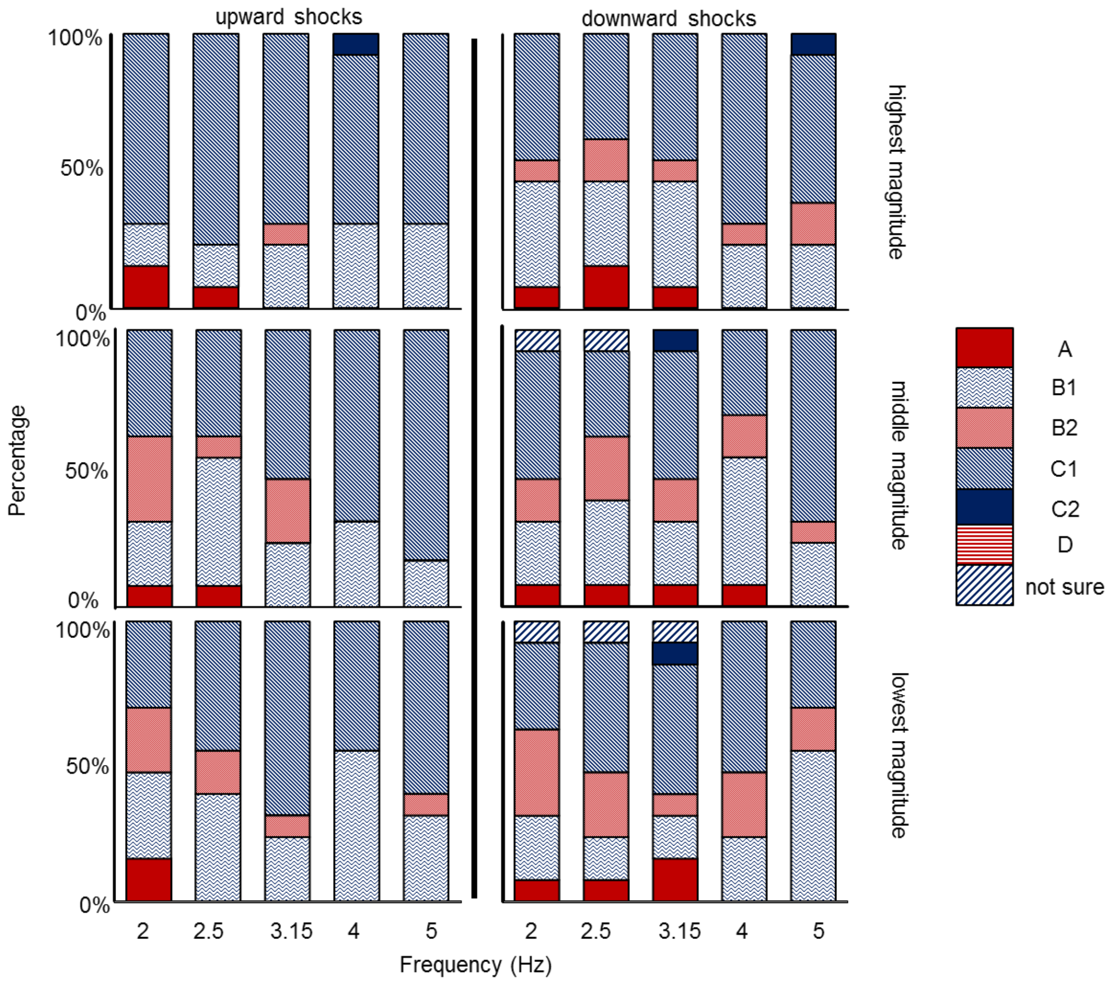


Figure 5.6 Location of discomfort during the 'loose belt' condition.

With the tight belt, the number of judgements indicating C1 was greater with upward shocks than with downward shocks when the peak acceleration was greater than or equal to 9.81 ms^{-2} at 2 Hz (p<0.039, McNemar test; Figure 5.7). As the shock magnitude increased at frequencies less than 3.15 Hz, the number of judgements indicating C1 as prime cause of discomfort increased (Figure 5.6), although there was not a statistically significant effect of the magnitude of the shocks on the location of discomfort (Figure 5.7).

Figures 5.6 and 5.7 show that the locations of most discomfort were the buttocks (location C1) and the upper body (location B1) when exposed to either upward or downward shocks. With high magnitude shocks having nominal frequencies less than 3.15 Hz, most discomfort was more frequently in the buttocks area (C1) during upward shocks than during downward shocks.

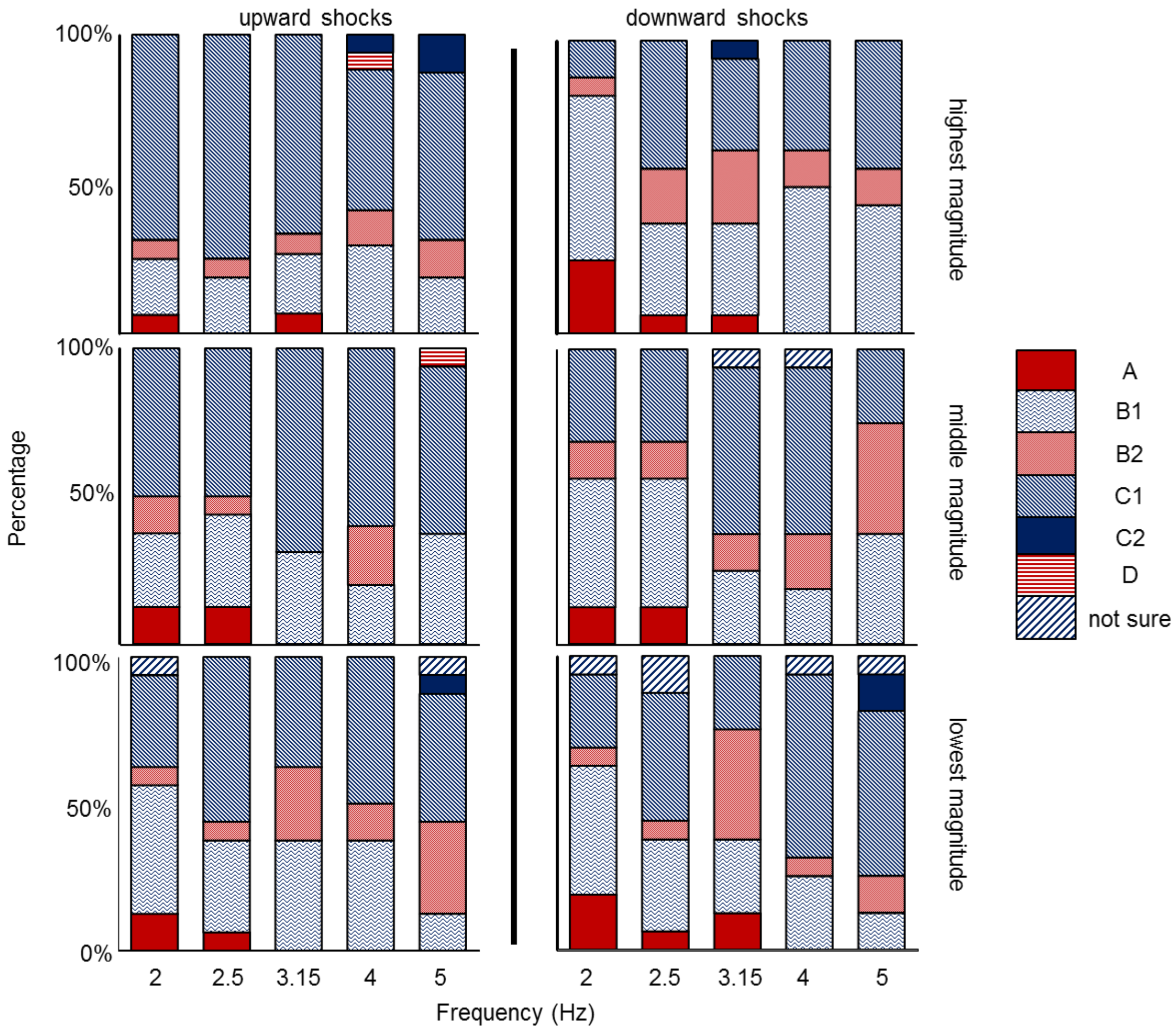


Figure 5.7 Location of discomfort during the ‘tight belt’ condition.

5.3.2.2 Between belt conditions

There were no statistically significant differences in locations of discomfort with most frequencies, magnitudes, and directions between wearing a ‘tight belt’ and wearing a ‘loose belt’. There was a greater number of subjects indicating B1 as the location of greatest discomfort caused by downward shocks at 5 Hz with the lowest magnitude of vibration ($p<0.031$) with loose belt than with a tight belt .

5.4 Discussion

The discomfort caused by upward shocks was greater than the discomfort caused by downward shocks at frequencies between 2 to 4 Hz and when the peak acceleration of the shocks was greater than, or close to, 1 g (i.e., 9.81 ms^{-2}).

Consistent with this study, Ahn and Griffin (2008) found that when the fundamental frequency of the shock was 2.0 Hz or 3.15 Hz, upward shocks were slightly more uncomfortable than downward shocks. Unlike this study, Howarth and Griffin (1991) and Zhou and Griffin (2016a) did not find a statistically significant effect of shock direction on the discomfort caused by vertical mechanical shocks. However, the median magnitudes estimates presented in Howarth and Griffin (1991) showed that at the highest magnitude (VDV= 2.5 $ms^{-1.75}$) upward shocks were slightly more uncomfortable than downward shocks at 1, 4 and 16 Hz. Results at the highest magnitudes also show that for both directions ratings were greater at 1 Hz than at 4 and 16 Hz.

The difference in discomfort between upward and downward shocks found in this study may have been caused by impact of the body with the hard seat after rising from the seat at the top of the motion. There was increased discomfort with shocks having dominant upward displacements in the range 2 Hz to 4 Hz. When the peak downward acceleration associated with an upward displacement exceeds 9.81 ms^{-2}, an unrestrained rigid body will separate from the seat. If the human body behaved like a rigid mass, when the acceleration is greater than 1 g, this phenomenon would happen at all frequencies. However, the human body is not rigid and for the magnitudes used in this study it only seems to have happened at frequencies less than 4 Hz. The body tissues in contact with the seat may be modelled as a spring that compresses and extends during vertical vibration. The ‘spring’ will eventually separate from the seat when it reaches its full extension. If the shock is not sufficient for the ‘spring’ to fully extend, the body will not leave the seat. This may explain why the body only left the seat with shocks having larger displacements at frequencies less than 4 Hz in this study.

This study found that with increasing magnitude of shock, the number of subjects who chose C1 (i.e. buttocks) as the location of greatest discomfort increased when the fundamental frequency of the shock was in the range 2 Hz to 3.15 Hz (Figures 5.6 and 5.7). Analysis of the locations of body discomfort suggests impact with the seat could be the reason for greater discomfort with upward shocks than with downward shocks of the same magnitude. Participants in the experiment reported that, although they felt relative motion in the upper body (i.e. at B1), they felt greatest discomfort at the buttocks because of the impact with the rigid seat pan experienced with the highest magnitudes.

Shocks with upward displacements were more uncomfortable than downward shocks with fundamental frequencies in the range 2 to 4 Hz when the peak acceleration was around 7.0 ms^{-2} and subjects were wearing a tight belt. In these conditions it was expected the body would not leave the seat. The findings suggest either the slack in the seat belt was sufficient to allow some separation and subsequent ‘impact’, or impact is not the only reason for differences in discomfort between upward and downward shocks found in this study.

The discomfort caused by upward shocks may have been greater than the discomfort caused by downward shocks because the subjects found the experience unusual, despite practice prior to commencing the experiment. The feeling of being propelled upward may have induced more stress and muscle tension.

5.4.1 Effect of seat belt tightness

Contrary to the hypothesis, the tightness of the lap-belt did not change either discomfort or body location of discomfort caused by either upward or downward shocks. The loose belt had only 2-cm of slack and may not have been sufficient to cause much difference in body motion, even when the acceleration exceeded 1 g. A less restrained condition should be investigated.

5.5 Conclusions

Shocks with dominant upward displacement and dominant downward acceleration become more uncomfortable than shocks with dominant downward displacement and dominant upward acceleration at fundamental frequencies less than 4 Hz when the unweighted peak acceleration is in the range 7.0 to 10.7 ms^{-2}.

Greater discomfort caused by upward shocks than downward shocks at fundamental frequencies less than 4 Hz may be partly due to subjects leaving the seat and the consequent impact with the surface of the seat. This is consistent with most discomfort being located at the buttocks with the higher magnitudes shock in this study.

Contrary to the initial hypothesis, there were no differences in discomfort or the location of discomfort when restrained by a ‘loose belt’ and a ‘tight belt’.

Chapter 6: THE DISCOMFORT CAUSED BY SHOCKS WHEN SITTING ON SOFT SEATS: THE MEASUREMENT AND PREDICTION OF SEAT VALUE

6.1 Introduction

The discomfort caused by vertical vibration and shocks has been widely investigated when subjects sit on a rigid seat (e.g. Miwa, 1967; Dupuis et al., 1972; Griffin et al., 1982; Morioka and Griffin, 2006a; Howarth and Griffin, 1991; Matsumoto and Griffin, 2005; Ahn and Griffin, 2008; Zhou and Griffin, 2016a). A few studies have investigated the effect of seat characteristics on the discomfort caused by vertical continuous vibration (e.g. Matsumoto Y. and Griffin, 1977; Corbridge and Griffin, 1986; Ebe and Griffin, 2000a,b; Basri and Griffin, 2014) but there are no known controlled studies of the effect of seat dynamics on the discomfort caused by vertical mechanical shocks. Measurements in disparate environments, such as in high speed craft (e.g. Rutherford, 2011) and cars (e.g. Paddan and Griffin, 2002), showed that low and high magnitude vertical shocks often occur.

6.1.1 Assessment of comfort with soft seats and during exposure to shocks

It is not possible to obtain the profile of seat transmissibility over a wide range of frequency using shock-type vibration as for as broadband random vibration. It is possible to use the ‘seat effective amplitude transmissibility’ calculated as the ratio between the vibration dose value (VDV) of the acceleration measured at the top surface of the seat and the VDV of the acceleration measured at the rigid base of the seat (Griffin, 1990):

$$\text{SEAT \%} = \frac{VDV_{top\ surface}}{VDV_{seat\ base}} \times 100$$

where both VDVs are frequency-weighted using the weighting applicable to vertical vibration at the seat-person interface.

The SEAT value is an indicator of the isolation efficiency of a seat (Griffin, 1978). Studies have investigated the applicability of the SEAT values for predicting overall discomfort when using compliant seats (e.g. Niekerk *et al.*, 2003; Basri and Griffin, 2014). High correlations were found between subjective responses and the SEAT values for 16 car seats (Niekerk *et al.*, 2003). Basri and Griffin (2014) found that the measured seat dynamic discomfort (MSDD) and the predicted discomfort (SEAT values) were broadly similar for three seats of different ‘hardness’, although they found statistically significant differences within each sitting condition at low and high frequencies (in the range 1 to 20 Hz). These differences were partially explained by assumptions and limitations in the currently standardised methods for predicting vibration discomfort.

The applicability of SEAT values to predict the effects of compliant seats on the discomfort caused by vertical mechanical shocks has not been investigated, although SEAT values seem to predict the effects of compliant seats on overall discomfort caused by vibration.

6.1.2 Prediction of the vertical seat transmissibility for vertical continuous vibration

Several lumped parameter models have been used to represent the dynamic response of the coupled system comprising the human body and a seat exposed to whole-body vibration (e.g. Wei and Griffin, 1998b; Lewis and Griffin, 2002; Toward and Griffin, 2011b; Tufano and Griffin, 2013). Simple linear lumped parameter models can provide good predictions of the dynamics of a seat during exposure to continuous vertical vibration (Wei and Griffin, 1998b; Toward and Griffin, 2011b). A two degree-of-freedom model of the human body provided better predictions of seat transmissibility than a single-degree-of-freedom model (Wei and Griffin, 1998b).

Other methods of predicting seat transmissibility have used the apparent mass of subjects measured on a rigid seat and the dynamic stiffness of soft seats measured with an indenter rig (Fairley and Griffin, 1986; Tufano and Griffin, 2013). This gave accurate fitting of the vertical seat transmissibility, and the stiffness and damping of several different types of seat (Fairley and Griffin, 1986) and seat cushions (Tufano and Griffin, 2013), but they require the availability of an indenter rig to measure seat dynamic stiffness.

Dynamic models of the coupled seat and human body system can be used to predict SEAT values of seats exposed to continuous vertical vibration and may have a role in predicting SEAT values of seats exposed to vertical mechanical shocks.

6.1.3 Models of the human body exposed to vertical mechanical shocks

Single-degree-of-freedom and two-degrees-of-freedom models can predict the dynamic response to vertical mechanical shocks of people sitting on a rigid seat (Zhou and Griffin, 2016b). However, the applicability of the linear model was limited to peak accelerations less than 1 g. In Zhou and Griffin (2016b) the force measured at the interface of the human body with the seat was used as the input to their models. When peak accelerations approached 1 g, sudden jumps in the force were measured and produced inaccurate predictions of the output acceleration. This occurred because the downward acceleration of the seat caused the subjects to momentarily leave the seat before subsequently impacting with the seat.

6.1.4 Applicability of models used for continuous vibration to exposure to vertical shocks

There are no known investigations of the applicability of linear models for predicting the vertical mechanical shocks experienced when sitting on soft seats. Furthermore, there are no known studies of the applicability of linear models for predicting the effects of a seat on discomfort by estimating SEAT with vertical mechanical shocks. A simple linear model of the coupled seat and human body system exposed to vertical mechanical shocks would assist the design of seats used in environments where vertical shocks are experienced.

6.1.5 Objectives and hypothesis of the study

The main objective of this study was to investigate how well the transmission of shocks through a seat cushion can be predicted using a simple lumped parameter model of the seat-body system that has been optimised for continuous vibration (e.g. random or sinusoidal vibration). In addition, the study attempted to determine a method of predicting the discomfort caused by vertical mechanical shocks using measurements and predictions of seat effective amplitude transmissibility.

It was hypothesised that:

i. When the magnitude of a vertical mechanical shock approaches 1 g, the ‘measured SEAT value’ (i.e. the ratio of the frequency-weighted VDV on a cushion to frequency-weighted VDV beneath the cushion) will tend to overestimate the true SEAT value (i.e., the ‘subjective SEAT value’: the ratio of magnitude estimates of discomfort experienced with the seat cushion to magnitude estimates of discomfort experienced without the cushion).
ii. When the magnitude of a shock approaches 1 g, the ‘predicted SEAT value’ (predicted by a three degree-of-freedom model of the cushion and human body optimised to the transmissibility of the cushion with random vibration) will provide a better estimate of the ‘subjective SEAT value’ than the ‘measured SEAT value’.

6.2 Method

6.2.1 Subjects

Eighteen male students of the University of Southampton participated in the study. They were aged 20 to 38 years old, had statures between 161 and 187 cm, and masses between 65 and 105 kg. The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (Reference number: 15158).

6.2.2 Apparatus

A 1-m stroke vertical electrohydraulic vibrator reproduced vertical mechanical shocks (Servotest Testing Systems Ltd., Surrey, UK). All stimuli were initially generated in HVLab Matlab Toolbox (version 2.0, ISVR, University of Southampton, UK) and then equalized to the response of the vibrator by a Servotest Pulsar system.

A rigid seat was rigidly mounted on the platform of the vibrator. The seat had an upright wooden backrest for safety purposes, but subjects did not support their bodies on the backrest. The height, width, and depth of the horizontal supporting seat surface were 41 cm by 71 cm by 51 cm, respectively.

Three conditions were tested:

(i) subjects sat without touching the backrest on the rigid seat;
(ii) subjects sat without touching the backrest on a block of foam 40-mm thick that was supported on the rigid seat;
(iii) subjects sat without touching the backrest on a block of foam 80-mm thick that was supported on the rigid seat.

The two blocks of foam had upper and lower surfaces 380 mm x 380 mm.

The accelerations at the base of the rigid seat were measured by using a capacitive micromachined accelerometer 2260-002 (Silicon Designs Inc.). When a block of foam was used, the acceleration at the top surface of the foam was measured using a SIT-pad with an integrated tri-axial accelerometer (Willow Technologies KXD94-2802).

A noise generator (HFRU Noise system 001, ISVR, University of Southampton, UK) produced white noise at 70 dBA via a pair of headphones so as to mask any variations in the noise of the vibrator.

6.2.3 Stimuli

The stimuli were vertical mechanical shocks with fundamental frequencies at the 13 preferred one-third octave centre frequencies in the range 1 to 16 Hz.

The shocks were formed from 1½ cycles of a sinusoid of the required fundamental frequency multiplied by a half cosine over the duration of the 1½-cycle sinusoid (Figure 6.1). The durations of the shocks depended on their fundamental frequency, decreasing from 1.5 s at 1 Hz to 0.09 s at 16 Hz.

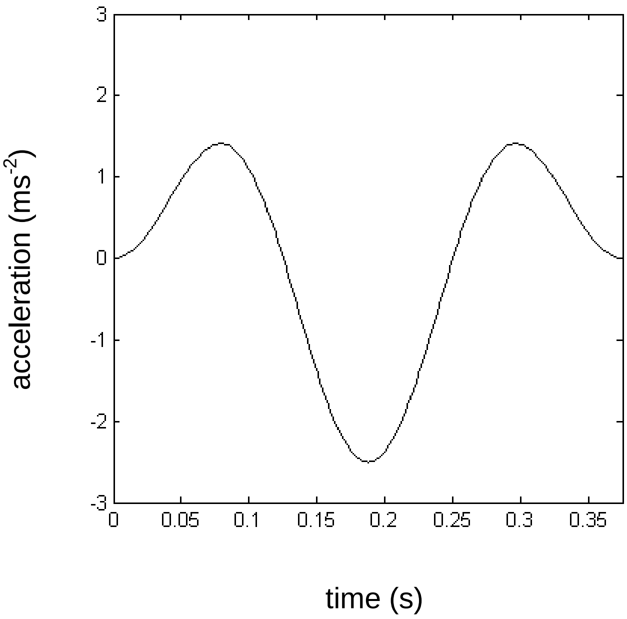


Figure 6.1 Example of unweighted shock acceleration waveform at 4 Hz.

The magnitudes of the shock motions were determined in terms of their W_b weighted vibration dose value, VDV, as defined in BS 6841:1987. Consequently at each magnitude, shocks with a different fundamental frequency were expected to produce similar discomfort when experienced on the rigid seat.

Three magnitudes were presented in 6 dB steps of frequency-weighted VDV: 0.5 $ms^{-1.75}$ (low magnitude), 1.0 $ms^{-1.75}$ (middle magnitude) and 2.0 $ms^{-1.75}$ (high magnitude). The three magnitudes referred to the acceleration measured at the rigid base of the seat. Table 6.1 shows the unweighted peak acceleration at each magnitude for each fundamental frequency of the mechanical shocks.

The total number of stimuli experienced by subjects was 117: 13 frequencies with 3 magnitudes and 3 seat conditions.

Table 6.1 Unweighted peak accelerations for each magnitude level and frequency of the input vibration.

unweighted peak acceleration (ms^{-2})			
Frequency (Hz)	VDV 0.5 $ms^{-1.75}$	VDV 1 $ms^{-1.75}$	VDV 2 $ms^{-1.75}$
1.0	2.0	4.0	8.0
1.25	2.1	4.1	8.2
1.6	2.1	4.1	8.3
2.0	1.9	3.9	7.7
2.5	1.7	3.4	6.8
3.15	1.4	2.9	5.7
4.0	1.3	2.5	5.1
5.0	1.2	2.4	4.8
6.3	1.2	2.4	4.8
8.0	1.3	2.6	6.1
10.0	1.4	2.8	5.6
12.5	1.6	3.1	6.3
16.0	1.8	3.7	7.3

6.2.4 Procedure

Subjects attended one session of approximately 1 hour. The session was split into three parts, one for each seat condition. The number of possible sequences in which the conditions could be ordered and performed was six, since there were three seating conditions. It was ensured that there were an equal number of participants for each sequence of conditions, therefore the number of participants was eighteen (a multiple of six).

Subjects sat in an upright posture without touching the backrest (Figure 6.2). They rested their hands on their laps and kept the eyes closed during exposure to the shocks. The angle between the thighs and the calves was about 95 degrees as to minimise the contact between thighs and seat. A flat footrest was used. Subjects wore the headphones presenting 70 dBA of white noise during the whole duration of the experiment. For safety purposes, subjects were provided with an emergency button that would stop the motion of the vibrator and they wore a loose lap belt.

Subjects were given training on how to rate vibration discomfort by using the method of absolute magnitude estimation before starting the experiment. The training session included both paper work (rating the apparent length of lines drawn on paper), and judging the discomfort caused by practice stimuli (10 motions of the type, frequency, and magnitude used during the experiment).

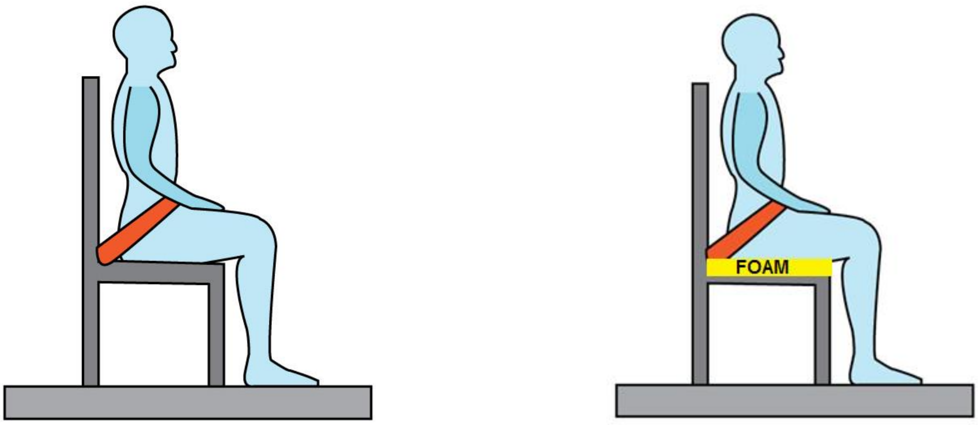


Figure 6.2 Subjects sat on a rigid seat in a comfortable upright posture (left side of the picture). Subjects sat on a soft cushion in a comfortable upright posture (right side of the picture).

Subjects were instructed to give a numerical rating to the discomfort produced by a first motion. They judged the subsequent stimuli in proportion to the discomfort they caused relative to the rating given to the first motion. They were free to start with any number, although 100 were suggested. The first stimulus they started with was a mechanical shock of fundamental frequency of 4 Hz and vibration magnitude of 1 ms$^{-1.75}$ W_b weighted VDV.

6.2.5 Measured vertical seat transmissibility

After being exposed to all mechanical shocks in all three seating conditions, the subjects were exposed to 60 s of broadband random vertical vibration.

The vibration had a flat power density spectrum in the range 0.5 to 25 Hz and was presented at three magnitudes: 0.5 ms^{-2} r.m.s., 1.0 ms^{-2} r.m.s., and 2.0 ms^{-2} r.m.s.

The vertical transmissibility of each foam cushion, $H(f)$, was calculated as the complex ratio between the cross power spectrum $G_{io}(f)$ of the input (vertical acceleration at the rigid base of the seat) and the output (vertical acceleration at the top surface of the foam cushion) and the energy spectrum $G_{ii}(f)$ of the input. The frequency resolution was 0.125 Hz.

seat transmissibility, $H(f) = \frac{G(f)_{io}}{G(f)_{ii}}$

6.2.6 Model of the coupled system human body and seat

A three degree-of-freedom model was used to represent the coupled seat and human body system (Figure 6.3). The parameters of the model m_1, m_2 and m_3 represented the masses of the seated human body, k_1 and k_2 and k_3 represented the stiffness of the block of foam and the seated human body, c_1 and c_2 and c_3 represented the damping of the block of foam and the seated human body.

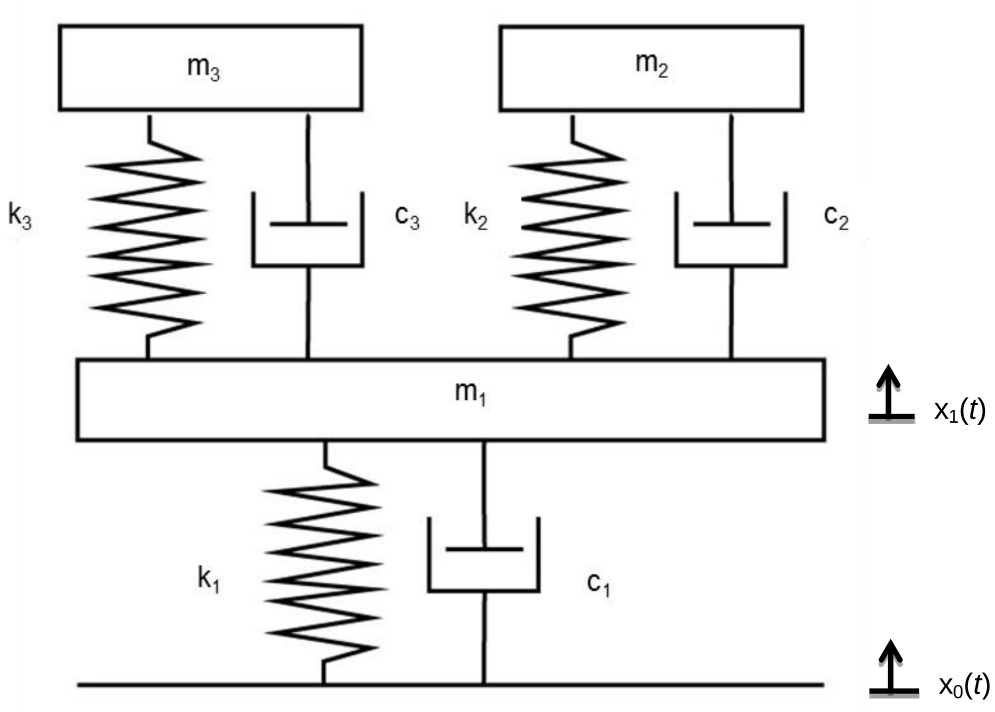


Figure 6.3 The three degree-of-freedom model used to model the system seated person and seat.

The equations of motion (equations 1, 2, and 3) of the model were solved both in the time domain and in the frequency domain.

$$m_1\ddot{x_1}(t) + k_1(x_1(t) - x_0(t)) + c_1(\dot{x}_1(t) - \dot{x}_0(t)) + k_2(x_1(t) - x_2(t)) + c_2(\dot{x}_1(t) + - \dot{x}_2(t)) + k_3(x_1(t) - x_3(t)) + c_3(\dot{x}_1(t) - \dot{x}_3(t)) = 0 \quad (1)$$

$$m_2\ddot{x_2}(t) + k_2(x_2(t) - x_1(t)) + c_2(\dot{x}_2(t) - \dot{x}_1(t)) = 0 \quad (2)$$

$$m_3\ddot{x_3}(t) + k_3(x_3(t) - x_1(t)) + c_3(\dot{x}_3(t) - \dot{x}_1(t)) = 0 \quad (3)$$

The equations of motion were solved in the frequency domain in order to find the optimum parameters of the model. The function fmincon of MATLAB R2014a

(MathWorks, Massachusetts, U.S.A.) was used to find the parameters that minimized an error function between the measured vertical seat transmissibility (see Section 2.6) and the vertical seat transmissibility predicted by the three degree-of-freedom model (equation 4; Wei and Griffin, 1998b). The error function was the root-mean-square error between the real parts and the imaginary parts of the measured and the predicted vertical transmissibility (equation 5).

$$T(\omega) = (F + Gi)/\{(H + L) + (M + N)i\} \quad (4)$$

Where:

$F = k_1P_1 - c_1P_2\omega$, $G = k_1P_2 - c_1P_1\omega$, $H = P_1 P_5 - P_2 c_1\omega - m_2 k_2 P_3 \omega^2$,

$L = m_2c_2c_3 - (m_3k_3P_4 \omega^2 - m_3c_2 c_3 \omega^4)$,

$M = P_2P_5 + c_1P_1\omega - (m_2c_2P_3 + m_2c_3k_2) \omega^3$,

$N = -(m_3 c_3 P_4 \omega^3 + m_3 k_3 c_2 \omega^3)$, $P_1 = m_2 m_3 \omega^4 + k_2 k_3 - (m_2 k_3 + m_3 k_2 + c_2 c_3) \omega^2$,

$P_2 = (c_2k_3 + c_3k_2)\omega - (m_2c_3 + m_3c_2) \omega^3$, $P_3 = k_3 - m_3 \omega^2$,

$P_4 = k_2 - m_2 \omega^2$, $P_5 = k_1 - m_1 \omega^2$.

$$Error = \sqrt[2]{\mathrm{mean}\left(\sum(\mathrm{Re}\{Z(f)_{predicted}\} - \mathrm{Re}\{Z(f)_{measured}\})^2 + \sum(\mathrm{Im}\{Z(f)_{predicted}\} - \mathrm{Im}\{Z(f)_{measured}\})^2\right)} \quad (5)$$

The sum of the three masses, m ($=m_1+m_2+m_3$), was fixed equal to the seated mass of each subject.

The seated mass of each participant was calculated from the modulus of the vertical apparent mass at 0.5 Hz. The vertical apparent mass was obtained when exposing the seated subjects on the rigid seat to 60 s of random vibration in the range 0.5 Hz to 25 Hz at 1.0 ms^{-2} r.m.s.

The optimum parameters for the three degree-of-freedom model were found using the measured seat transmissibility at the three magnitudes 0.5 ms^{-2} r.m.s., 1.0 ms^{-2} r.m.s., and 2.0 ms^{-2} r.m.s. The parameters obtained at each of these magnitudes were used in the model to predict the response of the foam cushions to low magnitude, middle magnitude, and high magnitude mechanical shocks.

The optimum values of m_1, m_2, m_3, k_1, k_2, k_3, c_1, c_2 and c_3 were used to solve the three degree-of-freedom model in the time domain for predicting the response of the foam cushions to mechanical shocks. To solve the equations of motion in the time domain the method of Runge – Kutta was used.

6.2.7 Statistical analysis

The hypotheses were tested using non-parametric tests. Differences between related samples were investigated adopting the Friedman two-way analysis of variance and the Wilcoxon matched-pairs signed ranks.

6.2.8 Median percentage error between measurements and predictions

Median percentage errors (MdPE) were calculated in order to quantify how well a prediction approximated measured values for each frequency and magnitude of mechanical shock.

The median percentage error between measured and predicted SEAT value was defined as:

$$\mathrm{MdPE}_{\mathrm{measured\_predicted}} = 100 * \mathrm{median}\left(\frac{\mathrm{SEAT}_{\mathrm{i}}^{\mathrm{measured}} - \mathrm{SEAT}_{\mathrm{i}}^{\mathrm{predicted}}}{\mathrm{SEAT}_{\mathrm{i}}^{\mathrm{measured}}}\right)$$

where i is a variable and represents the index referring to the i-th subject.

To quantify how much the measured and the predicted SEAT values differed from the subjective SEAT values, the following median percentage errors were also calculated:

$$\mathrm{MdPE}_{\mathrm{measured\_subjective}} = 100 * \mathrm{median}\left(\frac{\mathrm{SEAT}_{\mathrm{i}}^{\mathrm{measured}} - \mathrm{SEAT}_{\mathrm{i}}^{\mathrm{subjective}}}{\mathrm{SEAT}_{\mathrm{i}}^{\mathrm{measured}}}\right)$$

$$\mathrm{MdPE}_{\mathrm{predicted\_subjective}} = 100 * \mathrm{median}\left(\frac{\mathrm{SEAT}_{\mathrm{i}}^{\mathrm{predicted}} - \mathrm{SEAT}_{\mathrm{i}}^{\mathrm{subjectve}}}{\mathrm{SEAT}_{\mathrm{i}}^{\mathrm{predicted}}}\right)$$

6.3 Results

6.3.1 Measured vertical seat transmissibility

Figures 6.4 and 6.5 show the modulus of the measured vertical in-line transmissibility for the two blocks of foam used in this study. The resonance frequencies of the median seat transmissibility were 4 Hz for the 40 mm foam block and 3.5 Hz for the 80 mm foam block when the magnitude of the input random vibration was 1.0 ms^{-2} r.m.s.

Figure 6.6 compares the modulus of the median seat transmissibility obtained with the two thicknesses of foam block with 1.0 ms^{-2} r.m.s. of 60 s vertical Gaussian random vibration. At frequencies greater than 4 Hz the modulus of the median vertical transmissibility of the 40 mm block of foam was greater than the modulus of the median vertical transmissibility of the 80 mm block of foam.

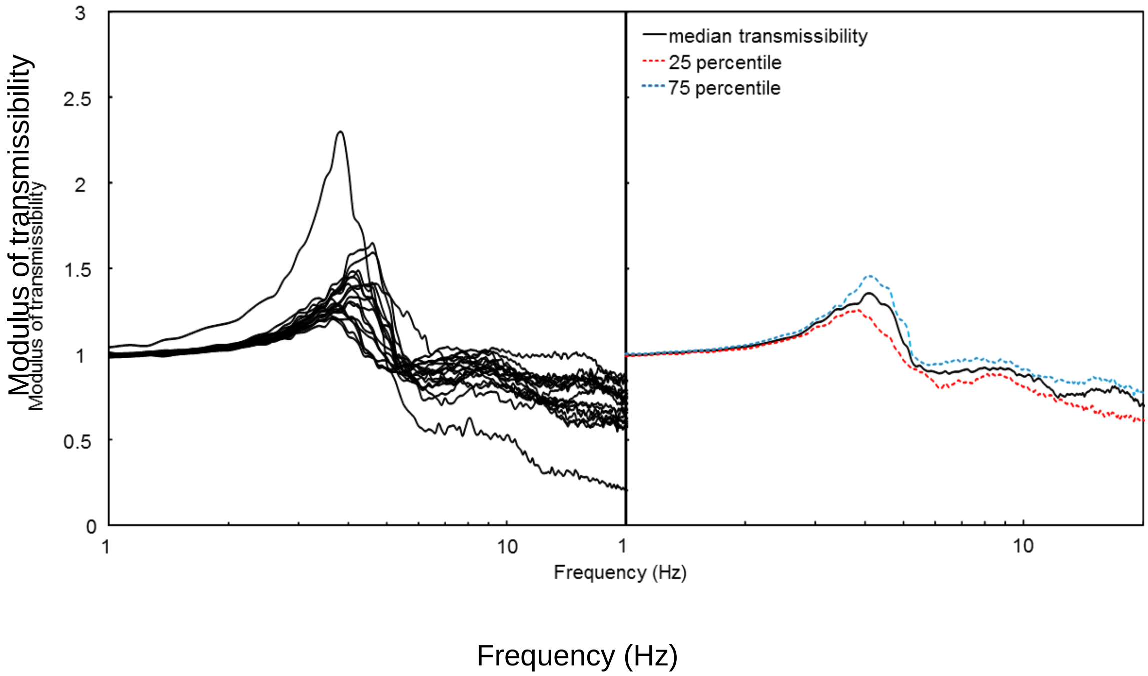


Figure 6.4 Moduli of the individual (left figure) and the median (right figure) vertical in-line transmissibility obtained for a 40-mm thick foam block during exposure to 60 s vertical Gaussian random vibration with 1.0 ms^{-2} r.m.s.

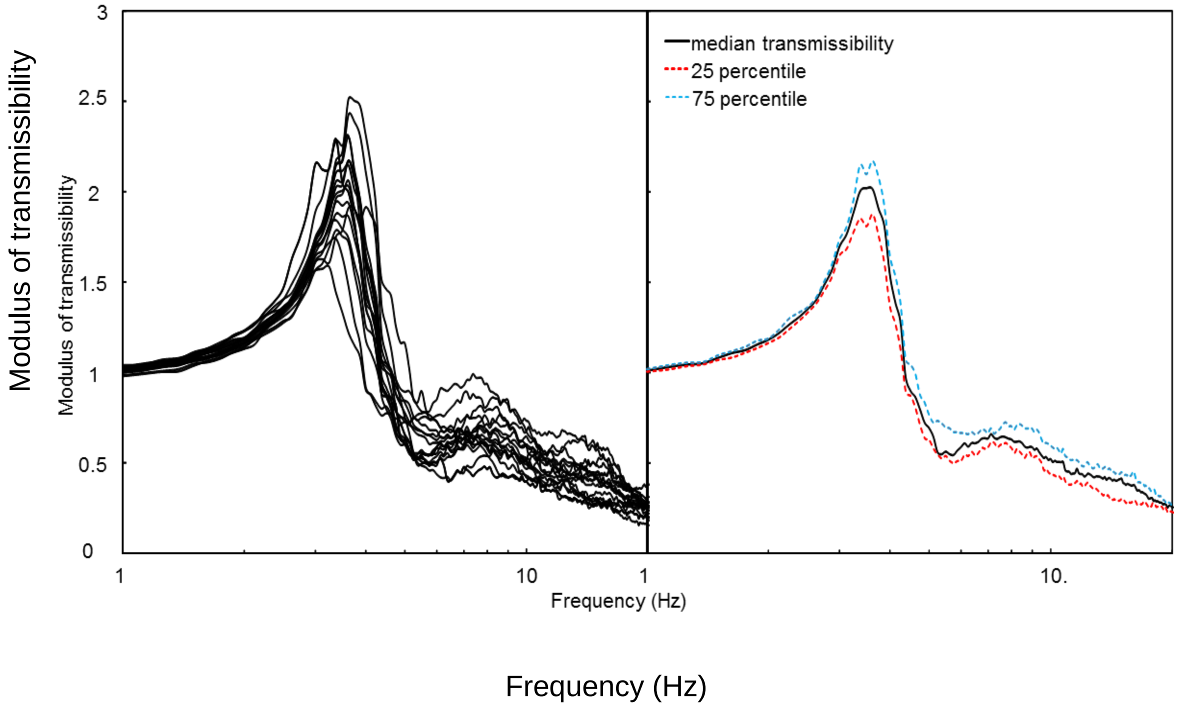


Figure 6.5 Moduli of the individual (left figure) and the median (right figure) vertical in-line transmissibility obtained for a 80-mm thick foam block during exposure to 60 s vertical Gaussian random vibration with 1.0 ms^{-2} r.m.s.

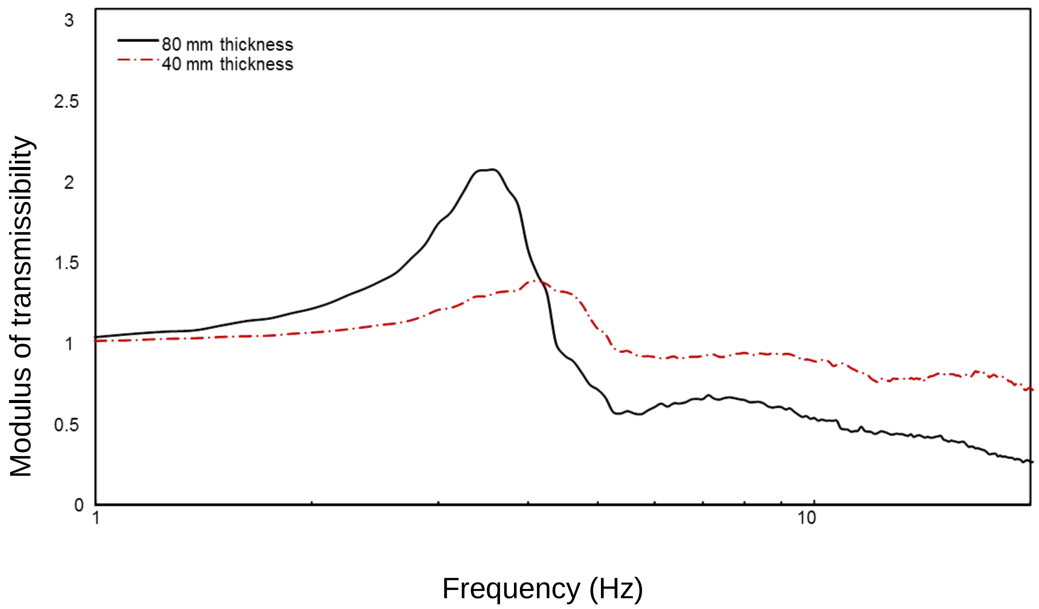


Figure 6.6 Moduli of the median vertical in-line transmissibility obtained for two foam blocks 80 mm and 40 mm thick during exposure to 60 s vertical Gaussian random vibration with 1 ms^{-2} r.m.s.

For the 40-mm block of foam, with increasing magnitude of random vibration the resonance frequency evident in the median transmissibility decreased from about 4.5 Hz to about 4 Hz (p<0.001, Friedman; Figure 6.7). The resonance frequency at the lowest magnitude was greater than the resonance frequency at the middle and the highest magnitude (p<0.001, Wilcoxon). The resonance frequency at the middle magnitude was also greater than the resonance frequency at the highest magnitude (p=0.011, Wilcoxon). The modulus at the resonance frequency depended on the magnitude of vibration (p<0.001, Friedman; Figure 6.7) and was lower at the highest magnitude of vibration (2.0 ms^{-2} r.m.s.) than at 1.0 ms^{-2} and 0.5 ms^{-2} r.m.s. (p<0.004, Wilcoxon).

For the 80-mm block of foam, with increasing magnitude of random vibration the resonance frequency evident in the median transmissibility decreased from about 4.0 Hz to about 3.3 Hz (p<0.001, Friedman; Figure 6.7). The resonance frequency at the lowest magnitude was greater than the resonance frequency at the middle and the highest magnitude (p<0.001, Wilcoxon). The resonance frequency at the middle magnitude was also greater than the resonance frequency at the highest magnitude (p<0.001, Wilcoxon). The modulus at the resonance frequency did not depend on the magnitude of vibration (p=0.234; Friedman).

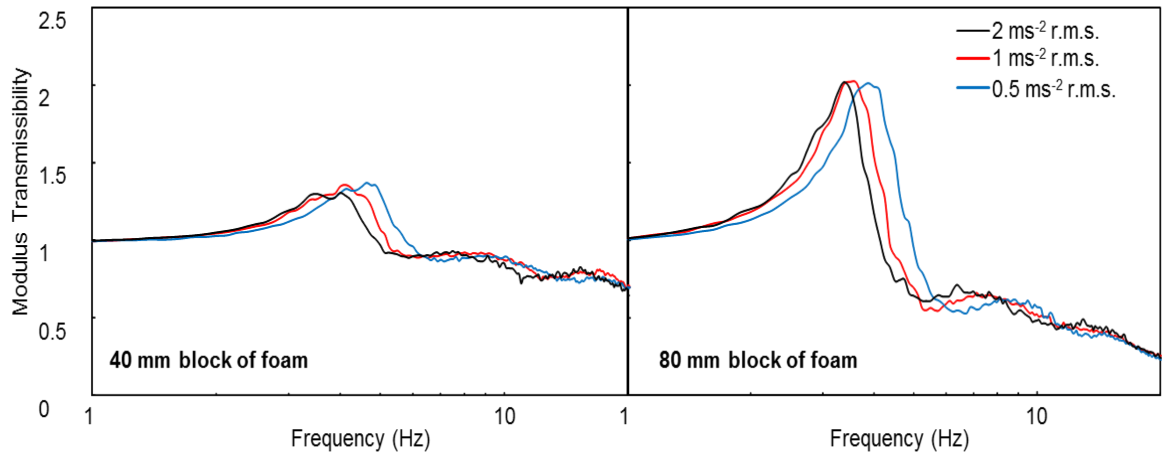


Figure 6.7 Effect of magnitude on the median vertical-in-line seat transmissibility.

6.3.2 Predicted vertical seat transmissibilities and predicted shock waveforms

Figures 6.8 and 6.9 show for a single subject the measured transmissibility of the 40-mm and 80-mm foam blocks and the seat transmissibility fitted with the three degree-of-freedom model. The figures show good fits to both the modulus and the phase of the vertical transmissibility. The subject selected had a sitting mass of 51 kg, close to the median sitting mass calculated over the eighteen participants (i.e. median mass of 52 kg). The sitting masses of the eighteen subjects fell in the range 44 kg and 76 kg.

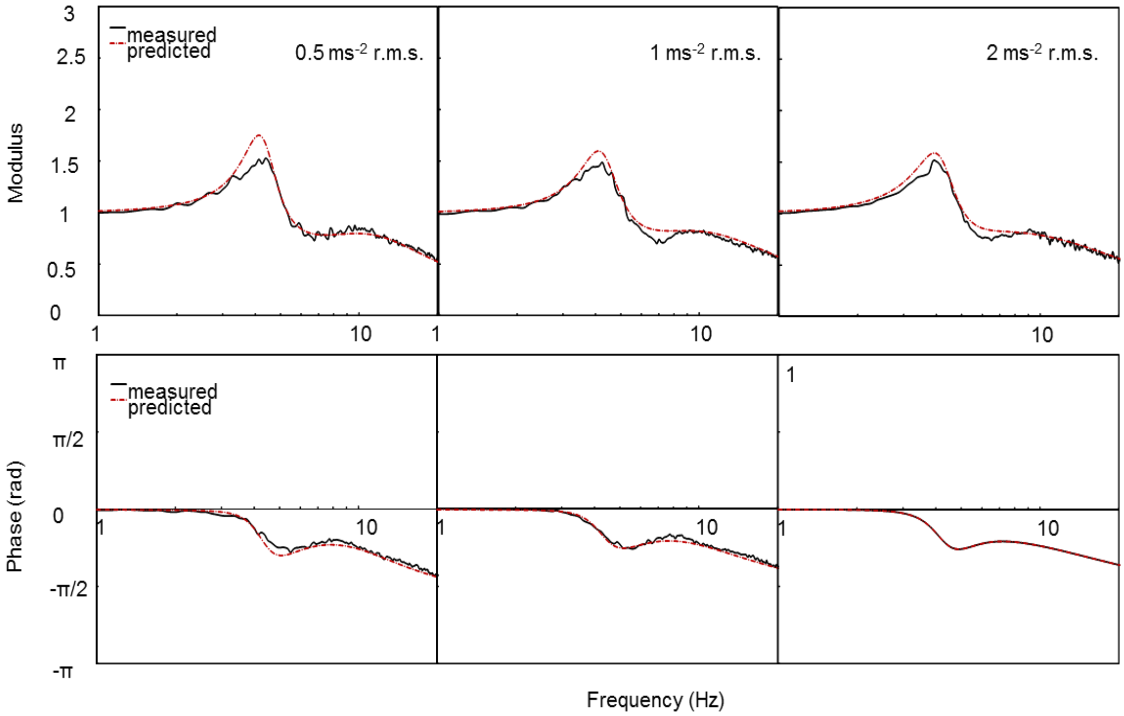


Figure 6.8 Modulus and phase of the predicted and measured vertical in-line transmissibility of a 40 mm thick block of foam obtained for one subject at all magnitudes of random vibration.

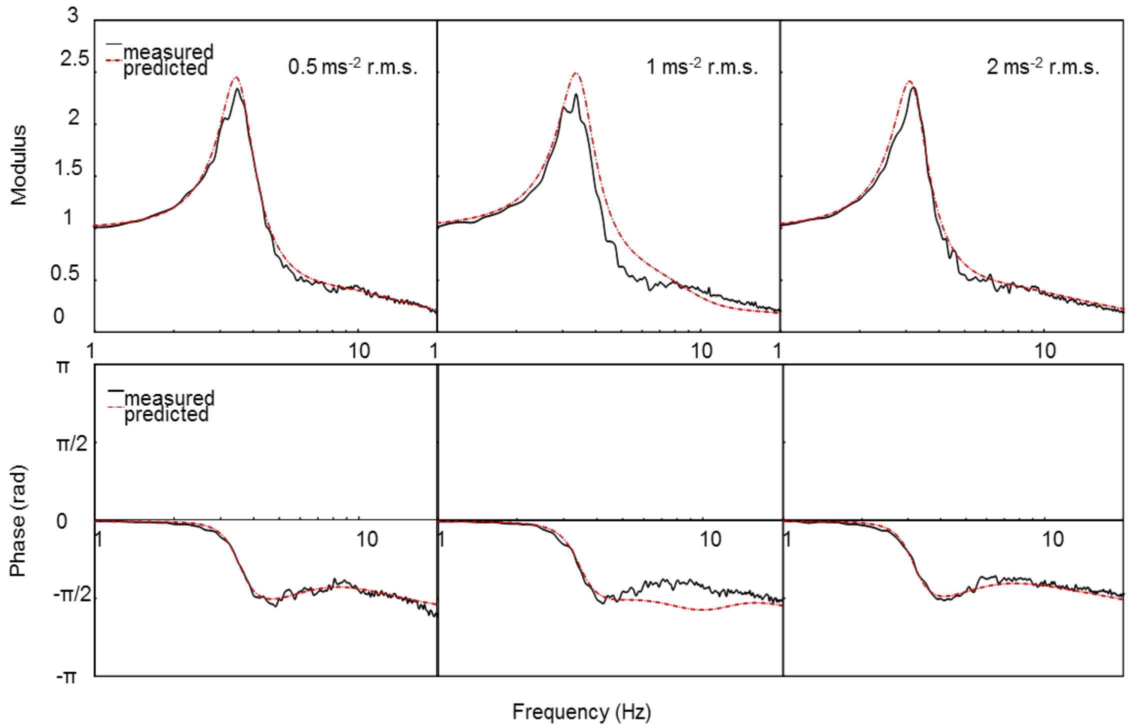


Figure 6.9 Modulus and phase of the predicted and measured vertical in-line transmissibility of a 80 mm thick block of foam obtained for one subject at all magnitudes of random vibration.

Figure 6.10 shows examples of the acceleration waveforms of the mechanical shocks with fundamental frequency of 2 and 16 Hz predicted by the three degree-of-freedom model for the same subject as used in Figures 6.8 and 6.9.

The model was able to predict shocks when a soft seat was used, if the shocks had peak accelerations below 1 g. However, when the acceleration at the top surface of the cushion reached 1 g the human body was lifted up and the acceleration recorded with the SIT PAD contained the acceleration at the time of the impact. This event could not be well represented by a linear model as used in this study. The measured VDV in these cases was greater than the predicted VDV (Figure 6.10; top right). This is considered in more detail in Section 3.5.

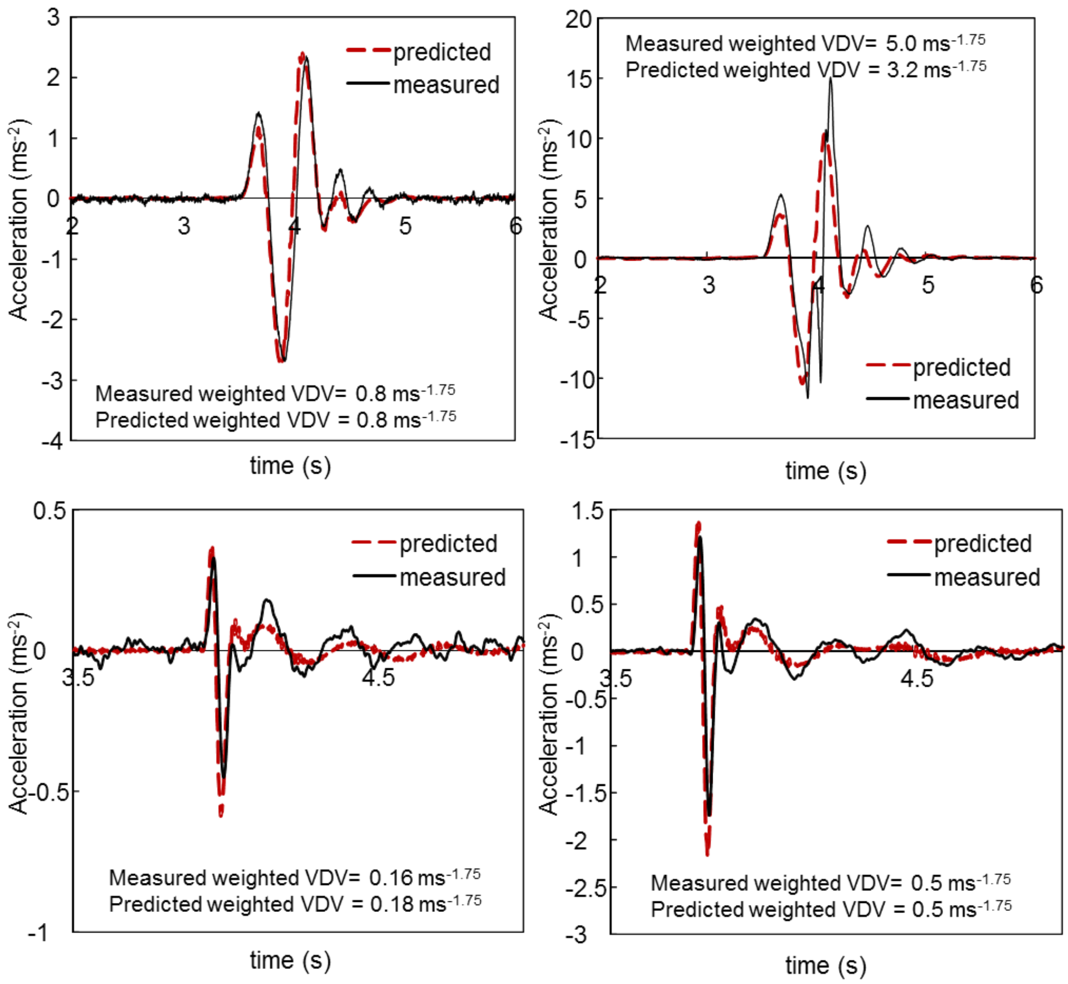


Figure 6.10 Predictions in the time domain and measurements of vertical shock accelerations for one subject applying a three degree-of-freedom model. The subject sat comfortably upright on a soft cushion 80 mm thick. At the top, low and high magnitude shocks with fundamental frequency of 2 Hz. At the bottom, low and high magnitude shocks with fundamental frequency of 16 Hz.

6.3.3 Measured SEAT values compared with subjective SEAT values

The subjective SEAT values included outliers and variability among subjects at many frequencies in the range 1 to 16 Hz at the low magnitudes and the middle magnitudes and with both blocks of foam. For each subject, the measured, predicted, and subjective SEAT values at the central frequencies of 1 Hz, 2 Hz, 4 Hz, 8 Hz, and 16 Hz were calculated as the average values over the frequencies in these octave bands. This procedure was repeated for each of the three magnitudes of vibration.

With the 40 mm foam block, the measured SEAT values were similar to the subjective SEAT values at most octave centre frequencies (Figure 6.11). However, the subjective

SEAT values were less than the measured SEAT values with the lowest magnitude at 1 Hz (p=0.025). The subjective SEAT value was greater than the measured SEAT with the middle magnitude at 16 Hz (p=0.035). The subjective SEAT was less than the measured SEAT value with the highest magnitude at 1 and 2 Hz (p<0.002). The median percentage errors between measured and subjective SEAT values for the 40-mm thick block of foam are shown in Table 6.2. At the middle magnitude of vibration (weighted VDV= 1.0 $ms^{-1.75}$) the median percentage errors were between about - 2% and +8% over the range 1 to 8 Hz, with negative errors indicating that the subjective SEAT values were greater than measured SEAT values (see Section 2.9). Greatest errors were found with the greatest magnitudes of shock, where at frequencies less than 2 Hz the mean errors went up to about 40%.

Table 6.2 Median percentage errors (%) between the measured SEAT values and the subjective SEAT values for a block of foam 40 mm thick.

MEDIAN PERCENTAGE ERRORS (%) $MdPE_{measured\ subjective}$					
Weighted VDV	1 Hz	2 Hz	4 Hz	8 Hz	16 Hz
0.5 $ms^{-1.75}$	23.84	-4.08	7.28	-10.24	-14.00
1 $ms^{-1.75}$	-2.48	7.73	1.04	6.64	-38.08
2 $ms^{-1.75}$	32.81	39.51	-1.63	-9.64	-40.54

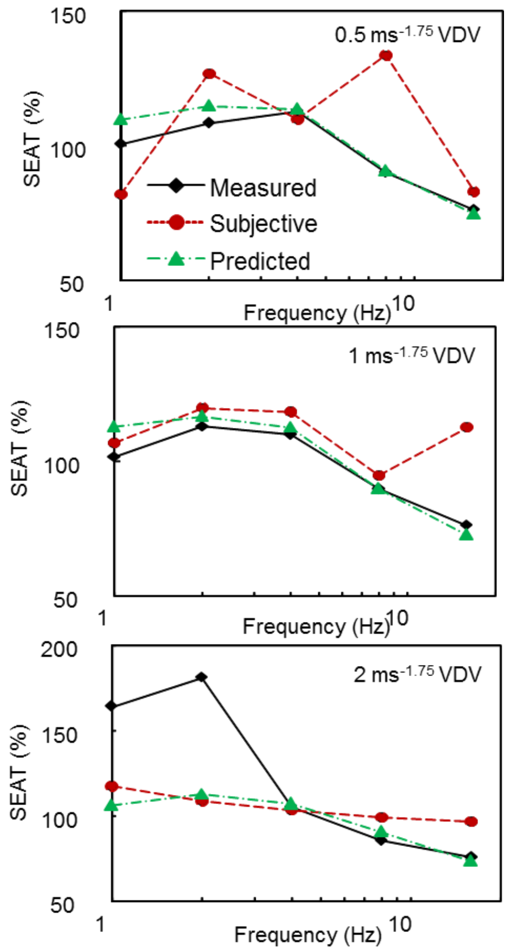


Figure 6.11 Mean measured, predicted, and subjective SEAT values of a block of foam of 40 mm thicknesses exposed to vertical mechanical shocks at each magnitude of vibration.

With the 80 mm foam block, the measured SEAT values were also similar to the subjective SEAT values at most octave centre frequencies with the lowest and middle shock magnitudes (Figure 6.12). However, subjective SEAT values were greater than measured SEAT values with the lowest magnitude at 8 and 16 Hz (p<0.005) and with the middle magnitude at 16 Hz (p=0.001). At the highest magnitude, the subjective SEAT values were less than the measured SEAT values at 1 Hz and 2 Hz (p<0.001), but greater at 8 and 16 Hz (p<0.001). Table 6.3 shows the median percentage errors between measured and subjective SEAT values for the 80 mm thick block of foam.

Table 6.3 Median percentage errors (%) between the measured and the subjective SEAT values for a block of foam 80 mm thick.

MEDIAN PERCENTAGE ERRORS (%) $MdPE_{measured\ subjective}$					
Weighted VDV	1 Hz	2 Hz	4 Hz	8 Hz	16 Hz
0.5 $ms^{-1.75}$	11.0	1.4	-0.2	-36.5	-72.1
1 $ms^{-1.75}$	8.2	11.7	-12.3	5.1	-107.5
2 $ms^{-1.75}$	47.5	44.2	-6.8	-41.5	-53.7

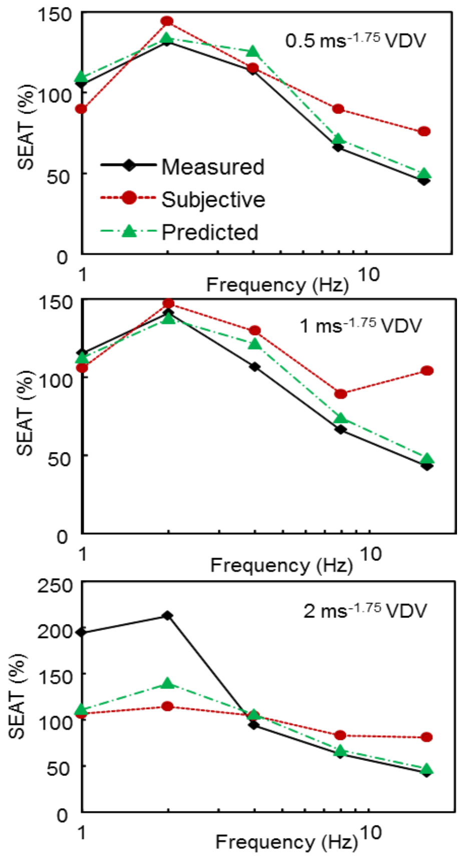


Figure 6.12 Mean subjective and measured SEAT values of a block of foam of 80 mm thicknesses exposed to vertical mechanical shocks at each magnitude of vibration.

6.3.4 Predicted SEAT values compared with subjective SEAT values

With the 40 mm foam block, the predicted SEAT values were similar to the subjective SEAT values at most octave centre frequencies (Figure 6.11). However, the subjective SEAT values were less than the predicted SEAT values with the lowest shock magnitude at 1 Hz (p=0.007). The subjective SEAT values were greater than the predicted SEAT values with the middle shock magnitude at 16 Hz (*p*=0.025), and the highest shock magnitude at 16 Hz (*p*=0.028). Table 6.4 shows the median percentage errors between predicted and subjective SEAT values for the 40 mm foam block. At the middle and the highest magnitudes of shock (weighted VDV of 1.0 $ms^{-1.75}$ and 2.0 $ms^{-1.75}$) the median errors are between about - 8% and +9 % over the range 1 to 8 Hz, with negative errors indicating that the subjective SEAT values were greater than the predicted SEAT values (see Section 2.9).

Table 6.4 Median percentage errors (%) between the predicted and the subjective SEAT values for a block of foam 40 mm thick.

MEDIAN PERCENTAGE ERRORS (%) $MdPE_{predicted\ subjective}$					
Weighted VDV	1 Hz	2 Hz	4 Hz	8 Hz	16 Hz
0.5 $ms^{-1.75}$	27.3	-1	-0.4	-10.4	-12.5
1 $ms^{-1.75}$	6.8	9.1	4.7	6.4	-37.5
2 $ms^{-1.75}$	0.4	4.1	-4.8	-7.6	-32.6

With the 80 mm foam block, the predicted SEAT values were similar to the subjective SEAT values at most octave centre frequencies (Figure 6.12). Subjective SEAT values were less than the predicted SEAT values with the lowest shock magnitude at 1 Hz (*p*=0.031) and greater at 8 and 16 Hz (*p*<0.012). Subjective SEAT values were greater than the predicted SEAT values with the middle shock magnitude at 16 Hz (*p*=0.001) and with the greatest magnitude at 16 Hz (*p*=0.004). Subjective SEAT values were smaller than the predicted SEAT values with the greatest magnitude at 2 Hz (*p*<0.001). Table 6.5 shows the median percentage errors between predicted SEAT values and the subjective SEAT values for the 80 mm foam block.

Table 6.5 Median percentage errors (%) between the predicted and the subjective SEAT values for a block of foam 80 mm thick.

MEDIAN PERCENTAGE ERRORS (%) $MdPE_{predicted\ subjective}$					
Weighted VDV	1 Hz	2 Hz	4 Hz	8 Hz	16 Hz
0.5 $ms^{-1.75}$	14.4	4.1	13.2	-27.8	-56.5
1 $ms^{-1.75}$	2.2	5.4	3.6	13.1	-73.3
2 $ms^{-1.75}$	4.6	17.5	7.7	-23.1	-66.3

6.3.5 Measured SEAT values and predicted SEAT values

The predicted SEAT values were similar to the measured SEAT values with the low and middle magnitude shocks, but differed greatly with low frequency high magnitude shocks (Figures 6.13 and 6.14).

With the 40 mm foam block, the measured SEAT values were less than the predicted SEAT values with the lowest magnitude shocks from 1.0 to 2.0 Hz ($p<0.002$) but were greater at 16 Hz ($p=0.043$). The measured SEAT values were less than the predicted SEAT values with the middle magnitude shocks at 1.0, 1.25, and 2.5 Hz but greater at 16 Hz ($p<0.0016$). The measured SEAT values were greater than the predicted SEAT values with the greatest magnitude shocks from 1 to 2.5 Hz ($p<0.001$) but less from 5 to 8 Hz ($p<0.008$) (Figure 6.13). Table 6.6 shows the median percentage errors between the measured and the predicted SEAT values for a 40 mm foam block. At the lowest and the middle magnitude the model was able to predict the SEAT values with a median percentage error less than 15%. At the highest magnitude the median percentage error were less than 15% at frequencies greater than 2.5 Hz but greater than 30% at frequencies from 1 to 2 Hz.

With the 80 mm foam block, there were significant differences between the measured SEAT values and the predicted SEAT values with the lowest magnitude shocks at all frequencies from 1 to 16 Hz ($p<0.016$), where the measured SEAT values were less than the predicted SEAT values, except at 1.25 and 2 Hz ($p>0.064$). With the middle magnitude shocks, the measured SEAT values were greater than the predicted SEAT values at all frequencies from 1 Hz to 1.6 Hz ($p<0.043$) but less from 2 to 16 Hz ($p<0.039$). With the greatest magnitude shocks, the measured SEAT values were greater than the predicted SEAT values from 1 to 2 Hz ($p<0.001$) and at 3.15 and 4 Hz ($p<0.004$), but less from 10 to 16 Hz ($p<0.025$) (Figure 6.14). Table 6.7 shows the median percentage errors between measured and predicted SEAT values for the 80 mm foam block. At the lowest and the middle magnitudes of shock, the model was able to predict the SEAT values with a median percentage error less than 20%. At the greatest magnitude, the median percentage error was less than 20% at frequencies greater than 4 Hz but greater than 35% at frequencies from 1 to 3.15 Hz, except at 2.5 Hz.

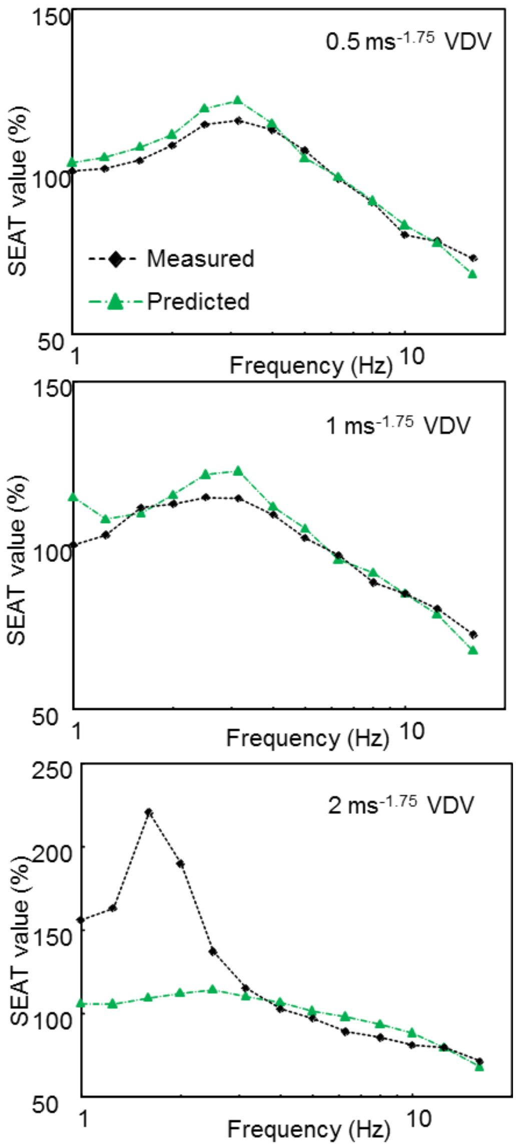


Figure 6.13 Median predicted SEAT values and measured SEAT values of a block of foam of 40 mm thicknesses exposed to vertical mechanical shocks at each magnitude of vibration.

Table 6.6 Median percentage errors (%) between the predicted and the measured SEAT values for a block of foam 40 mm thick.

MEDIAN PERCENTAGE ERRORS (%) $MdPE_{predicted\ measured}$													
Weighted VDV	1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5	16
0.5 $ms^{-1.75}$	-2.72	-3.73	-3.85	-3.38	-2.88	-2.09	-0.16	2.00	-3.38	-1.86	-4.22	-1.57	3.48
1 $ms^{-1.75}$	-14.53	-4.40	2.47	-1.95	-4.31	-5.26	-1.99	1.50	-0.25	-3.72	-0.61	0.40	6.78
2 $ms^{-1.75}$	31.57	34.82	50.06	40.46	16.04	3.89	-0.94	-5.39	-6.88	-8.70	-3.78	2.79	4.02

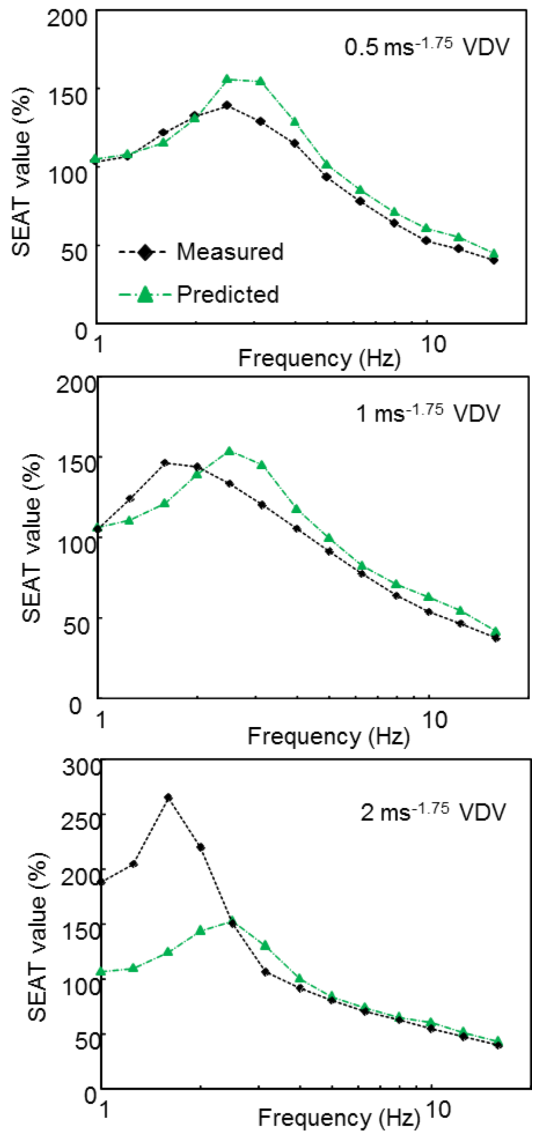


Figure 6.14 Median predicted and measured SEAT values of a block of foam of 80 mm thicknesses exposed to vertical mechanical shocks at each magnitude of vibration.

Table 6.7 Median percentage errors (%) between the predicted and the measured SEAT values for a block of foam 80 mm thick.

MEDIAN PERCENTAGE ERRORS (%) $MdPE_{predicted\_measured}$													
Weighted VDV	1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5	16
0.5 $ms^{-1.75}$	-2.17	-1.89	3.22	1.25	-9.15	-19.96	-11.32	-8.83	-9.65	-8.14	-16.06	-15.79	-9.33
1 $ms^{-1.75}$	-1.73	10.64	15.96	2.99	-14.78	-20.92	-12.46	-5.72	-8.51	-10.65	-15.28	-19.86	-8.71
2 $ms^{-1.75}$	42.05	44.68	52.93	35.31	-4.73	-23.42	-12.51	-3.76	-1.73	-2.25	-10.01	-16.04	-9.07

6.4 Discussion

6.4.1 Subjective SEAT values

The subjective SEAT values proposed in this study express the difference in using a soft cushion rather than a rigid seat in terms of comfort during exposure to high magnitude shocks. Subjective SEAT values were calculated as the ratio between the subjective rating given to the same stimulus with and without the cushion.

The findings of this study suggest that a block of polyurethane foam either 40 mm thick or 80 mm thick did not greatly improve the comfort of people exposed to vertical shocks in the frequency range 1 to 16 Hz, since subjective SEATs were around and sometimes greater than 100 % (Figure 6.11 and 6.12).

The results can be explained from the dynamic properties of the two cushions (Figures 6.4 to 6.9). At frequencies between 2 and 4 Hz greater subjective ratings than with a rigid seat are explained by the shock acceleration transmitted through the occupied cushion being amplified, as reflected in the seat transmissibility and the measured SEAT values (Figures 6.4 to 6.12).

6.4.1.1 Effect of thickness on the subjective SEAT values

Figure 6.15 compares the results obtained with the two blocks of foam of different thickness. At frequencies from 1 to 4 Hz the 80 mm foam block increased the discomfort caused by low and middle magnitude shocks more than the 40 mm foam block. Doubling the thickness of a cushion corresponds to reducing, ideally halving, its stiffness. The reduction in stiffness can be partly responsible for the increase in the modulus of the vertical seat transmissibility at the resonance, as reported by Zhang *et al.* (2015). Greater acceleration at the seat pan for an 80 mm foam block than for a 40 mm foam block consequently caused greater discomfort during shocks with fundamental frequencies around the resonance frequency.

At frequencies greater than about 8 Hz, the 80 mm foam block improved comfort with low, middle, and high magnitude shocks relative to the 40 mm foam block (Figure 6.15). However at frequencies greater than 8 Hz subjective SEAT values were still around 100% (Figures 6.11, 6.12) with both blocks of foam, indicating that the reduction of the transmission of the shocks through the seat (Figures 6.4 to 6.12) did not correspond to an appreciable reduction in overall discomfort.

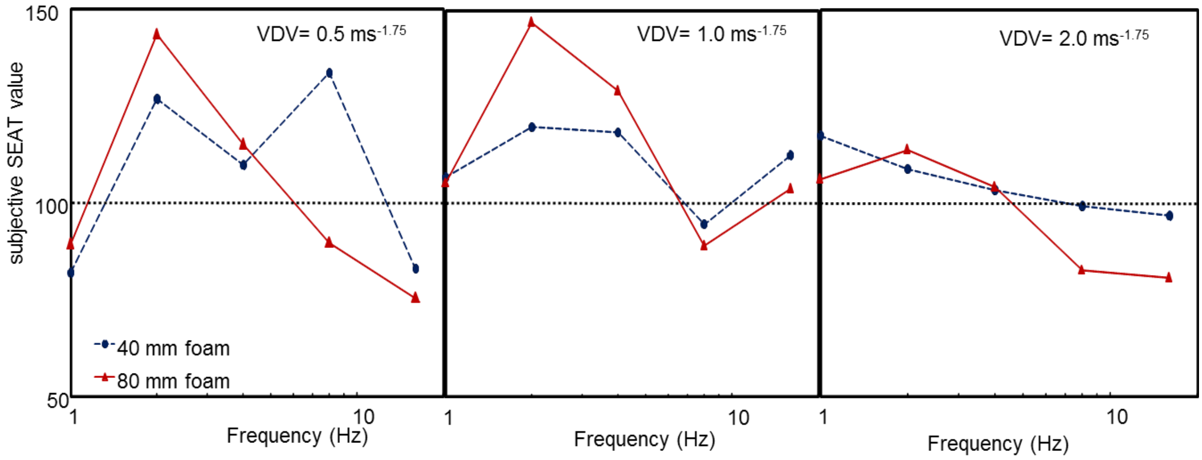


Figure 6.15 Subjective SEAT values for blocks of foam 40 mm and 80 mm thick.

The reduction of high frequency vibration at the seat pan may have increased the perception of vibration at the feet and increased vibration perception at the feet may explain partly why seat dynamics did not directly reflect the overall discomfort as expected.

In this study, the feet were resting on a flat rigid footrest attached to the rigid moving platform. Studies of discomfort caused by shock and vibration have found that the body locations of greatest discomfort tend to be legs and feet at frequencies greater than about 8 Hz (see Chapter 4; Ahn and Griffin, 2008; Basri and Griffin, 2014; Zhou and Griffin, 2014a, 2016a). Basri and Griffin (2014) noticed that the number of subjects indicating the feet or the calves as prime locations of greatest discomfort was greater when a soft seat was used than when a rigid seat was used at frequencies greater than about 10 Hz.

The results highlight the capability of a seat to reduce vibration at the seat pan but not necessarily reduce subject discomfort. This could suggest that when seats are designed to isolate vibration at the main supporting surface at seat-human body interface, the vibration perceived at specific parts of the body, such as feet or hands, may become significant and may play an important role on the overall comfort of passengers.

6.4.1.2 Use of the subjective SEAT value

The subjective SEAT value was a useful tool to link the properties of the seat to the comfort of people exposed to vertical shocks but it was sensitive to subject variability, especially with low magnitude vibration (Figure 6.11). A solution to this matter would be to give longer training to subjects before testing their comfort. Subjective SEAT values could be useful in laboratory studies that investigate the effect of introducing soft cushions of various thickness and shape on vibration comfort.

Analysing subjective SEAT values could give some information of how much improvement in comfort is gained by introducing modification to the seat.

6.4.2 Measured SEAT values

For both blocks of foam the measured SEAT values for shock were consistent with the seat transmissibility measured with random vibration and presented in Figures 6.4 and 6.5.

Median seat transmissibility of a 40-mm foam block and a 80-mm foam block showed a peak between 4 to 7 Hz and between 3 to 5 Hz (Figure 6.7) respectively, whereas the SEAT values showed a peak between 3 to 4 Hz and between 2 to 3 Hz respectively (Figures 6.13 and 6.14). Small differences in the modulus and in the resonance frequencies between SEAT values and seat transmissibility with random vibration should be expected and are related to the characteristics of the shocks in the frequency domain. Differently to the 60-s random vibration, shocks have a broad band energy spectrum that it is not equally distributed over their frequency range. When designing a seat for an environment that is most exposed to vertical shocks evaluation of SEAT values rather than seat transmissibility should be preferred.

The measured SEAT values were not suitable to describe the characteristics of the seat at the highest magnitudes with frequencies less than 3 Hz, because the body impacted with the seat and generated spikes in the acceleration measured at the top surface of the cushion.

6.4.3 Predicted SEAT values

The three degree-of-freedom model provided reasonable fits to the measured SEAT values during exposure to low and middle frequency shocks (Figures 6.13 and 6.14). As in this study, previous studies found linear models adequate for predicting the dynamic behaviour of compliant seats and square blocks of foam of different thicknesses when a seated person is exposed to vertical vibration (e.g., Wei and Griffin, 1998b; Toward and Griffin, 2011b). Wei and Griffin (1998b) found that a three degree-of-freedom model of the coupled seat and human body system was able to predict both phase and modulus of the vertical seat transmissibility when subjects were exposed to vertical broadband random vibration in the range 1.25 Hz to 25 Hz. A single degree-of-freedom and a two degree-of-freedom model were also found to be able to predict vertical mechanical shocks of people sitting on rigid seats for peak acceleration less than 9.81 ms^{-2} (Zhou and Griffin, 2016b).

It was found that predicted SEAT values were smaller than the measured SEAT values at the greatest magnitudes of the shocks with frequencies less than 3 Hz. Consistent with results obtained with high magnitude shocks by Zhou and Griffin (2016b), the model produced median percentage errors up to ± 50 % between predicted and measured SEAT values. This result was expected because:

i) the model is linear, that is the parameters of the model are fixed and the output of the model is related to the input through a linear function,
ii) the boundary conditions used in the model of the seat-human body system do not take into account the possibility that the body could leave the seat.

The model was not able to predict the non-linearity of the biodynamic responses in terms of the reduction in the resonance frequency with increasing magnitude of vibration (Figure 14). This should be expected since the parameters of the model were independent of the frequency and the magnitude of the shocks.

If the purpose of using the model is to: i) predict the acceleration of vertical shocks at the top surface of a seat when peak accelerations are greater than 1 g, or ii) predict the decrease in the resonance frequency of seat transmissibility with increasing magnitude of shocks, the model proposed in this study will not give accurate predictions. For these cases, the model should be implemented such that: i) the model simulates the human body leaving and impacting the seat, and ii) the optimum parameters of the model depend on the magnitude and the frequency of vibration.

If the purpose of the model is to predict the SEAT values to evaluate seat comfort when people are exposed to vertical shocks with peak acceleration less than 1 g, the model proposed in this study will give reasonable predictions (Figures from 6.11 to 6.14, Tables from 6.2 to 6.7).

6.4.4 The use of SEAT to predict comfort: comparisons between measured SEAT values, predicted SEAT values, and subjective SEAT values

With most frequencies and magnitudes of shock the measured SEAT values were similar to the subjective SEAT values (Figure 6.11).

The measured SEAT value was a good indicator of seat comfort during low and middle magnitude upward shocks (Figures 6.11 and 6.12). The results of this study were consistent with previous studies. With three different seats (‘soft’, ‘intermediate’ and 'hard') Basri and Griffin (2014) found that SEAT values well predicted the discomfort caused by vertical sinusoidal vibration in the frequency range 1 to 20 Hz with magnitudes of 0.2 to 1.6 ms^{-2} r.m.s., although they found the greatest errors in SEAT values at frequencies less than 5 Hz and greater than 8 Hz. Niekerk *et al.* (2003) measured the SEAT values and estimated the SEAT values from the seat transmissibility of 16 car seats. For vertical vibration at the seat top, they found that the correlation coefficient between the average subjective ratings and the average estimated SEAT values was around 0.9. In the same study, correlation coefficients between individual subjective ratings and measured SEAT values ranged from about 0.3 to about 0.8 over six subjects. From the present and previous results it seems that SEAT values may represent a good predictor of the effect of seats on discomfort caused by vertical vibration and mechanical shocks.

The measured SEAT value was not a good indicator of seat comfort during high magnitude upward shocks. It was hypothesised that when the shock approached 1 g the 'measured SEAT value' would tend to be greater than the 'subjective SEAT value', because if the body 'leaves the seat' the measured SEAT value would contain a shock as the body subsequently impacts on the accelerometer located on the seat surface. This hypothesis was confirmed by the results showing the measured SEAT values overestimated the subjective SEAT values with median errors up to 50% (Tables 6.2 and 6.3) when the VDV of the input shock was 2 $ms^{-1.75}$ and the fundamental frequency of the shock was 2 Hz or less.

The findings suggest it might be appropriate to remove the acceleration due to the impact only when evaluating comfort during exposure to high magnitude shocks. This may be useful in order to be able to use the measured SEAT value as indicator of comfort at the highest magnitudes of vibration.

According to the second hypothesis of this study, with high magnitude shocks having fundamental frequencies less than about 2 Hz, the predicted SEAT values were much closer than the measured SEAT values to the subjective SEAT values. The median percentage errors were less than ±5% with the predicted SEAT values but up to 50% with the measured SEAT values (Tables 6.2 to 6.5). The good prediction arose because the impact did not occur in the predicted SEAT values (since they were calculated from a linear model) and since the impact had little effect on subjective responses the predicted SEAT values the impact did not artificially increase the SEAT value.

6.5 Conclusions

Measured and predicted SEAT values reflect the effect of soft cushions of different thickness on the discomfort caused by vertical mechanical shocks. It can be concluded that the SEAT value can be used to evaluate the discomfort caused by vertical mechanical shocks with peak acceleration less than 1g.

The SEAT values predicted by using a three degree-of-freedom model of the coupled seat and human body system did not differ from the measured SEAT values at most of frequencies and magnitudes used in this study. The predicted SEAT values approximated the measured SEAT values accurately in case of exposure to low and the middle magnitude shocks with two soft cushions of different thickness.

A three degree-of-freedom linear model did not predict the non-linearity of the system seat-human body. Linear models should be used with caution when the peak acceleration of shocks approaches or exceeds 1 g.

Chapter 7: THE DISCOMFORT CAUSED BY VERTICAL VIBRATION: EFFECTS OF POSTURE WHEN SEATED AND STANDING

7.1 Introduction

The discomfort caused by vibration is assumed to depend primarily on the magnitude, the frequency, and the direction of the vibration (e.g., Griffin, 2007). The orientation of the body and the posture of the body affect the transmission of vibration into the body and through the body, so these factors may also influence vibration discomfort. Current standards for measuring, evaluating, and assessing the severity of whole-body vibration experienced by standing, sitting and recumbent people do not define these postures precisely or indicate the effects of variations in these postures (British Standards Institution, 1987; International Organization for Standardisation, 1997).

7.1.1 Effects of posture on the biodynamic responses of the human body when seated

When seated, the posture of the body affects both the vertical apparent mass of the body and the transmission of vertical vibration to the spine and the head (Kitazaki and Griffin, 1998). When seated comfortably upright, the vertical apparent mass and the vertical seat-to-head transmissibility of the body show a main resonance peak between 4 and 8 Hz (Hinz and Seidel, 1987; Paddan and Griffin, 1988a; Fairley and Griffin, 1989; Mansfield and Griffin, 2000; Matsumoto and Griffin, 2005; Toward and Griffin, 2011a). However, when changing from a sitting erect posture to a slouched posture the principal resonance frequency of the mean normalized apparent mass drops from about 5.2 to 4.4 Hz (Fairley and Griffin, 1989, Kitazaki and Griffin, 1998). With other configurations of the upper body, Mansfield and Griffin (2002) found increases in the resonance frequency of the apparent mass between “upright” and “anterior leaning” postures (from 5.27 to 6.06 Hz) and between “upright” and “kyphotic” postures (from 5.27 to 6.25 Hz) at 0.2 ms^{-2} r.m.s. However, the effect of posture on the biodynamic responses was less than the effect of the magnitude of vibration across all conditions investigated.

Changes in both the principal resonance frequency and the modulus of the apparent mass of the body have been found when sitting with an inclined backrest (Rakheja et al., 2002; Toward and Griffin, 2009), when changing the height of a footrest (Fairley and Griffin, 1989), and when holding a steering wheel (Toward and Griffin, 2010a).

A single degree-of-freedom lumped parameter model has been found to represent the vertical apparent mass of the body in many postures (e.g. sitting with no backrest, sitting with an inclined rigid and soft backrests, sitting with the hands on the laps, sitting with the hands on a steering wheel, sitting with various configurations of a footrest) (e.g., Fairley and Griffin 1989; Wei and Griffin, 1998b; Toward and Griffin 2010a). This suggests changes in body posture may increase or decrease in the resonance frequency of the apparent mass by increasing or decreasing the stiffness of the body (Toward and Griffin, 2010b).

7.1.2 Effects of posture on the biodynamic responses of the human body when standing

When standing with straight legs, the principal resonance frequency in the vertical transmissibility to the head is about 5 Hz, but the resonance frequency drops to about 3 Hz when standing with bent legs (Paddan and Griffin, 1988a, 1993). At frequencies greater than about 8 Hz, the vertical transmissibility to the head is greater when 'standing with straight legs' than when 'standing with bent legs' (Paddan and Griffin, 1993). Similarly, the resonance frequency in the vertical apparent mass of the standing body decreases from around 5 Hz to about 2.75 Hz when the knees are bent, and there is increased fore-and-aft cross-axis transmissibility to the knees around 2.75 Hz (Matsumoto and Griffin, 1998; Subashi et al., 2006). Subashi et al. (2006) investigated the vertical and fore-and-aft cross-axis apparent mass for five standing postures: upright, lordotic, knees bent, and knees more bent. It was found that the greatest differences in the resonance frequency of the vertical in-line apparent mass occurred between postures with straight legs and knees bent, where the resonance frequencies decreased from about 6 Hz to about 3 Hz. A difference was also found between 'knees bent' and 'knees more bent', where the main resonance frequency reduced from 3.13 Hz to 2.63 Hz. No differences in apparent mass were found when only the upper body position changed, suggesting that changes in the lower limbs have a greater effect on the responses of standing people to vertical vibration than changes in the posture of the upper body.

7.1.3 Comparison of the biodynamic responses of the body when sitting and standing

It seems that when either standing with straight legs or sitting upright on a rigid seat with no backrest, the principal resonance frequency of the body in the vertical direction is around 5 Hz and always within the range 4 to 8 Hz. However, at frequencies greater than about 7 Hz both the modulus of apparent mass and the vertical transmissibility to the head are greater when standing with straight legs than when sitting upright (comparing data in Paddan and Griffin,1988a and 1993; Matsumoto and Griffin, 2000).

Although upper body posture may have little effect on biodynamic responses to vertical vibration when standing or sitting (Subashi et al., 2006; Mansfield and Griffin 2002), it has not been investigated whether the upper body posture affects the subjective response to vertical vibration.

Bending the legs produces large changes in the biodynamic responses of standing people and might be expected to change their vibration discomfort if discomfort is caused by movements of the body that are changed by altering posture. With low frequencies of vertical vibration, bending the legs when standing produces greater changes in biodynamic responses than common changes in posture when sitting. With low frequencies of vertical vibration, bending the legs may therefore also have a greater effect on vibration discomfort than changing sitting posture.

7.1.4 Effects of posture on discomfort when sitting

The discomfort of seated people exposed to vertical vibration is highly dependent on the frequency of the vibration (e.g. Morioka and Griffin, 2006a, Zhou and Griffin, 2014a). When sitting with a backrest, increasing the inclination of the backrest (from 30° to 90°) increases the discomfort caused by vertical vibration at frequencies between 8 and 20 Hz (Basri and Griffin, 2013). In tractor drivers, twisting only the head, or twisting the head and trunk, increases their discomfort compared with a normal driving posture (Wikström, 1993), with increased activity of back muscles (i.e. left and right trapezius, left and right erector spinae muscles). Changing from an upright posture to a slouched posture did not cause a statistically significant change in equivalent comfort contours (Oborne and Boarer, 1982).

7.1.5 Effects of posture on discomfort when standing

When standing with straight legs, greatest sensitivity to vertical acceleration occurs in the frequency range 4 to 16 Hz (e.g., Chaney, 1965; Ashley, 1970; Jones and Saunders, 1972; Oborne and Clarke, 1974; Thuong and Griffin, 2011), broadly consistent with frequency weightings for vertical vibration advocated in current standards (e.g. British Standard 6841:1987; International Standard 2631-1:1997). There are no known studies of the discomfort caused by vertical vibration when standing with bent legs.

7.1.6 Comparison of discomfort when seated and standing

There are no known studies in which there was a direct comparison of the discomfort caused by vertical vibration when sitting and standing. At frequencies greater than 1.6 Hz, the frequency weighting for vertical vibration determined for people standing with straight legs (Thuong and Griffin, 2011) is similar to the frequency weighting Wb in British Standard 6841 (1987), which was based on the frequency-dependence of discomfort when sitting. However, for frequencies less than 1.6 Hz, the weighting Wb seemed to underestimate the discomfort of the standing subjects.

7.1.7 Effects of changing vibration magnitude

In standing and sitting postures, the frequency-dependence of biodynamic responses to vertical vibration depends on the magnitude of the vibration (Fairley and Griffin 1989; Matsumoto and Griffin, 1998; Mansfield and Griffin 2002). This so-called non-linearity might be expected to result in the frequency-dependence of vibration discomfort also depending on the magnitude of vibration when standing or sitting.

Studies of vibration discomfort have found that the rate of growth of vibration discomfort with increasing magnitude of vibration depends on the frequency of the vibration. This results in the frequency-dependence of vibration discomfort changing with the magnitude of vibration. This non-linearity in vibration discomfort has been found for many postures and directions of vibration including vertical vibration when sitting (e.g., Morioka and Griffin, 2006a; Zhou and Griffin,2014) and vertical vibration when standing (Thuong and Griffin, 2011).

7.1.8 Objectives and hypothesis of this study

The limitations in studies of vibration discomfort mean it is not clear whether the standardised methods of evaluating vertical vibration are suitable when people stand with their legs bent or sit leaning forward. In British Standard 6841 (1987) a note in Section 4 states: “The method of evaluation is applicable to erect standing postures. However, slight bending of the knees can affect the transmission of vibration to standing persons so this application will not always be appropriate”. Standing with bent legs and sitting leaning forward are common in many environments where people are exposed to vibration (e.g., high speed boats or motorcycles). This study was designed to investigate the extent to which a change in the posture of standing or sitting people affects their vibration discomfort.

It was expected that the frequency dependence of the equivalent comfort contours when ‘standing with straight legs’, ‘sitting upright’, or ‘sitting leaning forward’ will not differ in the frequency range 0.5 Hz to 16 Hz between the postures and it will be consistent with the Wb frequency weighting in BS 6841:1987 (see Oborne and Boarer, 1982; Thuong and Griffin, 2011). It was hypothesised that when ‘standing with bent legs’ the greatest sensitivity to vertical vibration will be between 2 Hz and 4 Hz, reflecting the decreased resonance frequency compared to the straight legs and sitting upright (e.g. Paddan and Griffin, 1993, Matsumoto and Griffin, 1998). As a consequence and major application Wb weighting would underestimate discomfort at frequencies around 2 to 4 Hz and overestimate discomfort at higher frequencies. It was also hypothesised that in all four postures the rate of growth of discomfort with increasing magnitude of vibration would depend on the frequency of vibration.

7.2 Method

7.2.1 Subjects

Fourteen male students and office workers at the University of Southampton participated in the study. They were aged 22 to 37 years, had statures between 160 and 185 cm, and weights between 56 and 120 kg. The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (Reference number: 10565).

Analysis of subject responses in the sitting postures was restricted to 12 of the 14 subjects due to loss of acceleration measurements at the seat for two subjects.

7.2.2 Apparatus

Vertical vibration was produced by a 1-m stroke vertical electrohydraulic vibrator (Servotest Testing Systems Ltd., Surrey, UK). All signals were generated using the HVLab Matlab Toolbox (version 2.0, ISVR, University of Southampton, UK), and equalized and reproduced by a Servotest Pulsar system. Accelerations were measured using a capacitive accelerometer 2260-002 (Silicon Designs Inc.) attached at the platform.

When standing, subjects wore a loose whole-body harness secured to a frame mounted on the vibrator platform to support them if they fell. Subjects were told to rest their hands on a handrail 105 cm above the platform, and use it to maintain balance if they thought they might fall.

When seated, subjects sat on a saddle seat rigidly mounted on the platform of the vibrator. The seat frame was made of aluminium and supported a firm cushion containing closed cell foam. The supporting surface of the foam was 55 cm above the platform of the vibrator on which the subjects rested their feet. Subjects sat so that they did not make contact with a low backrest. The shape and the dimensions of the upper surface of the saddle seat are shown in Figure 7.1. Acceleration at the interface with the seat cushion beneath the ischial tuberosities was measured using a SIT-pad containing a tri-axial accelerometer (Willow Technologies KXD94-2802).

When the subjects sat leaning forward, they rested their arms on a handrail 105 cm above the platform and 30 cm far from the front of the saddle seat.

A noise box (HFRU Noise system 001, ISVR, University of Southampton, UK) produced white noise at approximately 75 dB via a pair of headphones so as to mask any noise of the vibrator. Subjects were provided with a button that allowed them to stop the motion of the simulator at any time.

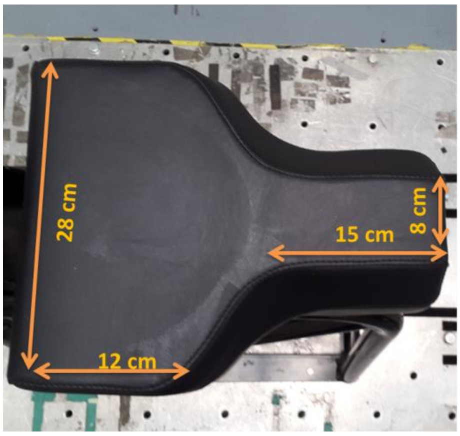


Figure 7.1 Upper surface of the saddle seat used in the experiment.

7.2.3 Stimuli

The motions were vertical sinusoidal vibrations at the preferred one-third octave centre frequencies in the frequency range 0.5 to 16 Hz. All motion stimuli had durations of 5 s and were enveloped with a half cosine of frequency 0.1 Hz.

The magnitudes of the motions were quantified in terms of their root-mean-square, r.m.s., and vibration dose value, VDV, both unweighted and frequency-weighted using weighting W_b (BS 6841:1987). At each fundamental frequency, eight magnitudes were presented in 2 dB steps. The magnitudes varied with the frequency of motion but were always within the range 0.3 to 3.2 ms^{-2} r.m.s. (unweighted) and within the range 0.2 to

3.0 $ms^{-1.75}$ (VDV frequency-weighted using W_b). The magnitudes measured at the platform and for each frequency of vibration are shown in Table 7.1.

Table 7.1 Magnitudes of vibration for each frequency measured at the rigid platform.

unweighted r.m.s (ms^{-2})																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1**	**1.25**	**1.6**	**2**	**2.5**	**3.15**	**4**	**5**	**6.3**	**8**	**10**	**12.5**	**16**
	0.3	0.4	0.6	0.7	0.7	0.7	0.6	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	0.4	0.5	0.7	0.9	0.9	0.8	0.7	0.5	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	0.5	0.6	0.9	1.1	1.1	1.0	0.9	0.7	0.6	0.4	0.4	0.4	0.4	0.3	0.4	0.4
	0.6	0.7	1.1	1.4	1.4	1.3	1.1	0.8	0.7	0.5	0.5	0.4	0.4	0.4	0.5	0.5
	0.8	0.9	1.4	1.7	1.8	1.6	1.3	1.1	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.8
	1.0	1.1	1.7	2.1	2.1	2.0	1.7	1.4	1.3	1.0	0.9	0.7	0.7	0.7	0.9	1.1
	1.2	1.4	2.2	2.6	2.6	2.4	2.1	2.1	1.6	1.2	1.1	1.0	1.0	1.1	1.2	1.3
	1.6	1.8	2.6	3.2	3.2	3.0	2.7	2.6	2.1	1.6	1.4	1.3	1.3	1.3	1.5	1.7
unweighted VDV ($ms^{-1.75}$)																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1**	**1.25**	**1.6**	**2**	**2.5**	**3.15**	**4**	**5**	**6.3**	**8**	**10**	**12.5**	**16**
	0.6	0.8	1.2	1.5	1.5	1.3	1.2	0.8	0.7	0.6	0.5	0.5	0.5	0.5	0.5	0.5
	0.8	1.0	1.5	1.8	1.8	1.7	1.4	1.1	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.7
	1.0	1.2	1.8	2.2	2.3	2.1	1.8	1.3	1.1	0.9	0.7	0.7	0.7	0.7	0.8	0.8
	1.3	1.5	2.3	2.8	2.8	2.6	2.2	1.7	1.4	1.1	0.9	0.9	0.9	0.9	0.9	1.0
	1.6	1.8	2.8	3.5	3.5	3.2	2.7	2.2	1.7	1.4	1.2	1.1	1.1	1.1	1.2	1.7
	2.0	2.3	3.5	4.3	4.3	3.9	3.4	2.8	2.7	2.0	1.7	1.4	1.4	1.4	1.9	2.2
	2.5	2.9	4.3	5.3	5.3	4.8	4.2	4.2	3.3	2.5	2.2	2.1	2.1	2.1	2.3	2.7
	3.1	3.6	5.3	6.5	6.5	6.0	5.4	5.2	4.1	3.1	2.7	2.6	2.6	2.7	2.9	3.4

7.2.4 Procedure

Subjects attended two sessions on two different days. They stood in two postures ('standing with straight legs' and 'standing with bent legs') in the first session and sat in two postures (‘sitting upright’ and ‘leaning forward’) in the second session (Figure 7.2). Both sessions had two parts with a 5-minute break between parts.

a) b) c) d)

Figure 7.2 The four postures: ‘standing with bent legs’ (a), ‘standing with straight legs’ (b), ‘sitting upright’ (c) and ‘leaning forward’ (d).

In the standing session, half of the participants started with bent legs and the others started with straight legs. When the legs were bent, the front of each knee was directly above the toes. The distance between the feet was equal to the width of the shoulders.

In the sitting session, half of the participants started with an upright posture and the others started with the leaning forward posture. When leaning forward the subjects rested their arms on the rail in order to keep stable with the angle between the back and the vertical about 40°.

In both sessions the subjects had their eyes closed during exposures to vibration.

The method of absolute magnitude estimation was used to obtain judgements of the discomfort caused by each frequency and magnitude of vibration in all four postures (Stevens, 1957, Huang and Griffin, 2014).

Before commencing the experiment, participants were trained how to use absolute magnitude estimation (see Chapter 3) to rate the apparent length of lines and, subsequently, 14 practice motion stimuli.

Both sessions lasted about one hour and included a total of 256 test stimuli (i.e., 8 magnitudes at 16 frequencies in two postures).

7.2.5 Equivalent comfort contours

It was assumed that the subjective magnitude (i.e., vibration discomfort), ψ, was related to the objective magnitude (i.e., vibration magnitude), φ, through Stevens' power law:

$$\psi = k \cdot \varphi^n$$

where k is a constant and the exponent n is called the rate of growth of discomfort. From the measured accelerations and the magnitude estimates of the subjects, the values of n and k were calculated by regression between log ψ and log φ at each frequency of vibration for all individual subjects in all four postures.

When sitting, the objective magnitude was the vertical acceleration measured on the seat with the SIT-pad for each subject. When standing, the objective magnitude was the vertical acceleration measured at the platform.

Prior to calculating n and k, the subjective data from an individual within a session were normalized by dividing each of their judgements by the median value of their 256 judgements in that session and then multiplying by 100.

Having obtained the values of n and k, both individual and median equivalent comfort contours were calculated by determining the vibration magnitude, φ, required to obtain subjective magnitudes, ψ, of 63, 80, 100, 125 and 160 at each frequency in the range 0.5 to 16 Hz.

The median equivalent comfort contours presented below were obtained using median values of n and k calculated from the individual values of n and k.

7.2.6 Locations of discomfort

Subjects also indicated the part of the body where they felt most discomfort by referring to the body maps shown in Figure 7.3.

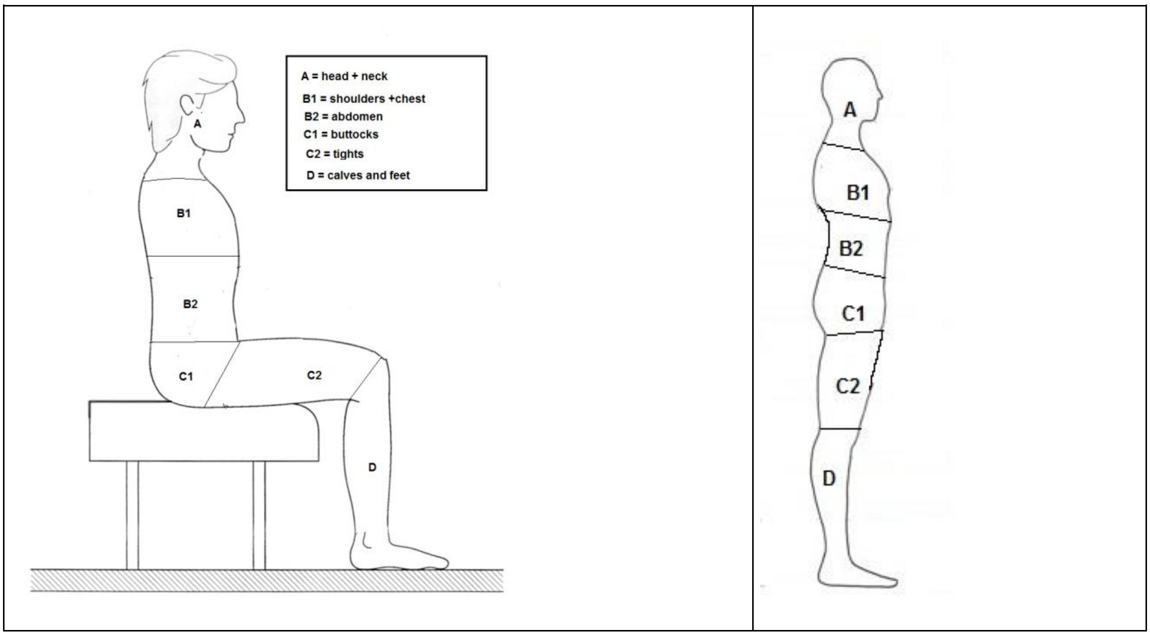


Figure 7.3 Body maps used during when sitting (left) and standing (right). A = 'head and neck', B1 = 'chest and shoulders', B2 = 'abdomen', C1 = 'buttocks', C2 = 'tights', D = 'calves and feet'.

7.2.7 Saddle seat transmissibility

The transmissibility of the saddle seat was calculated as the ratio between the unweighted VDV measured on the seat (i.e., output signal) and the unweighted VDV at the platform (i.e., input signal) at all frequencies with all magnitudes of vibration.

$$\textit{Transmissibility} = VDV_{seat}/VDV_{platform}$$

7.2.8 Statistical analysis

The rate of growth of discomfort and the equivalent comfort contours were used to test the hypotheses. Non-parametric tests were used in the statistical analysis. In order to investigate differences between related samples; the Friedman two-way analysis of variance and Wilcoxon matched-pairs signed ranks were used. Cochran's Q test and McNemar test were used in the case of categorical data (i.e. body locations of discomfort). The values shown below are not corrected for multiple comparisons.

7.3 Results

7.3.1 Rate of growth of discomfort

In all four postures, the rate of growth of discomfort varied with the frequency of vibration (p<0.001, Friedman; Figure 7.4).

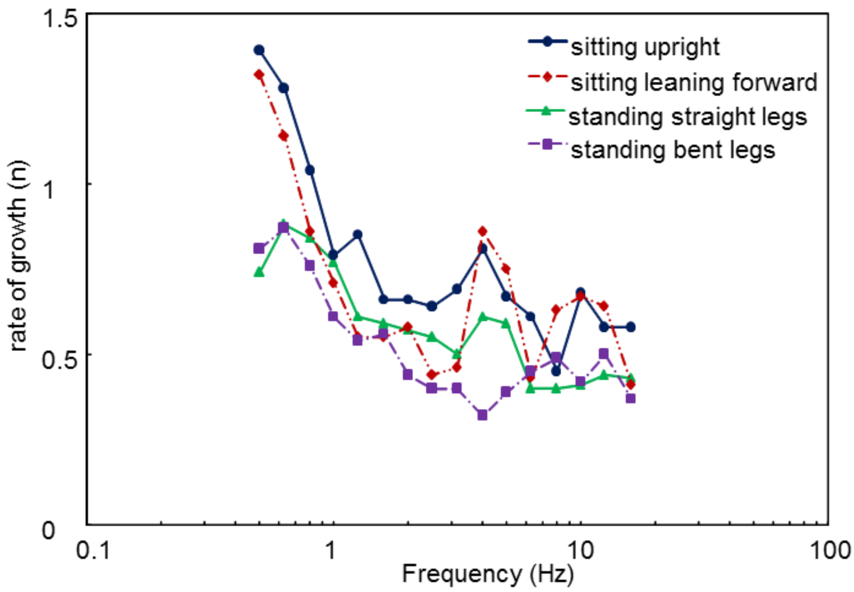


Figure 7.4 Rate of growth of discomfort when sitting ('upright' ━●━, 'leaning forward' ━♦ ▪ ▪) and when standing (straight legs ━▲━, bent legs (■━ ▪)).

The rate of growth of discomfort was significantly greater when sitting upright than when leaning forward at 3.15 Hz (p=0.009) and 16 Hz (p=0.050).

The rate of growth of discomfort was significantly greater when standing with straight legs than standing with bent legs at 2.5 Hz (p=0.041), 4 Hz (p=0.007), and 5 Hz (p=0.048).

Although it was not possible to apply statistical analysis due to a different sample of subjects used in the two sessions, the rate of growth obtained with the two standing postures seemed to be slightly lower than in the two sitting postures. From 2.5 Hz to 5 Hz the rate of growth for standing with straight legs showed a frequency dependence more similar to the rate of growth obtained with the sitting postures, however at all other frequencies it was more similar to the rate of growth obtained with the other standing posture.

7.3.2 Equivalent comfort contours

In all four postures, the unweighted VDV required for a subjective magnitude of ψ = 100 was strongly dependent on the frequency of vibration (p<0.001, Friedman; Figure 7.5).

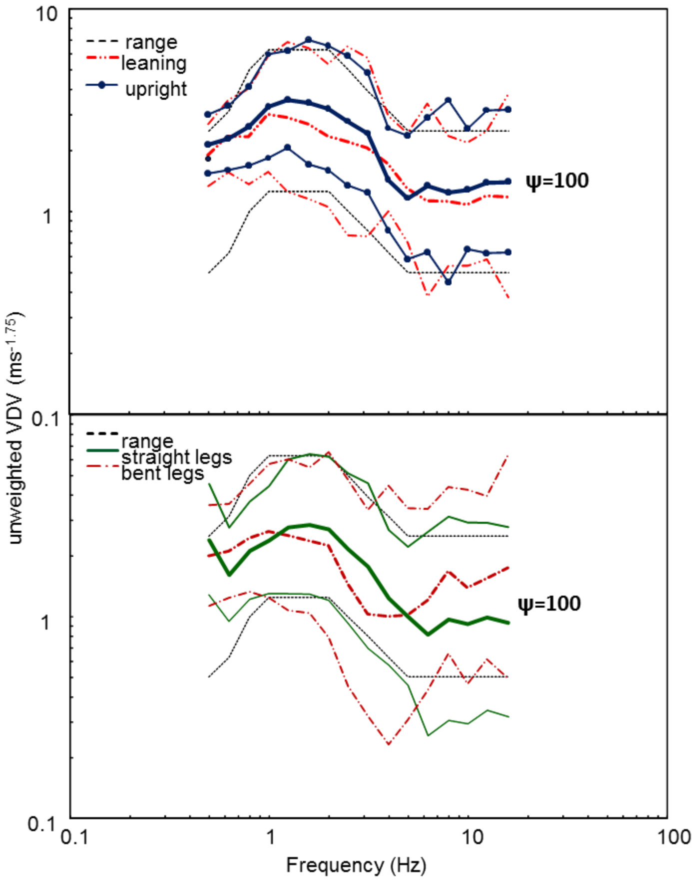


Figure 7.5 Effects of sitting and standing postures on equivalent comfort contours. Subjective magnitudes *ψ*=63, 100 and 160. Postures: sitting upright —●—,leaning forward ▬ ▪ ▪, standing with straight legs ▬▬, standing with bent legs ▬ ▪. Range of magnitudes used in the experiment------.

When seated, the acceleration required for a subjective magnitude *ψ* of 100 was greater when sitting upright than when sitting leaning forward at frequencies of 1.6, 2, 2.5 ($p<0.025$, Wilcoxon) and 6.3 Hz ($p=0.005$).

When standing, in the frequency range 2 to 3.15 Hz a greater unweighted VDV was required to cause the same discomfort (i.e., ψ = 100) with straight legs than with bent legs ($p<0.01$, Wilcoxon). In the frequency range 5 to 16 Hz, a greater unweighted VDV was required to cause the same discomfort with bent legs than with straight legs ($p<0.041$, Wilcoxon).

7.3.3 Locations of discomfort

In all four postures the location of greatest discomfort at each frequency was independent of the magnitude of vibration ($p>0.05$, Cochran's Q test). The effects of frequency and posture on the location of discomfort was therefore investigated using responses to the middle magnitude of vibration).

When standing with straight legs, the percentage of people who chose either the head (location 'A') or the thighs (location 'C2') as the prime location of discomfort varied with the frequency of vibration (p=0.024, 0.045, respectively, Cochran's Q test; Figure 7.6).

When standing with bent legs, the percentage of people who chose either the chest (location 'B1') or the feet and calves (location 'D') as the prime location of discomfort varied with the frequency of vibration (p=0.043, p<0.001, Cochran's Q test; Figure 7.6).

The location where greatest discomfort was reported did not vary between the two sitting postures, or between the two standing postures, except that with 16-Hz vibration location D (feet) was more common with 'bent legs' than with 'straight legs' (p<0.016, McNemar).

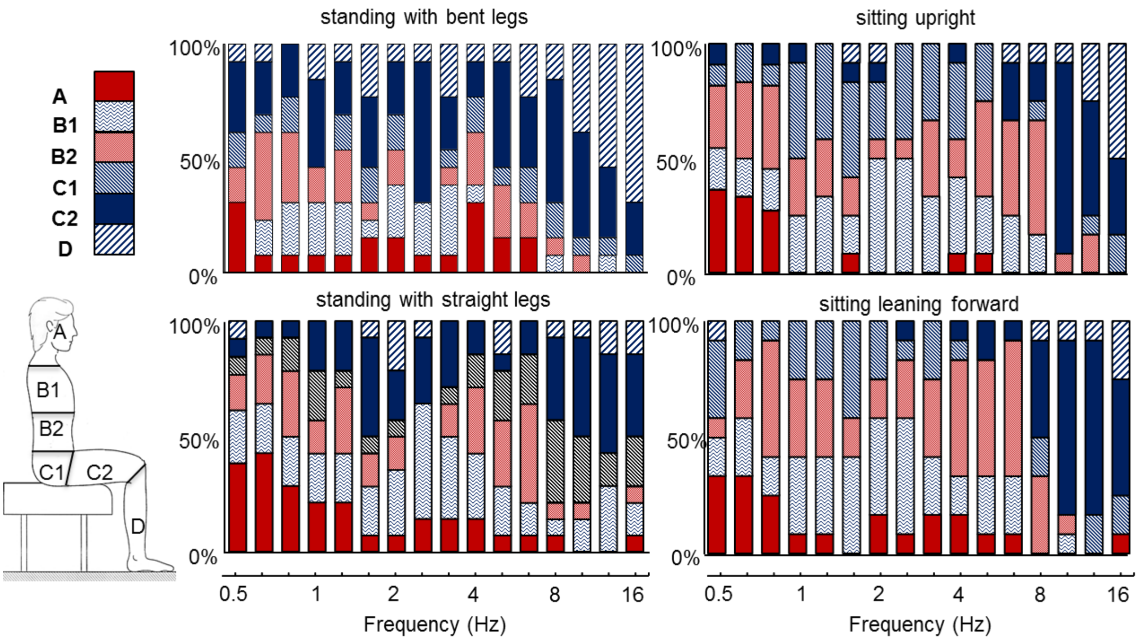


Figure 7.6 Effects of posture and vibration frequency on the location of discomfort. Middle magnitude of vibration (1.25 $ms^{-1.75}$ weighted VDV) in all postures. Locations of discomfort as defined in Figure 2

7.3.4 Saddle seat transmissibility

Figure 7.7 shows the median transmissibility with both upright and leaning forward sitting postures, where the median transmissibilities have been calculated over all subjects for each of the eight magnitudes of vibration.

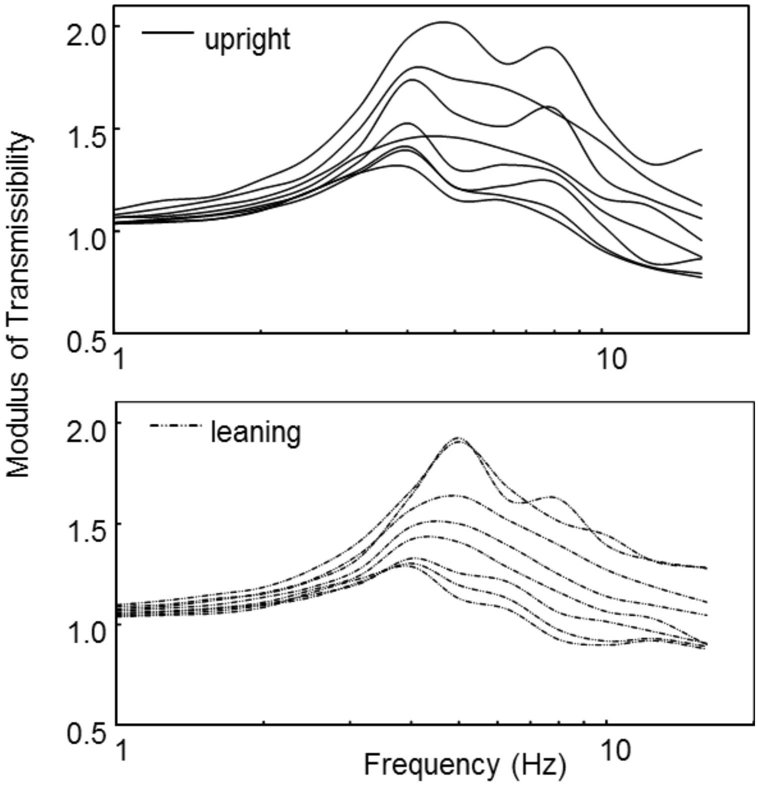


Figure 7.7 Median vertical transmissibility of the saddle seat when sitting upright and sitting leaning forward at all magnitudes of vibration (0.3 to 3.2 ms^{-2} r.m.s. (unweighted).The upper lines show the transmissibilities with the lowest magnitudes and the lower lines show the transmissibilities with the highest magnitudes.

The median transmissibility of the saddle seat shows a resonance around 4 to 5 Hz, with amplification in the range 3.15 to 8 Hz (Figure 7.7). At every frequency of vibration, the transmissibility depended on the magnitude of vibration (p<0.001, Friedman). At high frequencies the modulus of the vertical seat transmissibility decreased with increasing magnitude of vibration. At each of the eight magnitudes of vibration, and at each of the 16 frequencies of vibration, the seat transmissibility when sitting upright was compared with the seat transmissibility when sitting leaning forward. The seat transmissibility obtained sitting upright and sitting leaning forward did not differ at most frequencies or magnitudes of vibration (p>0.05, Wilcoxon), except at the highest magnitude of vibration at 3.15, 6.3, 8.0, 12.5 and 16 Hz (p<0.034, Wilcoxon), where the up to 8 Hz transmissibility was slightly greater with upright posture and from 12.5 Hz was slightly lower with upright than with leaning forward.

7.4 Discussion

7.4.1 Rate of growth of vibration discomfort

The rate of growth of discomfort varied with the frequency of vibration (Figure 7.4), causing changes in the shapes of the equivalent comfort contours as the magnitude of vibration changed (Figure 7.5). Many previous studies of vibration discomfort have found an effect of vibration magnitude on the frequency-dependence of vibration discomfort using other magnitudes and frequencies of vibration (e.g., velocity from 0.02 to 1.25 ms^{-1} r.m.s. and from 2 Hz to 315 Hz, Morioka and Griffin, 2006a), other stimuli (e.g., vertical mechanical shocks, Ahn and Griffin, 2008) and other postures (e.g., sitting with various angles of backrest, Basri and Griffin, 2013; Thuong and Griffin, 2011). The effect of vibration magnitude on the frequency-dependence of vibration discomfort found with the four postures in the present study shows that no single frequency weighting will give an accurate prediction of vibration discomfort at all magnitudes in any of the four postures.

7.4.2 Effect of posture when standing

The frequency of greatest sensitivity to acceleration decreased from the range 5 to 7 Hz with straight legs to the range 3 to 4 Hz with bent knees (see Figure 7.5). Biodynamic studies with similar standing postures found the resonance in the vertical transmissibility to the head reduced from around 5 Hz with straight legs to around 3 Hz with 'bent legs' (Paddan and Griffin, 1993). In the same study, head motion in the fore-and-aft axis was more pronounced when subjects stood with bent legs than with straight legs. The principal resonance of the apparent mass in an upright standing posture (straight legs locked) was around 5 Hz (and close to the apparent mass resonance of the seated body) but decreased to around 2.75 Hz with bent knees (Matsumoto and Griffin, 1998). In the same study, transmissibility to the knees in the fore-and-aft direction presented a main peak around 3 Hz, suggesting the resonance was associated with bending of the knees. A resonance around 3 Hz suggests increased motion of the whole body that could compromise comfort. Most of the subjects indicated the feet as the location of greatest discomfort when they were exposed to vibration in a standing posture with bent legs at frequencies greater than 10 Hz (Figure 7.6). At frequencies greater than about 5 Hz, vertical floor-to-head transmissibility is less when standing with bent legs than when standing with straight legs (Paddan and Griffin, 1993). So when the legs are bent at the knees it becomes more likely that the sensations caused by higher frequencies are felt in the lower legs or the feet, as seen in Figure 7.6.

7.4.3 Effects of sitting posture

Sitting leaning the upper body forward resulted in more discomfort than sitting upright, with the difference statistically significant for a subjective magnitude of 100 at frequencies from 1.6 Hz to 2.5 Hz and at 6.3 Hz ($p < 0.025$; Figure 7.5).

Few studies have investigated the discomfort caused by vibration when sitting leaning forward, but Osborne and Boarer (1982) found no significant differences between an upright posture and a slouched posture with sinusoidal vertical vibration in the range 2.5 Hz to 60 Hz. Although the differences were not statistically significant, their equivalent comfort contours had a trend for sitting slouched to be more uncomfortable than sitting upright at 6 and 8 Hz. The postures used in this study and in the study of Osborne and Boarer (1982) are slightly different. In Osborne and Boarer (1982) subjects sat slouched with the arms resting on the knees. In the study reported here, the subjects leant their upper body keeping the spine straight and rested the arm on a handrail 105 cm above the platform and 30 cm forward of the front of the seat (Figure 7.2).

Comparisons of vertical apparent mass and vertical seat to pelvis pitch transmissibility between 'sitting upright' and 'anterior lean' do not show great differences between the two postures at most magnitudes of random vibration studied by Mansfield and Griffin (2002). This limited effect on biodynamic responses of leaning the body forward is consistent with the limited effect on subjective responses. The handrail in the present study limited the forward motion of the upper body, but it may have resulted in greater pitch motion of the pelvis so increasing discomfort around 6.3 Hz when 'leaning forward'.

Although not statistically significant, at frequencies greater than about 6.3 Hz and a subjective magnitude of ψ=100, Figure 7.5 shows a trend for the leaning forward posture to be more uncomfortable than sitting upright. Mansfield and Griffin (2002) show vertical seat to pelvis pitch transmissibilities with more evident peaks in their anterior lean posture than in their upright posture, a first peak between 8 to 12 Hz and second peak between 14 Hz to 20 Hz, with both resonance frequencies decreasing with increasing the magnitude of vibration.

At frequencies greater than about 8 Hz the handrail might have been represented an extra source of vibration and so increased discomfort in this posture. Slightly greater discomfort at all frequencies when leaning forward may alternatively, or additionally, have been caused by increased muscle tension needed to keep the posture stable.

7.4.4 Seat transmissibility

The saddle seat employed in the study was designed for use in high speed marine craft. At no frequency in the range 0.5 to 16 Hz did the seat attenuate vibration (Figure 7.7). The transmissibility was greater than 1 at all frequencies in the range 0.5 to 16 Hz and as much as 2 around 5 Hz (with lower magnitude motions). This indicates the seat could almost double the acceleration. If the rate of growth of discomfort, n, was 1, a doubling of vibration magnitude would correspond to a doubling of the discomfort.

7.4.5 Frequency-dependence of vibration discomfort

When expressed in terms of unweighted r.m.s. acceleration, the equivalent comfort contours obtained when standing with straight legs, sitting upright, and sitting leaning forward seem consistent with contours reported previously (Figure 7.8).

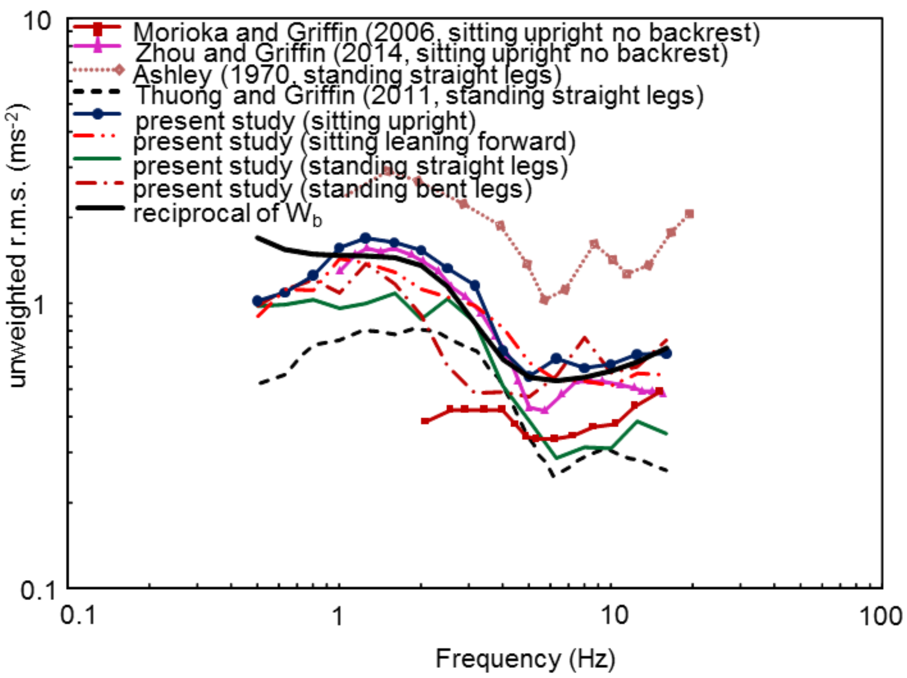


Figure 7.8 Comparison of equivalent comfort contours from the present and past studies.

Some differences between the contours obtained in different studies might be attributable to the use of different psychophysical methods and different experimental settings (e.g., absence of a handrail). However, in all conditions where subjects were either sitting upright or standing with their legs straight, the acceleration required to cause a degree of discomfort decreased as the frequency of vibration increased from 2 Hz to 5 or 6 Hz. A similar finding when sitting upright with no backrest, sitting leaning forward, and standing with straight legs is consistent with the use of frequency weighting W_b when evaluating exposures to vertical vibration in these three postures. However, when standing with bent legs, the acceleration required to cause a degree of discomfort decreases as the frequency of vibration increases from 1.6 to 3 Hz, after which the contours gradually rise. A frequency weighting that gives greatest weight to frequencies from 5 to 16 Hz, such as W_b, will therefore underestimate vibration discomfort at frequencies from 2 to 4 Hz when standing with bent legs.

7.4.6 Applicability of frequency weightings in current standards

Figure 7.9 compares the two median equivalent comfort contours (all four postures with ψ = 100 for 16 frequencies from 0.5 to 16 Hz) in terms of vibration dose values frequency weighted by W_b. If the weighting was perfect for evaluating vertical vibration when sitting in any posture, the contour would be a horizontal line.

When sitting, the variability in the 16 weighted values in each of the two lines in Figure 7.9 (top) relative to the median value of each line was estimated separately. When sitting 'upright, relative to the median value of 1.30 $ms^{-1.75}$, the weighted VDV varies between a maximum of +1.38 dB (at 3.15 Hz) and a minimum of -3.7 dB (at 0.5 Hz), with an average error of -0.43 dB. When sitting 'leaning forward', relative to the median value of 1.12 $ms^{-1.75}$, the weighted VDV varies between a maximum of +1.77 dB (at 4 Hz) and a minimum of -3.42 dB (at 0.5 Hz), with an average error of -0.18 dB. With both postures, at frequencies less than about 1 Hz, the frequency weighting W_b underestimated the discomfort.

When standing, the variability of the 16 weighted values in each of the two lines in Figure 7.9 (bottom) relative to the median value of each line was again estimated separately. When standing with 'straight legs', relative to the median value of 0.98 $ms^{-1.75}$, the weighted VDV varies between a maximum of +1.39 dB (at 1.6 Hz) and a minimum of -3.6 dB (at 0.63 Hz), with an average error of -0.11 dB. When standing with 'bent legs', relative to the median value of 0.99 $ms^{-1.75}$, the weighted VDV varies between a maximum of +4.89 dB (at 16 Hz) and a minimum of -3.72 dB (at 3.15 Hz), with an average error of +0.35 dB. In BS 6841:1987 it is noted that the frequency weighting W_b is applicable to erect standing postures but that it may not always be appropriate when the knees are bent. This study shows that if the legs are bent, the application of frequency weighting W_b will tend to underestimate discomfort at frequencies around 2 to 3 Hz and overestimate discomfort at frequencies greater than about 5 Hz.

Figure 7.10 compares the contours for the four postures in terms of the weighted VDV. The contours obtained standing with straight legs, sitting upright, and sitting leaning forward seem to follow a similar pattern from 0.5 to 16 Hz, being flat at frequencies greater than about 1 Hz. In contrast, the frequency-dependence of the contour obtained when standing with bent legs shows greater sensitivity from 2 to 4 Hz and reduced sensitivity from 8 to 16 Hz.

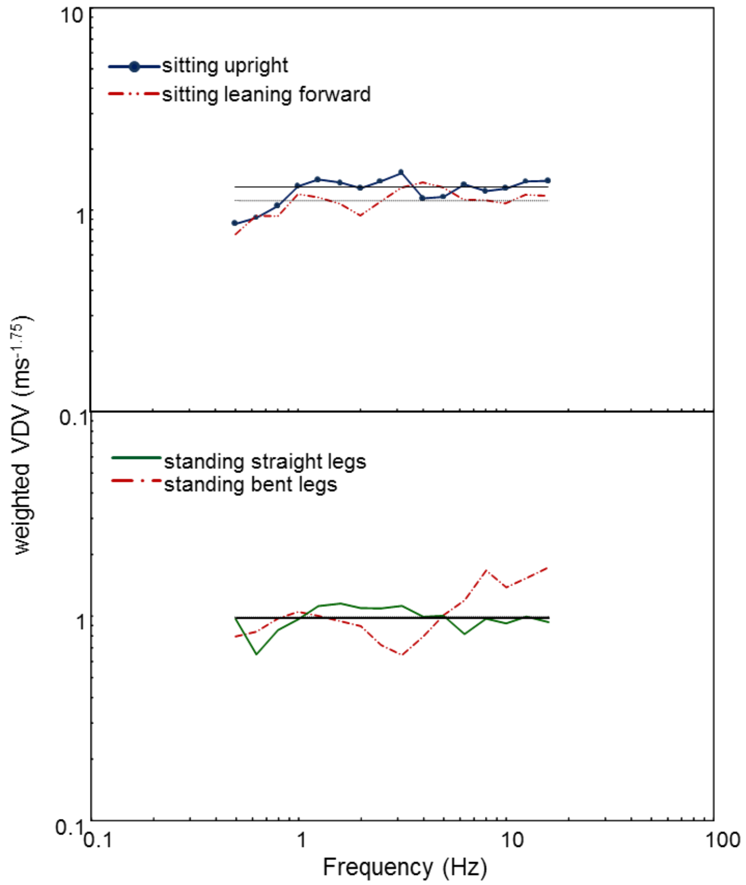


Figure 7.9 Median equivalent comfort contours expressed in terms of W_b frequency-weighted VDV. Postures: sitting 'upright' (—●—), sitting 'leaning forward' (▬ ▪▪), standing 'straight legs' (▬▬) and standing 'bent legs' (▬ ▪); subjective magnitude ψ=100.

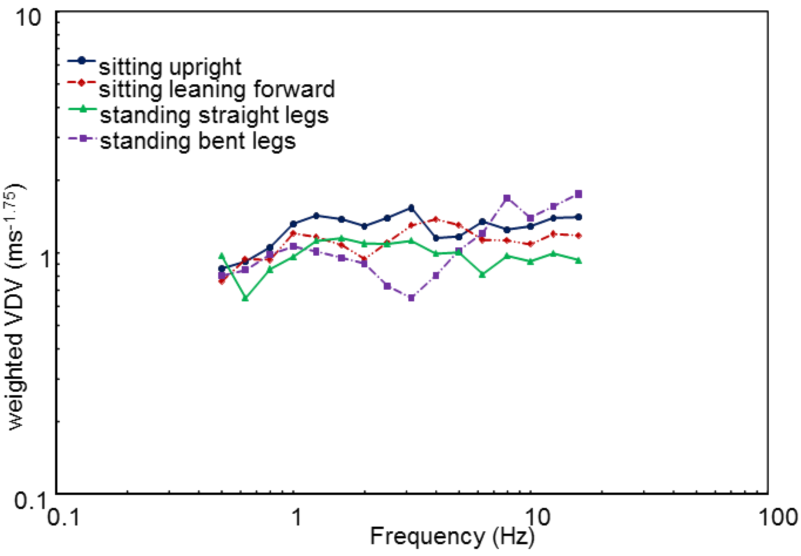


Figure 7.10 Median equivalent comfort contours expressed in terms of W_b frequency-weighted VDV. Postures: sitting 'upright' (—●—), sitting 'leaning forward' (▬ ♦▪▪), standing 'straight legs' (▬▬▲) and standing 'bent legs' (▬ ■▪); subjective magnitude ψ=100.

7.5 Conclusions

Bending the legs increases the discomfort caused by vertical vibration in the frequency range 2 to 3.15 Hz but reduces the discomfort caused by frequencies greater than about 5 Hz.

In the range 1.6 to 2.5 Hz, there is slightly more discomfort when sitting leaning forward than when sitting upright.

It may be concluded that frequency weighting W_b is reasonable for evaluating vertical vibration when people sit upright, sit leaning forward, or stand with straight legs, but it is not appropriate when standing with the knees bent. In this posture the weighting will underestimate discomfort caused by frequencies between 2 to 4 Hz and overestimate discomfort caused by frequencies greater than 5 Hz. In all four postures, the frequency-dependence of vibration discomfort depends on the magnitude of vibration, so no frequency weighting will provide an accurate prediction of discomfort at all magnitudes.

Chapter 8: GENERAL DISCUSSION

8.1 Introduction

The overall objectives of this thesis were: i) to advance understanding of the effects of frequency, magnitude, direction, and seat dynamics on the discomfort caused by mechanical shocks, and ii) to advance understanding of the effects of posture on the discomfort caused by vertical vibration. This chapter discusses the main questions that this work sought to answer:

(i) Do the frequency-dependence and the magnitude-dependence of discomfort caused by shocks differ from the frequency-dependence and the magnitude-dependence of discomfort caused by vibration?

(ii) Does the magnitude of a vertical shock determine whether the direction of the shock influences discomfort?

(iii) Can the methods used for evaluating seat comfort and seat transmission during continuous vibration be used also with vertical mechanical shocks?

(iv) Does the appropriate frequency weighting for discomfort caused by vertical vibration depend on the postures of standing and sitting people?

8.2 The subjective response to vertical shocks compared to the subjective response to vertical vibration

8.2.1 The difference in frequency dependence

The work presented in Chapter 4 of this thesis shows that the frequency-dependence of the discomfort caused by shocks differs from the frequency-dependence of the discomfort caused by vibration. With unweighted VDV, shocks with fundamental frequency greater than 4 Hz induce less discomfort than vibration, with the equivalent comfort contours for shocks having a flatter shape than equivalent comfort contours for vibration (Figure 8.1). This occurs because a shock is characterized by many frequency components and the subjective response to a shock is influenced by the combined contribution of multiple frequencies, where the contribution of each frequency depends on the spectral distribution.

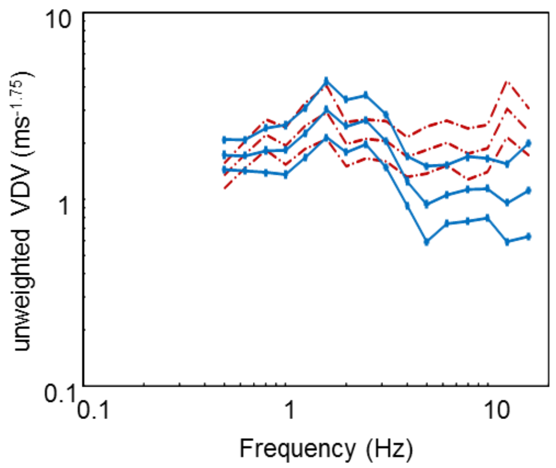


Figure 8.1 Equivalent comfort contours for shocks (●▬) and vibration (▬+▬) in terms of unweighted VDV for subjective magnitudes of ψ= 80, 100, 125.

Analysis of body maps presented in Chapters 4 and 7 suggests that the subjective ratings may partly depend on where in the body, either the lower body (i.e. buttocks and thighs) or the upper body (i.e. head, shoulders, chest and abdomen) the vibration causes greatest discomfort. The equivalent comfort contours for sinusoidal vibration show greatest sensitivity from 4 to 16 Hz (Figure 8.1). Between 4 and 8 Hz, the locations of greatest discomfort are the upper body (i.e. head, shoulders, chest and abdomen) as shown in Figure 8.2 and previous studies (e.g. Whitham and Griffin, 1978; Basri and Griffin – no backrest condition, 2013; Zhou and Griffin, 2014a). At frequencies greater than 10 Hz, where sensitivity to vibration is less, the locations of greatest discomfort are the buttocks, the thighs, and the feet. With shocks in the range 4 to 8 Hz, the body map of Figure 8.3 shows that the areas of greatest discomfort are the buttocks and the thighs.

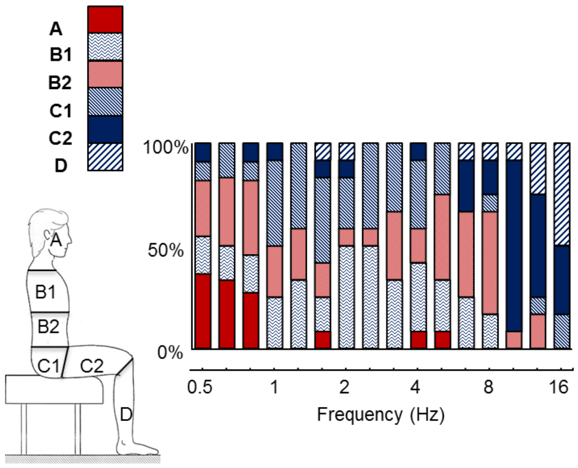


Figure 8.2 Body locations of greatest discomfort caused by vertical sinusoidal vibration with fundamental frequency in the range 0.5 to 16 Hz at the middle magnitudes (i.e. 1.25 ms$^{-1.75}$ weighted VDV). Body locations presented in Chapter 7 of this thesis.

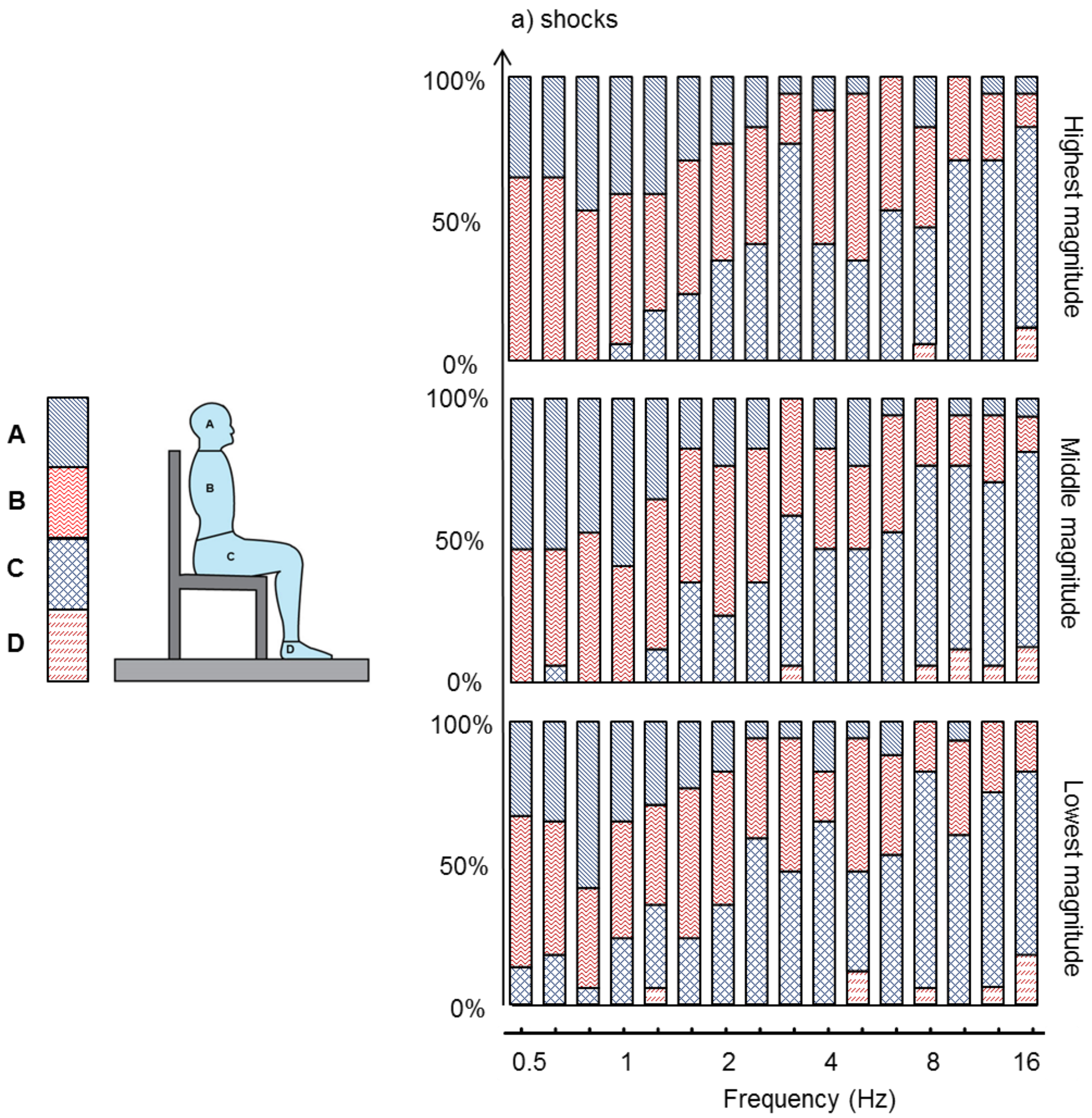


Figure 8.3 Body locations of greatest discomfort caused by vertical shocks with fundamental frequency in the range 0.5 to 16 Hz.

The differences in the spectral characteristics between vertical shocks and sinusoidal vibration with the same fundamental frequency may suggest a difference in the transmission of shocks and vibration to and through the body. Although many studies investigated the biodynamic response to vibration (e.g. Paddan and Griffin, 1988a, b; Fairley and Griffin, 1989; Mansfield and Griffin, 2002; Zhou and Griffin, 2014b) and not many studies investigated the biodynamic response to shocks (e.g. Matsumoto and Griffin, 2005, Zhou and Griffin, 2016b), there is still a need of a study that compares directly the biodynamic responses to shocks and continuous vibration.

8.2.2 The difference in the magnitude dependence

The exponent *n*, together with the constant *k*, (in Stevens' power law) link the subjective perception of the vibration to the objective magnitude of the vibration (e.g. the acceleration). The work presented in Chapter 4 of this thesis shows that the magnitude-dependence of the discomfort caused by shocks differs slightly from the magnitude-dependence of the discomfort caused by vibration. The exponent *n* for shock was greater than the exponent *n* for vibration at 0.63, 0.8, 2, 3.15, 5, 6.3, 12.5 and 16 Hz, and, with both types of motion, the exponent depends on the fundamental frequency of the motion (Figure 8.4). This means that when the magnitude of motion changes, the frequency-dependence of equivalent comfort contours changes within each waveform (i.e. shock or vibration) and between the waveforms.

The rate of growth of discomfort may have been greater for shocks than for vibration because a shock is characterised by many frequency components and it can be supposed that the exponent *n* for shocks is a combination of the contributions from more than one frequency component (i.e. the values of *n* for vibration). The exponent *n* for shocks is therefore expected to decrease with increasing frequency but to be slightly greater than the exponent *n* for vibration. This occurs because the values of the exponent *n* for vibration vary from 1.2 to 0.6 between 0.5 Hz and 2 Hz (i.e. quadrupling the frequency *n* halves); whilst the values of the exponent *n* for vibration vary from 0.7 to 0.4 between 2.5 Hz and 16 Hz (i.e. increasing the frequency by six times *n* reduces by 0.3, Figure 8.4). Therefore frequency components less than 2 Hz will have a greater contribution to *n* for shocks than frequency components greater than 2.5 Hz.

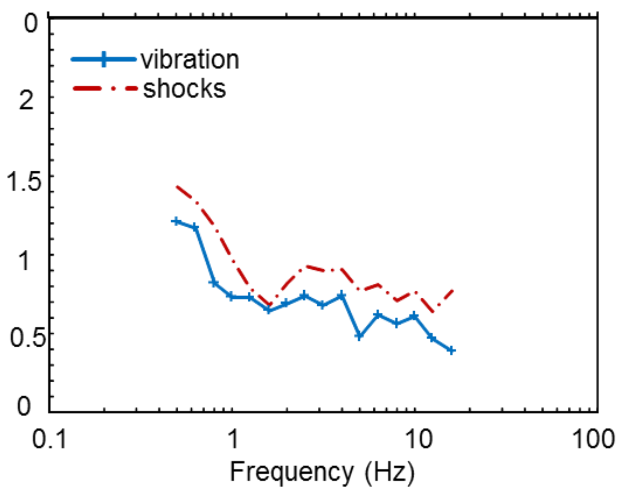


Figure 8.4 Rate of growth of discomfort, *n*, for vibration (—+—) and shocks (▬ ▪) with inter-quartile ranges (**- - - -**). Median values for 17 subjects.

8.2.3 Implication of the findings on the methods for assessing vertical shocks and vibration

When the equivalent comfort contours for shocks were expressed in terms of weighted VDV and a subjective magnitude of ψ=100 (as in Chapter 4) they rise with increasing frequency from 0.5 to 16 Hz from 0.4 $ms^{-1.75}$ to 1.9 $ms^{-1.75}$ (Figure 8.5), although the equivalent comfort contours should be ideally horizontal when expressed in terms of weighted VDV. Between 0.5 Hz and 2 Hz the weighted VDV increases from 0.4 to 1.1 $ms^{-1.75}$ (i.e. the ratio between the variation of VDV and the variation in frequency is 0.5 $ms^{-1.75}$/Hz). Between 2 Hz and 4 Hz the weighted VDV increases from 1.1 to 1.4 $ms^{-1.75}$ (i.e. the ratio between the variation of VDV and the variation in frequency is 0.15 $ms^{-1.75}$/Hz). From 5 Hz to 16 Hz the weighted VDV increases from about 1.7 to 1.9 $ms^{-1.75}$ (i.e. the ratio between the variation of VDV and the variation in frequency is 0.02 $ms^{-1.75}$/Hz).The difference in the weighted VDV between low and high frequencies is mainly due so to the change between 0.5 and 2 Hz. This indicates that the W_b weighting is reasonably appropriate for shocks having fundamental frequencies greater than about 2 Hz but, relative to the higher frequencies, the discomfort caused by shocks with frequencies less than 2 Hz will be underestimated.

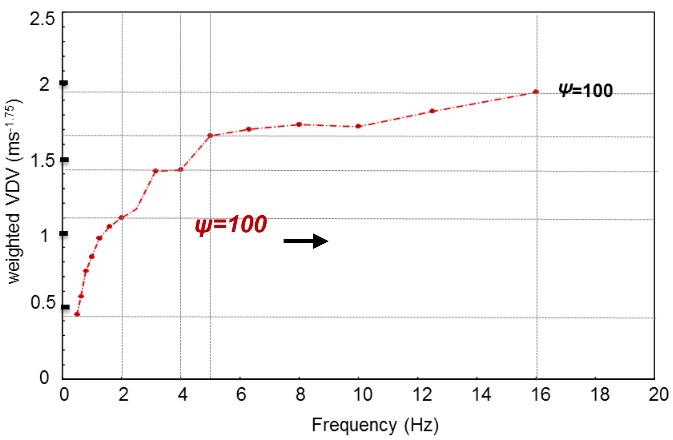


Figure 8.5 Equivalent comfort contours for shocks (●▬) in terms of weighted VDV for a subjective magnitude of ψ= 100. Data are presented in a linear scale.

The inappropriateness of W_b at frequencies less than 2 Hz with shocks having magnitudes in the range 0.5 to 2 $ms^{-1.75}$ weighted VDV (i.e. about 1 to 4 $ms^{-1.75}$ unweighted VDV) is because the rate of growth of discomfort for shocks depends on frequency (see Sections 8.2.2 and 8.3) and the weighting factors for frequencies less 2 Hz were derived from studies of discomfort with sinusoidal vibration having magnitudes between 0.25 and 0.75 ms^{-2} unweighted r.m.s. In terms of r.m.s., the magnitudes used in this study were between 0.5 ms^{-2} to 4 ms^{-2} r.m.s. for shocks with fundamental frequencies between 0.5 and 2 Hz. The findings presented in this thesis and in previous studies (e.g. Morioka and Griffin, 2006a), show that a single frequency weighting will not work accurately at all magnitudes of either vibration or shock.

The effect of magnitude on the frequency-dependence of discomfort is not the only reason for the inappropriateness of W_b at low frequencies. In Chapter 4, the effect of the high pass filters used to implement the frequency weightings, when the fundamental frequency of a shock was less than 0.8 Hz, was shown and discussed. The characteristics in frequency of the high pass filters, in terms of gain and phase, lead to inaccurate calculations of the weighted exposure expressed in terms of VDV. This occurs because shocks with fundamental frequencies less than about 0.8 Hz contain non-negligible energy at frequencies less than, and around, 0.4 Hz, which is the cut-off frequency of the high pass filter (i.e. the frequency at which the power of the input signal is halved). Consequently, 'part of the magnitude' of the shock due to these components will be 'cut out' and this will affect the final VDV. The VDV will be also affected by the phase response of all the filters used to implement the frequency weighting W_b. The phase response distorts the input shock, because it delays the different frequency components of the shocks by different amounts. The relevant standards provide for both the characteristics of phase and gain for each frequency weighting. However, contrary to the gains, the characteristics of the phase responses of the filters used in the frequency weightings were implemented from convenience rather than evidence. Because the phase of frequency components has an effect on the discomfort caused by vertical vibration (Matsumoto and Griffin, 2002b) and because the VDV should reflect the severity of a motion, the ideal overall phase response of the frequency weightings should reflect also the effect of phase between frequency components on the human response to vibration. The phase of the 0.4 Hz high-pass filter may have a particularly distorting effect when it is used with shocks having components at frequencies around 0.4 Hz. Problems associated with the use of the 0.4 Hz high-pass filter have also been reported when predicting the discomfort caused by low frequency lateral oscillation (Beard and Griffin, 2016).

At frequencies greater than 4 Hz, shocks are less uncomfortable than vibration with the same unweighted VDV (Figure 8.1) or weighted VDV (Figure 8.6, left) or unweighted peak acceleration (Figure 8.6, right). The standards provide the same frequency weighting W_b for evaluating vertical vibration and shocks (BS 6481:1987 and ISO 2631-1). The significant difference found in this thesis might suggest the two waveforms should be assessed using two different frequency weightings. However, taking into account that the difference is reduced when accelerations are weighted (compare Figure 8.1 and Figure 8.6 (left)) and that contours are broadly horizontal at frequencies greater than 2 Hz with both shock and vibration, the implementation of two different frequency weightings would seem unnecessary and would complicate the assessment of continuous motions that contain occasional shocks. Furthermore, it seems likely that if it was justified to use a different frequency weighting for vibration and shock, there will probably need to be a different weighting for each type of shock (e.g. each shock waveform). Any difference in the frequency-dependence of discomfort for shock and vibration at frequencies between 4 and 16 Hz may be considered a minor matter compared to the effect of motion magnitude on the frequency-dependence of discomfort with both shock and vibration.

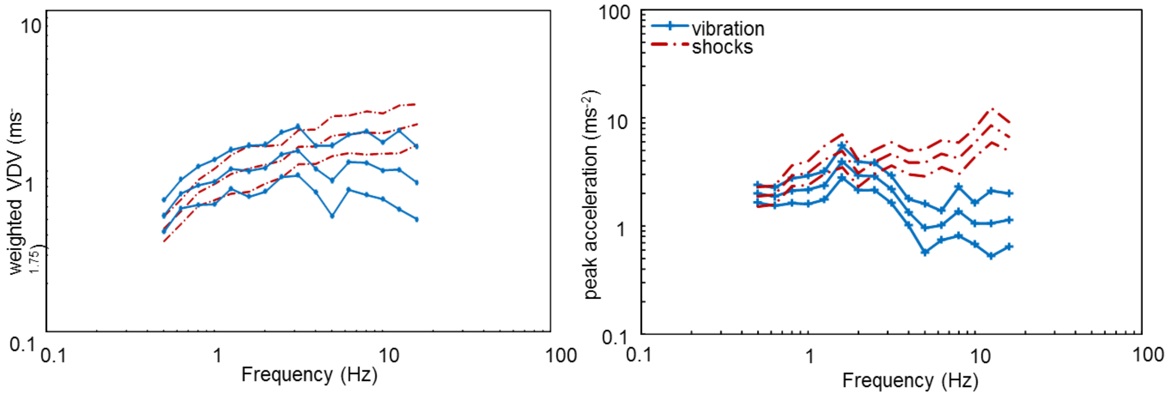


Figure 8.6 Equivalent comfort contours for shocks (●▬) and vibration (▬+▬) in terms of weighted VDV (left) and unweighted peak acceleration (right) for subjective magnitudes of ψ= 80, 100, 125.

8.3 Effect of magnitude on the subjective response to vertical mechanical shocks: the combined effect of magnitude and direction

The work presented in this thesis showed that the frequency-dependence of the discomfort caused by vertical shocks with fundamental frequencies in the range 0.5 to 16 Hz changes with the magnitude of the shock (Figure 8.1). This means that the subjective response to shocks is non-linear and that the weight that each fundamental frequency has on discomfort differs according to the magnitude of the motion.

As found in this and previous studies (e.g. Ahn and Griffin, 2008; Zhou and Griffin, 2016a) the non-linearity in the subjective responses is explained by the frequency-dependence of the rate of growth of discomfort (Figure 8.4). A possible reason of the frequency-dependence of the rate of growth of discomfort is the different mechanisms responsible for discomfort at different frequencies. In the range 0.5 to 16 Hz, analysis of the body locations shows that at frequencies from 0.5 to 2.5 Hz the upper body (i.e. head, shoulders, chest and abdomen) is the main source of discomfort (Figure 8.3), whereas from about 3 Hz to 16 Hz the lower body is the location of greatest discomfort (i.e. buttocks, thighs, calves).

The work presented in this thesis shows that the magnitude of a shock also determines whether the direction of a vertical shock affects discomfort (Chapter 5).

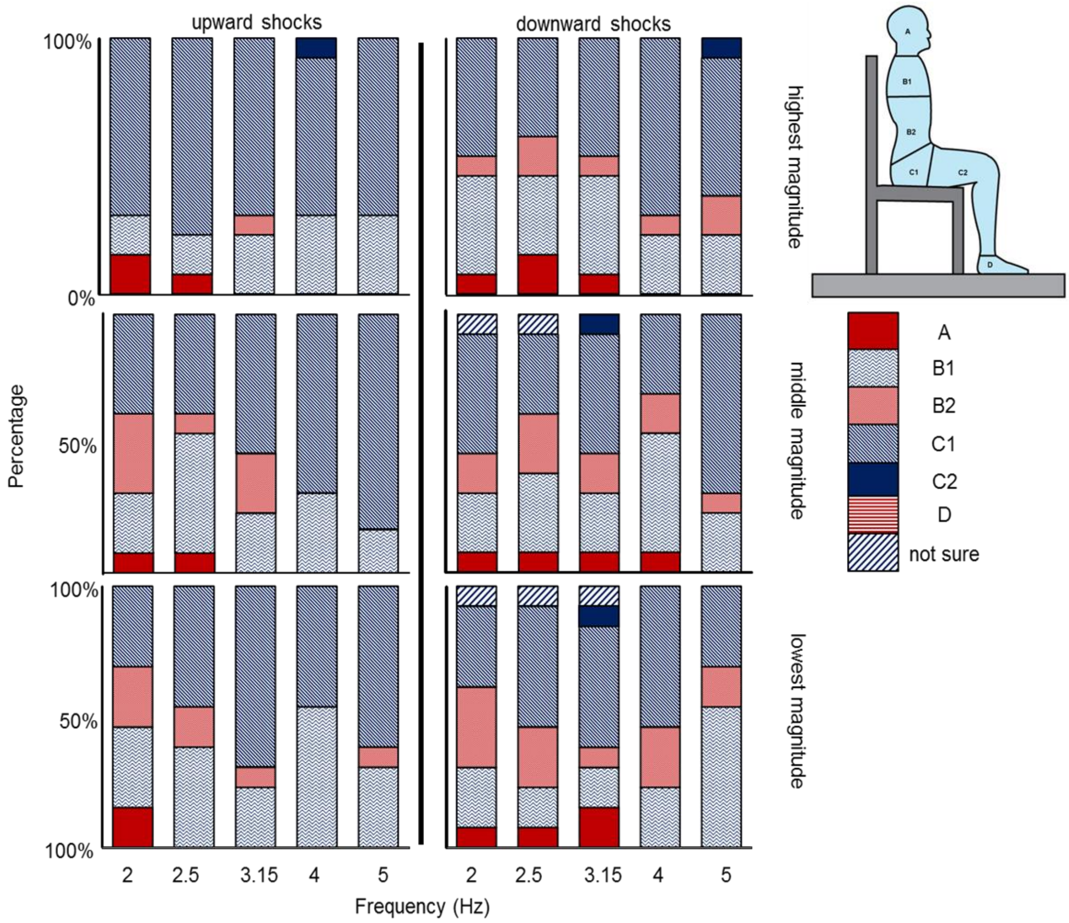


Figure 8.7 Location of discomfort presented in Chapter 5 during exposure to low magnitude vertical shocks (peak acceleration around 7.6 ms^{-2}), middle magnitude vertical shocks (peak acceleration around 8.6 ms^{-2}) and high magnitude vertical shocks (peak acceleration around 10.7 ms^{-2}). 'Loose belt' condition.

Up to about 8.0 ms^{-2} (peak acceleration), upward displacements and downward displacements cause similar discomfort (Howarth and Griffin, 1991; Ahn and Griffin, 2008; Zhou and Griffin, 2016a) and similar biodynamic responses (Zhou and Griffin, 2016b). With peak acceleration greater than about 8.0 ms^{-2}, upward displacements are more uncomfortable than downward displacements when the fundamental frequency of the shock is less than 4 Hz. This occurs because with upward displacements the body leaves, and subsequently impacts with, the seat. The analysis of body locations and subject feedback presented in Chapter 5 shows that the impact with the hard seat was the main cause of the significant difference in discomfort between upward and downward shocks found in this thesis (Figure 8.7). The impact with the seat is not reflected in the acceleration of a rigid seat but will increase the driving forces acting at the interface between the body and the seat. Zhou and Griffin (2014a, 2016a) demonstrated that the discomfort caused by vibration and force can be predicted using the force measured between the human body and the seat. The impact forces measured at the seat should be investigated to clarify the factors affecting differences between upward and downward displacements as found in this thesis.

8.4 Applicability of the same methods for evaluating seat comfort and seat transmission during vibration and shocks

When the body is exposed to either random or sinusoidal vertical vibration, linear models are suitable to describe the dynamic responses of the human body seated either on hard or soft seats (e.g. Fairley and Griffin, 1989; Wei and Griffin, 1998a, b; Tufano and Griffin, 2013; Zhou and Griffin, 2014). The work presented in Chapter 6 of this thesis shows that a linear model can also be used to predict the SEAT values of occupied blocks of foam during exposure to shocks. However, the applicability of the model is limited to shocks with peak accelerations less than 1 g. When the peak acceleration approached 1 g and the fundamental frequency of the shock was less than about 3 Hz, the predicted SEAT values underestimated the measured SEAT values, by up to 50%. This occurs because the measured SEAT values will not only be influenced by the acceleration transmitted through the foam but also by the acceleration of the impact of the body with the foam (Figure 8.8 - input weighted VDV of 2 $ms^{-1.75}$). If the predicted SEAT values are obtained from a model that is linear, it will not able to predict any non-linearity, such as leaving the seat. If the occurrence of an impact is of interest to the experimenter the model should be modified so as to simulate such an event.

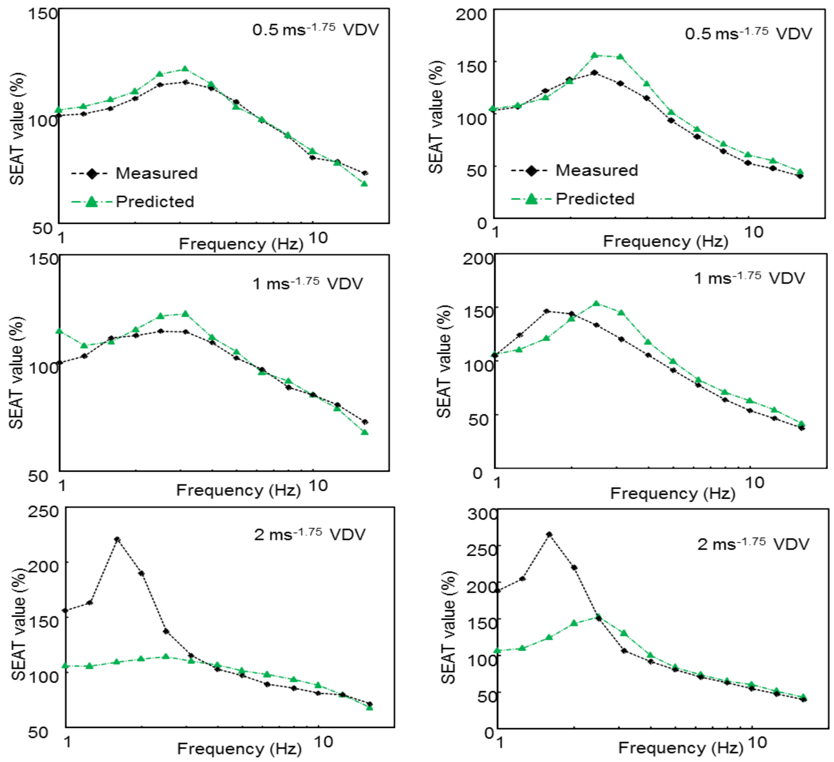


Figure 8.8 Median measured and predicted SEAT values of a block of foam of 40 mm (left) and 80 mm (right) thickness exposed to vertical mechanical shocks at three magnitudes of vibration.

The SEAT values that can be predicted by simple lumped parameters models can be used to predict seat comfort. Consistent with previous studies with vibration and compliant seats (e.g. Niekerk *et al.,* 2003; Basri and Griffin, 2014), the work presented in Chapter 6 shows that predicted and measured SEAT values reflect the subjective response to vertical shocks when the peak acceleration of the shock is less than 1 g. However, the work presented in Chapter 6 includes some limitations: the applicability of SEAT values were tested with square blocks of foam of only two thicknesses and the backrest was not included. Real seats are characterised by more complex geometry that can affect vibration transmission and comfort. Future research should investigate the applicability of SEAT values for predicting the discomfort caused by vertical shocks with a wide range of seats.

A useful application of the above findings could be in the concept phase of designing a seat in environments where shocks are likely, such seating systems for fast boats. The implementation of the model is simple and it is not time-consuming. It would be sufficient to estimate in a first stage the seat isolation, shock transmission, and seat comfort using SEAT values.

8.5 Effect of posture on the frequency dependence of discomfort caused by vertical vibration

The results obtained in both Chapter 4 (i.e. during exposure to vibration) and Chapter 7 (i.e. exposure to vibration with four different postures) show that the frequency-dependence of equivalent comfort contours obtained with the three postures ‘standing with straight legs’, ‘sitting upright’ and ‘sitting leaning forward’ for a subjective magnitude of ψ= 100 is consistent with the W_b frequency weighting (Figure 8.9). With these postures the greatest sensitivity to vibration occurs at frequencies between 4 Hz and 16 Hz, where the standardised frequency weighting W_b gives the greatest weight. However, the frequency-dependence of the rate of growth with all four postures confirms that the optimum frequency weighting will depend on motion magnitude.

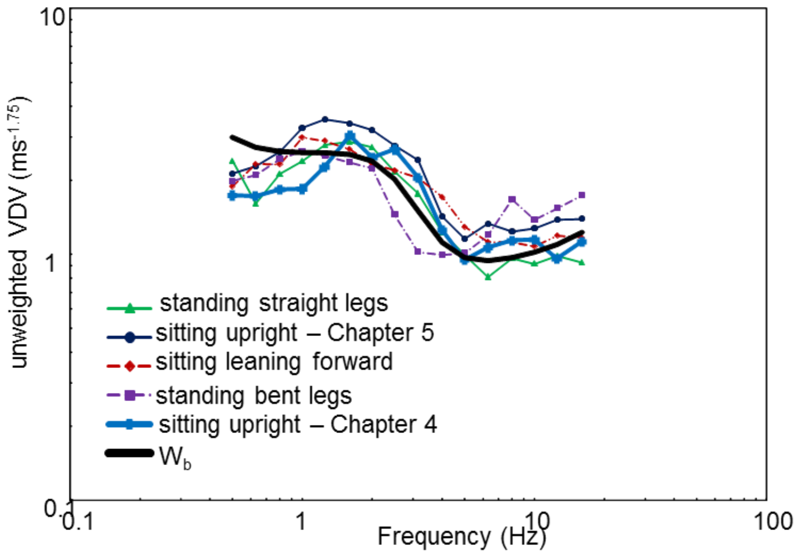


Figure 8.9 Equivalent comfort contours for a subjective magnitude ψ = 100 and different postures in terms of unweighted VDV ($ms^{-1.75}$).

The frequency-dependence of the discomfort caused by vibration was significantly different when ‘standing with bent legs’ than when ‘standing with straight legs’. When ‘standing with bent legs’, the greatest sensitivity to vibration occurred at frequencies between about 2 and 4 Hz (Figure 8.10). At frequencies greater than 5 Hz the contours rise again up to 16 Hz, showing less sensitivity to high frequencies (Figure 8.10). Consequently, the frequency weighting W_b seems not to reflect the frequency-dependence of discomfort caused by vertical vibration when standing with bent legs (Figure 8.9). Clearer evidence occurs when the equivalent comfort contours are expressed in terms of weighted VDV (Figure 8.11). The weighted acceleration drops at frequencies between 2 and 4 Hz, meaning that the weighting W_b underestimates discomfort when standing with bent legs (Figure 8.11). The result in Chapter 7 is supported by previous biodynamic studies that show a decrease in the resonance frequency from about 5 to about 3 Hz in both the vertical transmissibility to the head and the vertical apparent mass when 'standing with bent legs' compared to 'standing with straight legs', 'sitting upright' or 'sitting leaning forward' (Mansfield and Griffin, 2002; Matsumoto and Griffin, 1998; Subashi *et al.*, 2006).

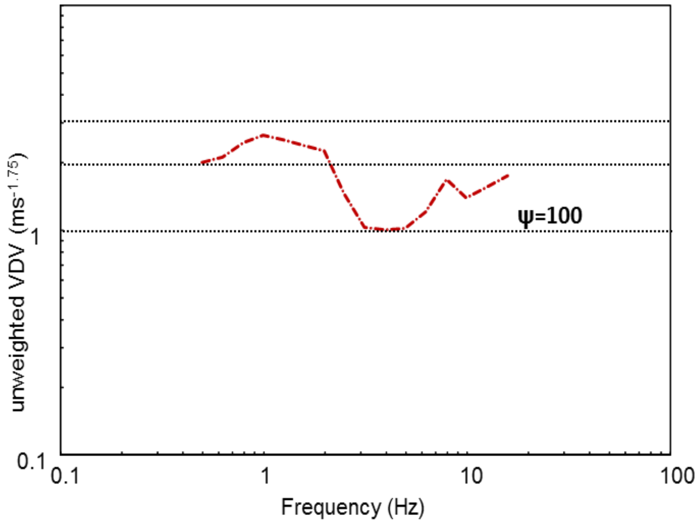


Figure 8.10 Equivalent comfort contours for a subjective magnitude ψ = 100 and with a standing with bent legs posture (•▬) in terms of unweighted VDV (ms$^{-1.75}$).

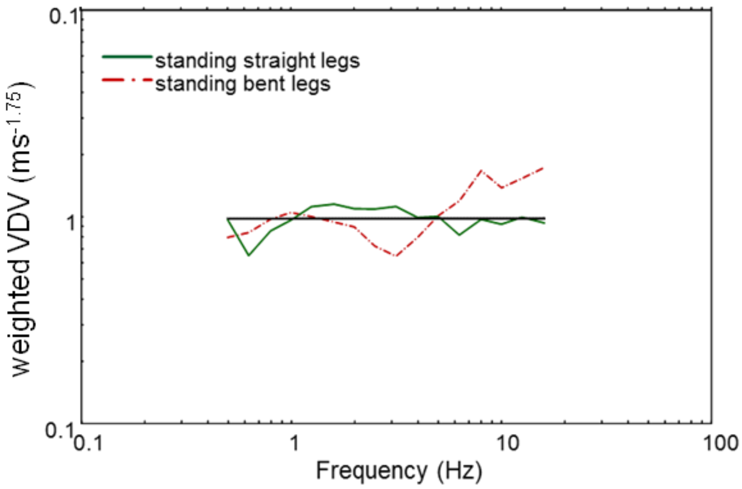


Figure 8.11 Equivalent comfort contours in terms of weighted VDV (ms$^{-1.75}$) with the postures standing with 'straight' (▬) and 'bent' (•▬) legs for a subjective magnitude ψ = 100

Previous biodynamic studies and the work presented in this thesis suggest that a modification of the frequency weighting W_b provided by the standard is needed when the vibration of standing people with their legs bent is to be assessed. As shown in this thesis, the modification involves the introduction of greater weight at frequencies from about 2 to 4 Hz.

Chapter 9: CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The rate of growth of discomfort with increasing magnitude of motion depends on the fundamental frequencies of both shocks and vibration. This implies that the 'weight' that each fundamental frequency has on the subjective response to either shock or vibration changes with the magnitude of either shock or vibration.

The magnitude-dependence and frequency-dependence of the discomfort caused by vertical mechanical shocks differs from the magnitude-dependence and frequency-dependence of the discomfort caused by vertical vibration. For the magnitudes in investigated in these studies, fundamental frequencies in the range 0.5 to 16 Hz, vibration caused greater discomfort than shocks with same unweighted or weighted VDV at frequencies greater than about 4 Hz.

The direction (i.e. upward or downward displacement) affects the discomfort caused by low frequency vertical shocks when peak accelerations approach or exceed 1 g and fundamental frequencies are in the range 2 to 4 Hz. With these motions the body may leave the seat and the occurrence of a subsequent impact of the body with a hard seat may present a non-negligible source of discomfort and be responsible the shock direction affecting discomfort.

A three-degree-of-freedom linear model of the coupled human body and seat system can be used to predict the SEAT values of blocks of polyurethane foam of various thicknesses when the body is exposed to vertical upward shocks. Both measured and predicted SEAT values can be used as indicators and predictors of the seat comfort during exposure to vertical shocks when the peak accelerations are less than 1 g. Measurements of acceleration to calculate SEAT values may not reflect the discomfort caused by the shocks when peak accelerations approach or exceed 1 g.

The optimum parameters of the three-degree-of-freedom linear model for the coupled human body and seat system used to predict vertical shocks transmitted through a seat can be found by using the transmissibility of the seat measured with random vibration.

The posture of the body affects the discomfort caused by vertical vibration in the range 0.5 to 16 Hz. For the sitting and standing postures investigated in this thesis, the change in posture that significantly affected the frequency-dependence of equivalent comfort contours was the bending of the knees when standing. Compared to normal standing, people who stand with their knees bent are more sensitive to vibration at frequencies between 2 and 4 Hz than between 4 and 8 Hz.

9.2 Recommendations for future research

There has been little research on the effects that shocks have on discomfort and human health. Most studies with shocks, including those in this thesis, investigated vertical motions (e.g. Matsumoto and Griffin, 2005; Ahn and Griffin, 2008; Zhou and Griffin, 2016a). In some environments, such as cars and fast boats, shock-type vibration can occur along other axes such as fore-and-aft and pitch. Although non-linearity of subjective responses has been confirmed with fore-and-aft vibration (e.g. Morioka and Griffin, 2006a), there is not yet a study that investigates the frequency-dependence and the magnitude-dependence of discomfort caused by fore-and-aft shocks or the locations of the body of greatest discomfort. It would be expected that subjective responses to fore-and-aft and lateral shocks will differ from the response to vertical shocks, because both the biodynamic and the subjective responses to vibration depend on the axis of vibration excitation (e.g. Griffin et al., 1982, Parsons and Griffin, 1978, 1982, Morioka and Griffin, 2006a, Paddan and Griffin, 1988a, 1988b). Interest in response to fore-and-aft shocks is strengthened by the expectation that, like vertical shocks at high magnitude, the response to a shock in one direction may differ from the response in the opposite direction. Most seats have backrests which influence vibration discomfort (Parsons et al., 1982; Basri and Griffin, 2011, 2012), and may result in different discomfort for forward shocks than rearward shocks.

The locations of discomfort caused by shocks and vibration depend on the fundamental frequency of the shock or vibration. It would be helpful to have a model able to predict the location of discomfort from the characteristics of shock or vibration at the interfaces between the body and the environment. However, this is likely to be complex since, for example, the forces acting on the back from a backrest change over the height of the backrest (Jalil and Griffin, 2008) and so the locations of discomfort caused by fore-and-aft shock or vibration will depend on the distribution of vibration over the height of the backrest.

This study compared the effects of upward and downward high magnitude vertical shocks on discomfort. Peak accelerations up to about 11 ms^{-2} were studied in the range of frequencies from 2 to 5 Hz. To understand better the causes of the differences found between upward and downward shocks, measurements of muscle activity and impact forces at the body-seat interface should be performed. A wider range of magnitudes, possibly greater than ±11 ms^{-2} should be investigated, although care is required to avoid risks to subject health.

Appendices

Appendix A DYNAMIC STIFFNESS OF A SADDLE SEAT

In the experiments described in Chapter 7 a saddle seat has been used to test the effect of two different sitting postures on the discomfort caused by vertical vibration in the range 0.5 Hz to 16 Hz. The effect of seat transmissibility on the results obtained in the study has been discussed in the discussion section of chapter 5. However, more information about the dynamic properties of the saddle seat is given in this appendix. To this purpose, the dynamic stiffness of the seat has been measured using an indenter rig (Wei and Griffin, 1998b; Zhang *et al.*, 2015).

In the following paragraphs the methods adopted for measuring the seat dynamic stiffness and the results are presented.

A.1 Apparatus

Measurements of the dynamic stiffness were performed using an indenter rig and a vertical electro-dynamic vibrator (Ling V860). Figure A.1 and Figure A.2 show the HFRU indenter rig and its schematic representation respectively.

An accelerometer Entran EGCS-DO-10V was used to measure the input acceleration at the vibrator platform. A force transducer Kistler 9321A was used to measure the force during the dynamic tests.

A SIT-BAR was used as indenter (Figure A.3, Whitham and Griffin, 1977; Wei and Griffin, 1998b).

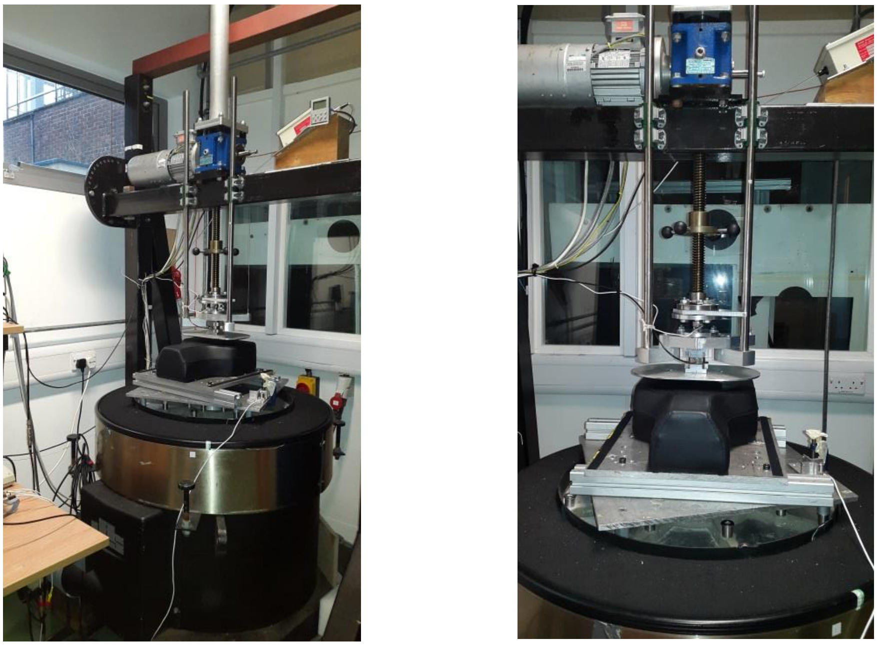


Figure A.1. Settings for measuring the dynamic stiffness of a seat cushion.

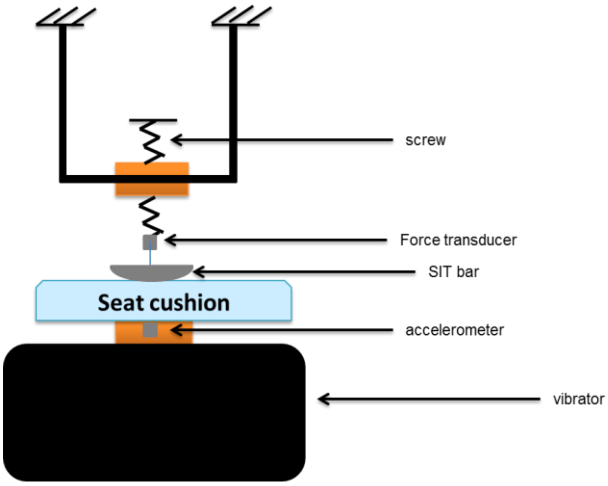


Figure A.2. Scheme of a typical indenter rig used to measure the dynamic properties of seats or foams.

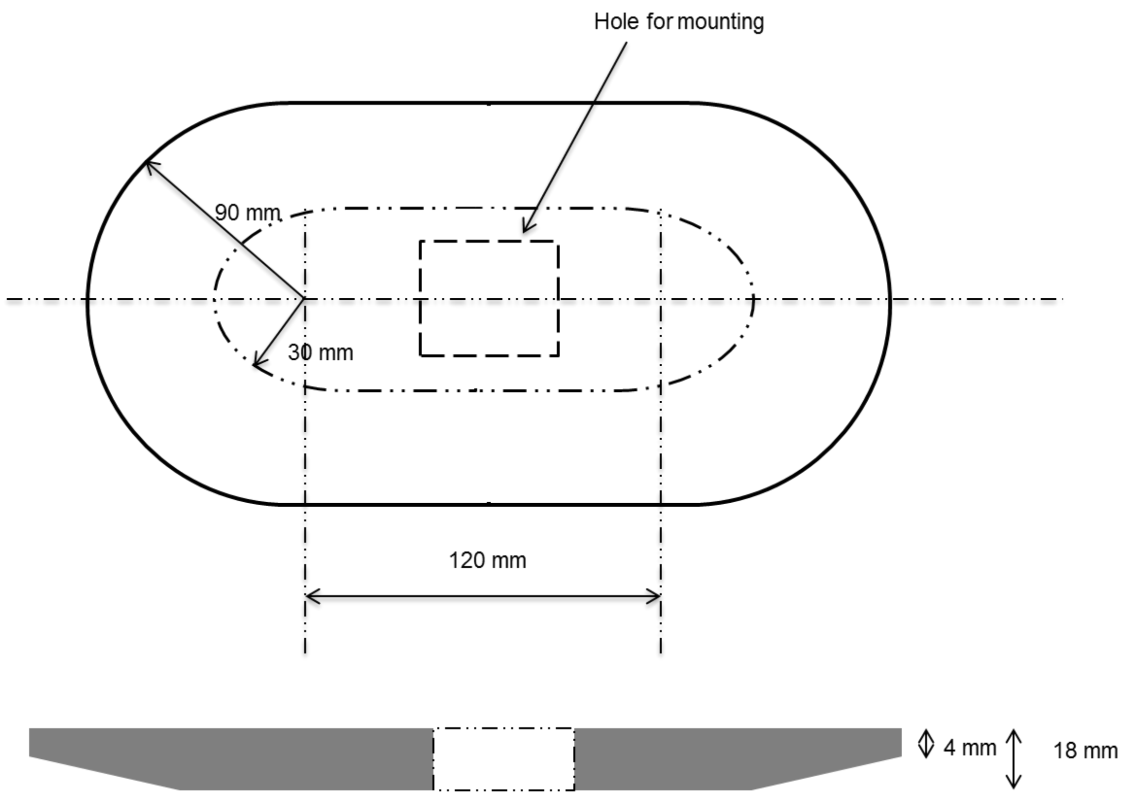


Figure A.3. SIT BAR indenter head used for the dynamic stiffness tests.

A.2 Procedure

Prior to measuring the dynamic forces, a static preload was applied at the top surface of the saddle seat. A preload of 400 N was applied by screwing down the SIT-BAR indenter head.

After preloading, the dynamic forces at the indenter head and the acceleration at the vibrator platform were measured during 60 s of vertical broadband random vibration in the range 1 to 20 Hz and magnitude 1 ms^{-2} r.m.s. acceleration. Force and acceleration were used in order to obtain the dynamic stiffness of the seat.

A.3 Analysis of dynamic stiffness

The dynamic stiffness $Z(f)$ was defined as the complex ratio between the cross spectral density $G_{xF}(f)$ of the input displacement $x(t)$ and the output force $F(t)$, and the power spectral density $G_{xx}(f)$ of the input displacement:

$$Z(f) = \frac{G_{xF}(f)}{G_{xx}(f)}$$

Appendix A

The system indenter and seat cushion shown in Figure A.2. can be simplified by a single degree-of-freedom system shown in figure A.4.

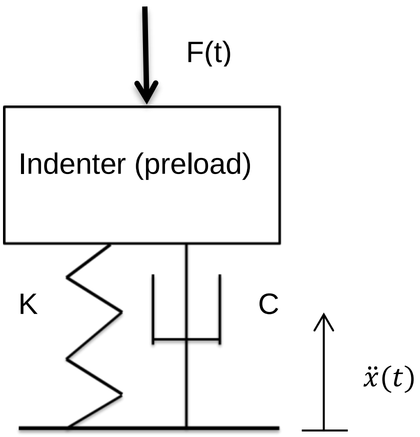


Figure A.4. Single degree-of-freedom model for the system indenter rig and seat.

In figure A.4 the seat is represented by a spring of stiffness *K* and a damper of damping *C*. The response of the seat, that is the measured output force F(t) at the indenter, is therefore:

$$F(t) = C\,\dot{x}(t) + K\,x(t) \qquad (1)$$

where $x(t)$ and $\dot{x}(t)$ are the input displacement and the velocity.

Applying Laplace transform and for s= iω, the above equation can be used to extract the dynamic stiffness *Z*(*f*) as:

$$\frac{F(\omega)}{X(\omega)} = Z(\omega) = i\omega C + K \qquad (2)$$

where *f* is the frequency and *ω* = 2π*f*.

Using a simple degree of freedom model, the *K* is the real part of the transfer function between the measured dynamic force and the input displacement.

Using a simple degree of freedom model, the *C* is the imaginary part of the transfer function between the measured dynamic force and the input displacement divided by *ω*.

Because in these experiments, the input acceleration rather than the input displacement has been measured, the complex ratio between force *F* (*ω*) and acceleration A (ω) has been derived, to avoid any integration and high pass filtering. The dynamic stiffness can be obtained by applying the following relation:

$$Z(\omega) = -\omega^2 \frac{F(\omega)}{A(\omega)} \qquad (3)$$

A.4 Results

Figure A.5 shows the real and the imaginary parts of the dynamic stiffness of the saddle seat cushion in the frequency range 1 Hz to 20 Hz.

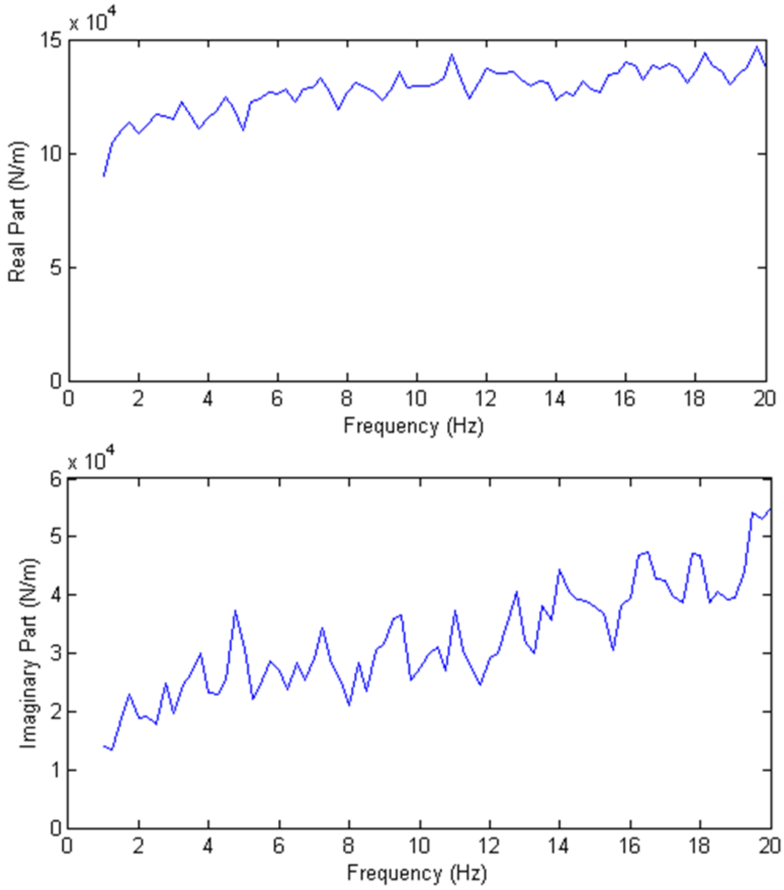


Figure A.5. Real and imaginary parts of the complex dynamic stiffness.

From equation (2) the constant stiffness K and damping C can be calculated from the real and the imaginary parts of the transfer function $Z(\omega)$, since:

$$K = \text{Re}\,\{Z(\omega)\}$$

$$C = \frac{\text{Im}\{Z(\omega)\}}{\omega}$$

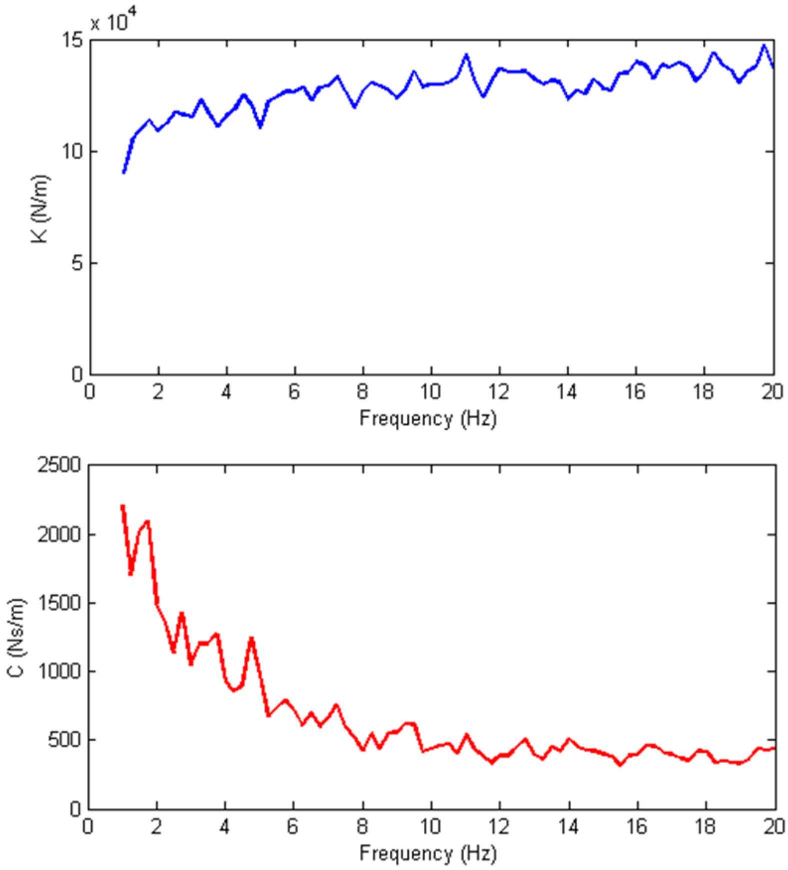


Figure A.6. Values of *K* (top) and *C* (bottom) as a function of the frequency and obtained using a one degree-of-freedom-model of the system indenter and seat.

Figure A.6 shows *K* and *C* in the frequency range 1 Hz to 20 Hz. Both stiffness and damping varied with the frequency of vibration. The stiffness K tended to slightly increase with increasing the frequency of vibration (Figure A.6) and had a median value of K=13*10^4 N/m across the frequencies in the range 1 to 20 Hz. The damping tended to decreased rapidly from frequencies in the range 1 to about 5 Hz. The damping *C* had a median value of *C*=460 Ns/m across the frequencies in the range 1 to 20 Hz. The coherency between the measured output force and the input acceleration was greater than 0.9 in the range 1 Hz to 20 Hz (Figure A.7).

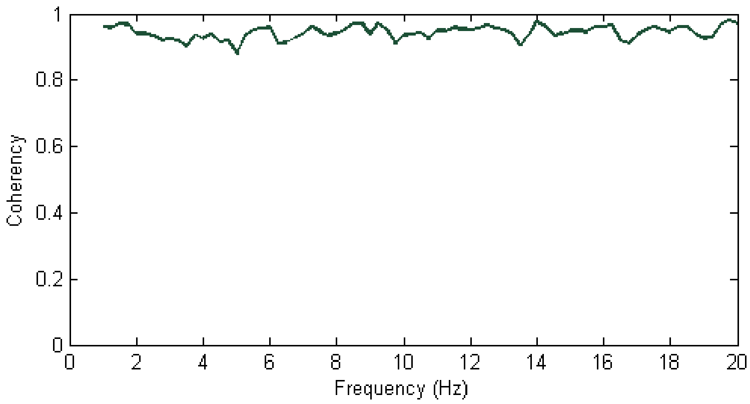


Figure A.7. Coherency between the input acceleration measured at the vibrator platform and the output force measured at the indenter

A.5 Discussion

High values of stiffness and damping were obtained for the saddle seat. Similar trends for the stiffness and damping were found by other studies that measured the dynamic stiffness either with an indenter rig (Wei and Griffin, 1998b; Zhang *et. al.*, 2015) or human subjects (Tufano and Griffin, 2013). Higher values of the stiffness and the damping were found here respect to the results obtained by Wei and Griffin (1998b) and Zhang *et al.* (2015). The real part of the dynamic stiffness obtained in this study was closer to the results obtained by Tufano and Griffin (2013) with hard foam. The synthetic leather that covered the saddle seat pan may have increased partly and in a small amount the measured dynamic stiffness (Zhang, 2014).

Similarly to Zhang *et al.* (2015) the damping increased greatly at frequencies below about 5 Hz, although they used a simple squared block of foam with no cover.

Appendix B DYNAMIC STIFFNESS OF POLYURETHANE BLOCKS OF FOAM

In the experiment described in Chapter 6, two square blocks of polyurethane foam were used to test the effect of seat dynamics on the discomfort caused by vertical mechanical shocks in the range 1 to 16 Hz. The effect of the transmissibility of the foam has been discussed in the discussion section of Chapter 6. Information on the dynamic properties of the two blocks of foam is given in this appendix. To this purpose, the dynamic stiffness of the seat has been measured using an indenter rig (Wei and Griffin, 1998b; Zhang *et al.*, 2015).

In the following paragraphs the methods adopted for measuring the seat dynamic stiffness and the results are presented.

B.1 Apparatus

Measurements of the dynamic stiffness were performed using an indenter rig and a vertical electro-dynamic vibrator (Ling V860). Figure B.1 and Figure B.2 show the HFRU indenter rig and its schematic representation, respectively.

An accelerometer Entran EGCS-DO-10V was used to measure the input acceleration at the vibrator platform. A force transducer Kistler 9321A was used to measure the force during the dynamic tests.

A SIT-BAR was used as indenter (Figure B.3, Whitham and Griffin, 1977; Wei and Griffin, 1998b).

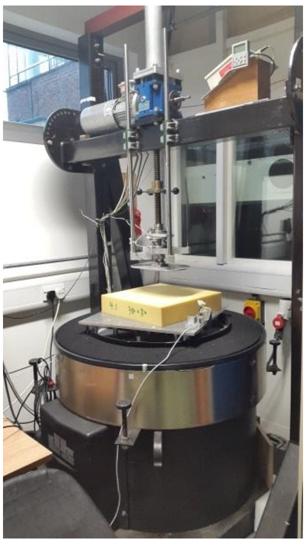


Figure B.1. Arrangement for measuring the dynamic stiffness of blocks of foam.

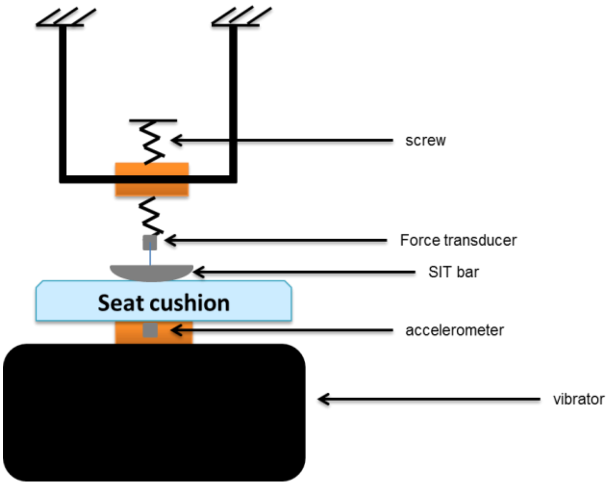


Figure B.2. Representation of an indenter rig used to measure the dynamic properties of seats or foams.

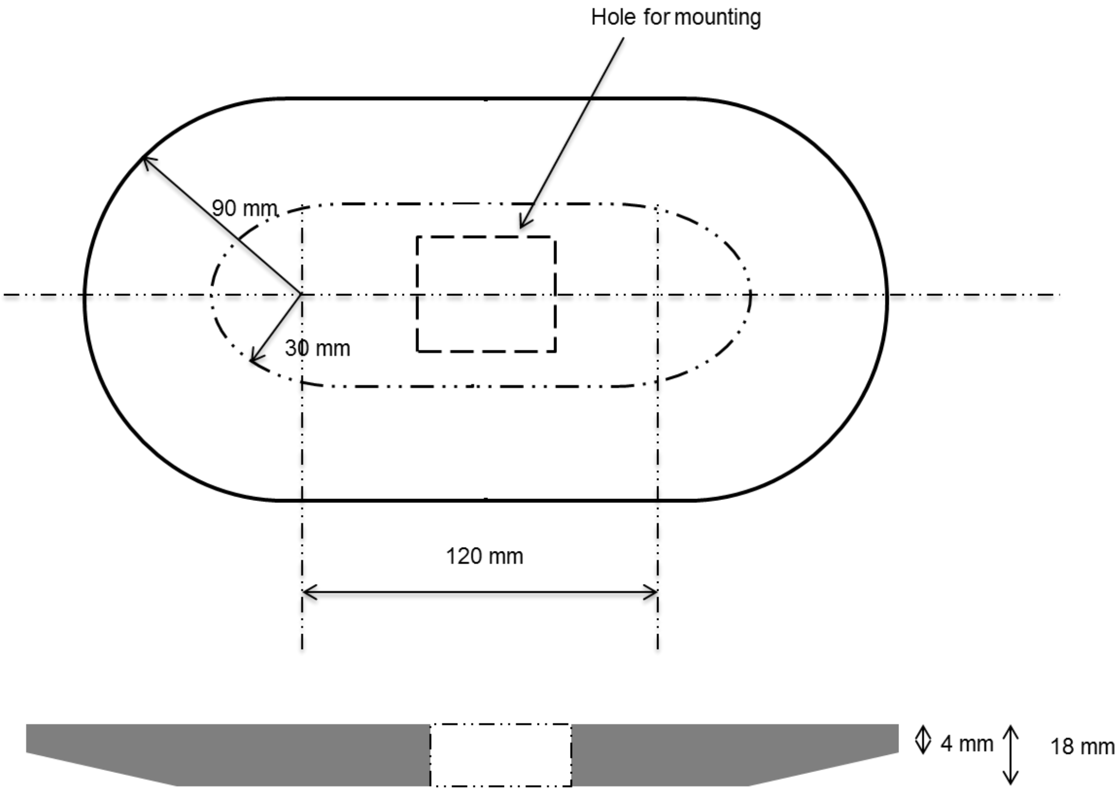


Figure B.3. SIT-BAR indenter head used for the dynamic stiffness tests.

B.2 Procedure

Prior to measuring the dynamic forces, a static preload was applied at the top surface of each block of foam. A preload of 400 N was applied by screwing down the SIT-BAR indenter head.

After preloading, the dynamic forces at the indenter head and the acceleration at the vibrator platform were measured during 60 s of vertical broadband random vibration in the range 1 to 20 Hz at a magnitude of 1.0 ms^{-2} r.m.s. Force and acceleration were measured in order to obtain the dynamic stiffness of the seat.

B.3 Analysis of dynamic stiffness

The dynamic stiffness, $Z(f)$, was defined as the complex ratio between the cross spectral density, $G_{xF}(f)$, of the input displacement, $x(t)$, and the output force, $F(t)$, and the power spectral density, $G_{xx}(f)$, of the input displacement:

$$Z(f) = \frac{G_{xF}(f)}{G_{xx}(f)}$$

The system consisting of the indenter and the block of foam shown in Figure B.2 can be simplified to a single degree-of-freedom system shown in Figure B4.

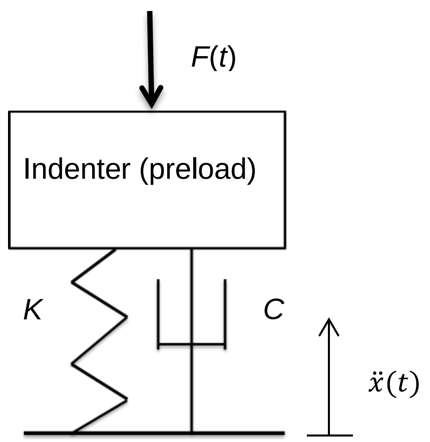


Figure B.4. Single degree-of-freedom model of the indenter rig and seat.

In Figure B.4 the block of foam is represented by a spring of stiffness K and a damper of damping C. The response of the block of foam that is the measured output force, $F(t)$ at the indenter, is therefore:

$$F(t) = C\,\dot{x}(t) + K\,x(t) \qquad (1)$$

where $x(t)$ and $\dot{x}(t)$ are the input displacement and the velocity.

Applying Laplace transform and for *s*= i*ω*, the above equation can be used to extract the dynamic stiffness *Z*(*f*) as:

$$\frac{F(\omega)}{X(\omega)} = Z(\omega) = i\omega C \ + K \tag{2}$$

where *f* is the frequency in Hz and *ω* = 2π*f* (radians per second).

Using a single degree-of-freedom model, *K* is the real part of the transfer function between the measured dynamic force and the input displacement.

Using a single degree-of-freedom model, *C* is the imaginary part of the transfer function between the measured dynamic force and the input displacement divided by *ω*.

Because in these experiments, the input acceleration rather than the input displacement was measured, the complex ratio between force, *F* (*ω*), and acceleration, *A*(*ω*), was derived, to avoid any integration and high pass filtering. The dynamic stiffness can be obtained by applying the following relation:

$$Z(\omega) \ = -\omega^2 \ \frac{F(\omega)}{A(\omega)} \tag{3}$$

B.4 Results

B.4.1 Dynamic stiffness of the 40 mm foam block

Figure B.5 shows the real and the imaginary parts of the dynamic stiffness of the 40-mm block of foam in the frequency range 1 to 20 Hz.

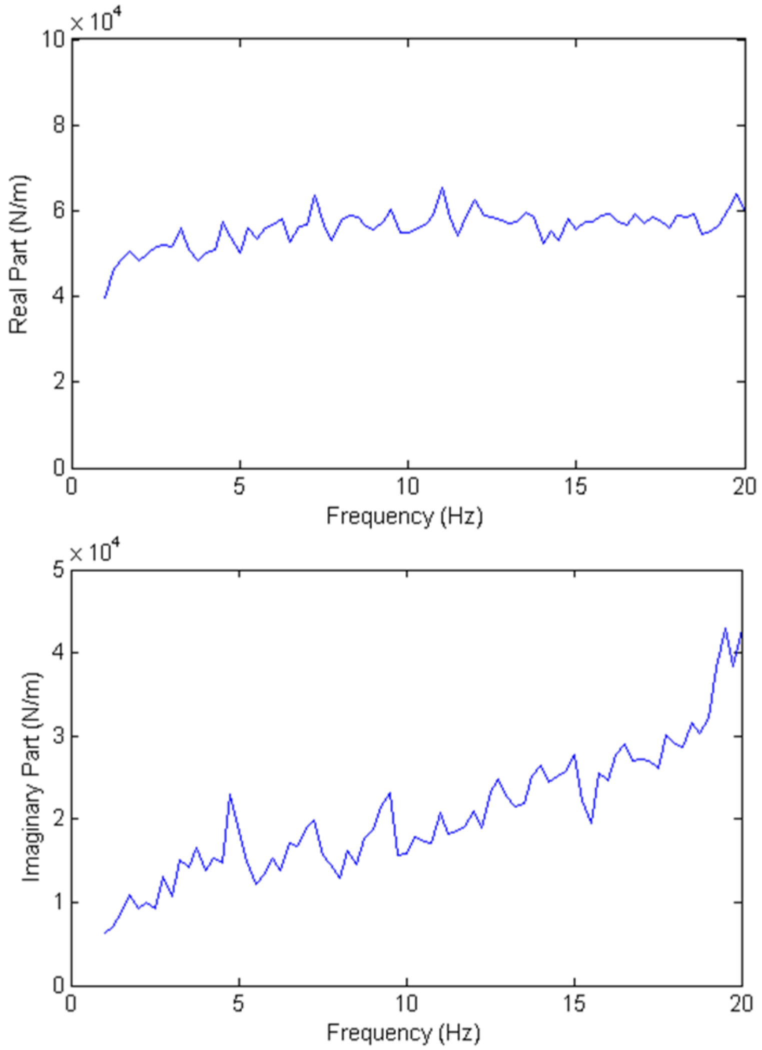


Figure B.5. Real and imaginary parts of the complex dynamic stiffness.

From equation (2) the constant stiffness, *K*, and damping, *C*, can be calculated from the real and the imaginary parts of the transfer function $Z(\omega)$, since:

$$K = \mathrm{Re}\,\{Z(\omega)\}$$

$$C = \frac{\mathrm{Im}\{Z(\omega)\}}{\omega}$$

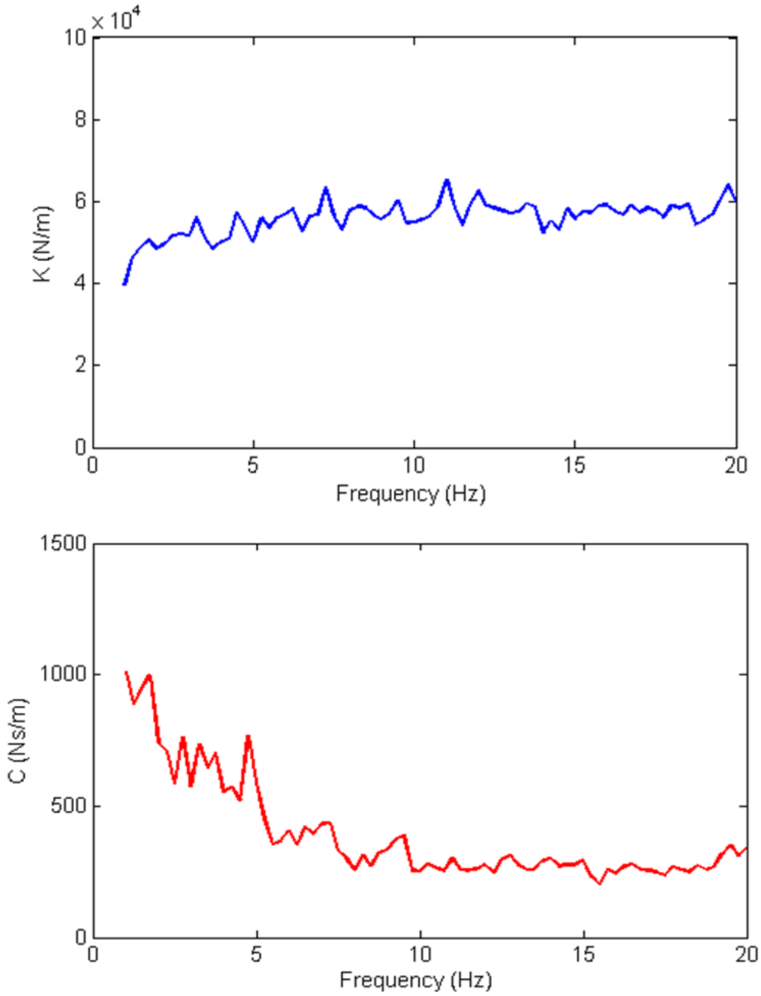


Figure B.6. Values of *K* (top) and *C* (bottom) as a function of the frequency as obtained using a single degree-of-freedom-model of the indenter and seat system.

Figure B.6 shows *K* and *C* in the frequency range 1 to 20 Hz. Both stiffness and damping varied with the frequency of vibration. The stiffness K tended to increase slightly with increasing the frequency of vibration (Figure B.6) and had a median value of K=5.7*10^4 N/m across the frequency range 1 to 20 Hz. The damping tended to decrease rapidly over frequencies in the range 1 to 5 Hz. The damping *C* had a median value of *C*=300 Ns/m across the frequency range 1 to 20 Hz. The coherency between the measured output force and the input acceleration was greater than 0.9 over the range 1 to 20 Hz (Figure B.7).

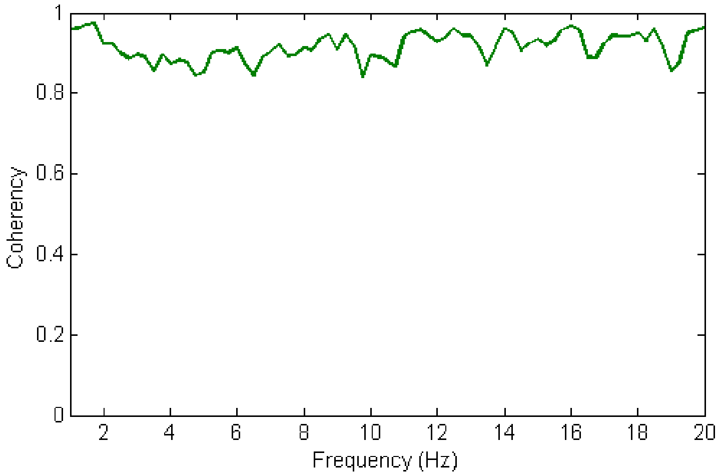


Figure B.7. Coherency between the input acceleration measured at the vibrator platform and the output force measured at the indenter

B.4.2 Dynamic stiffness of the 80 mm foam block

Figure B.8 shows the real and the imaginary parts of the dynamic stiffness of the 80 mm block of foam in the frequency range 1 to 20 Hz.

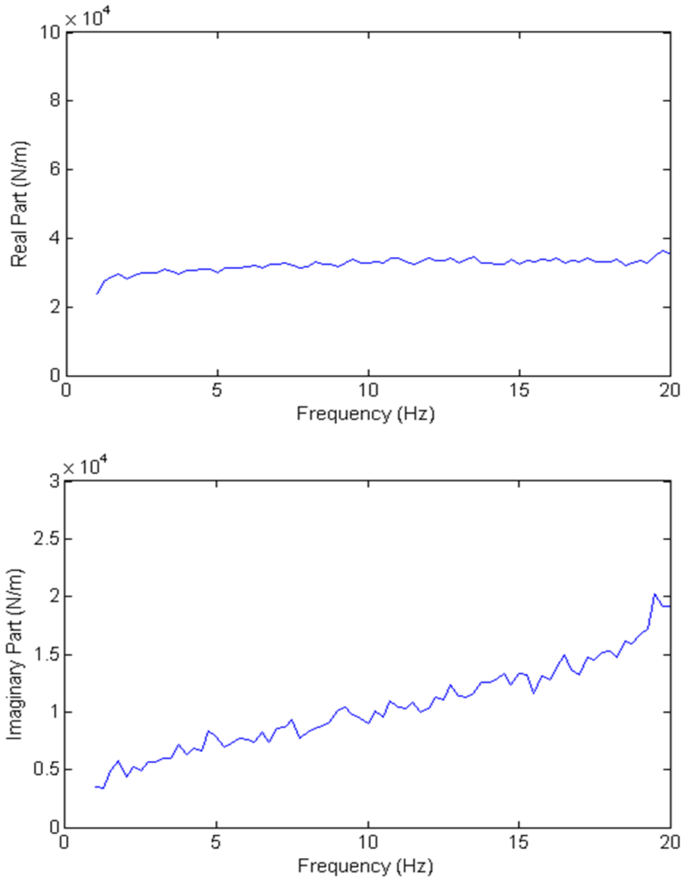


Figure B.8 Real and imaginary parts of the complex dynamic stiffness.

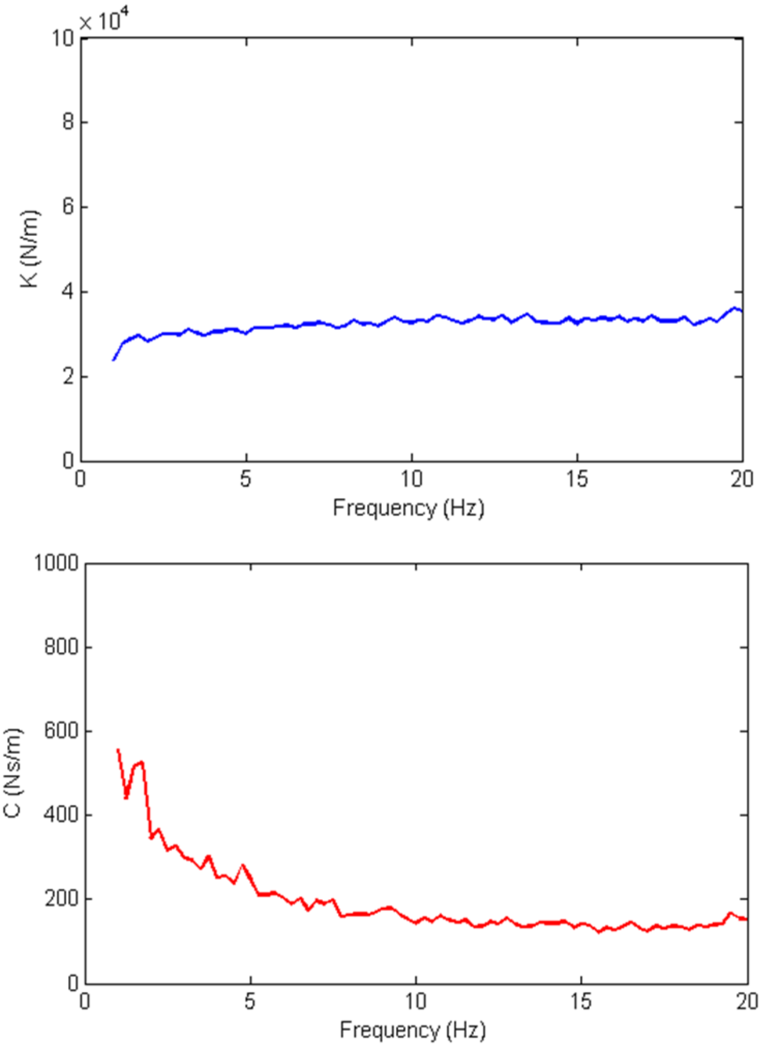


Figure B.9 Values of *K* (top) and *C* (bottom) as a function of the frequency as obtained using a single degree-of-freedom-model of the indenter and seat system.

Figure B.9 shows *K* and *C* in the frequency range 1 to 20 Hz. Both stiffness and damping varied with the frequency of vibration. The stiffness *K* tended to slightly increase with increasing the frequency of vibration (Figure B.9) and had a median value of $K=3.3*10^4$ N/m across the frequencies in the range 1 to 20 Hz. The damping tended to decreased rapidly from frequencies in the range 1 to 5 Hz. The damping *C* had a median value of *C*=155 Ns/m across the frequencies in the range 1 to 20 Hz. The coherency between the measured output force and the input acceleration was greater than 0.9 in the range 1 to 20 Hz (Figure B.10).

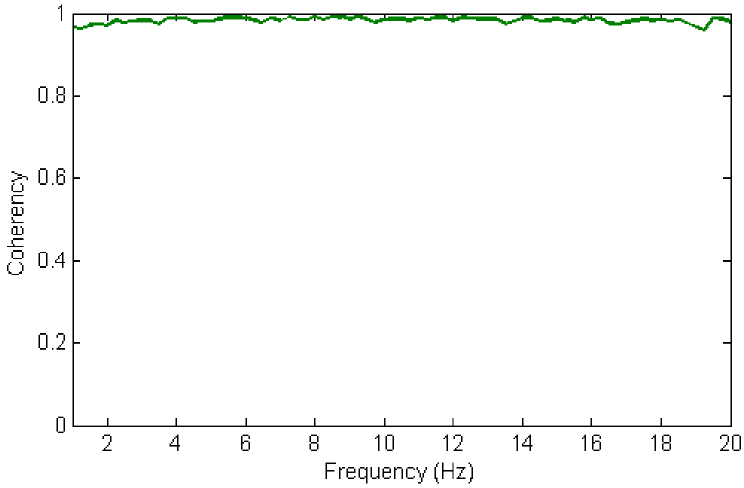


Figure B.10 Coherency between the input acceleration measured at the vibrator platform and the output force measured at the indenter

B.5 Discussion

The stiffness *K* was lower with the 80 mm block of foam than with a 40 mm block of foam. The two measured median values of *K* were 3.3* 10^4 N/m and 5.7* 10^4 N/m for the 80 mm and the 40 mm foam blocks, respectively. Doubling the thickness of the same material corresponds to putting in series two springs having the same value of *k*. For an ideal system, the equivalent stiffness k_{eq} would be equal to *k*/2, since the springs are subjected to the same force *F*:

$$F = F_1 = -k^*x_1 = F_2 = -k^*x_2 \quad (1)$$

$$F = -k_{eq}^*(x_1+x_2) \quad (2)$$

where x_1 and x_2 are the displacements of each of the two springs. From equations 1 and 2 it can be derived that k_{eq} is equal to *k*/2. From the results the value obtained for the stiffness *K* of an 80mm foam block is almost the half of the stiffness *K* of a 40mm foam block.

Similar reasoning applies to the damping for a series of two dampers with the same damping constant *c*. The equivalent damping constant would be about *c*/2. The experimental results supported the theory. The median damping constants obtained over the range 1 to 20 Hz were 155 N*s/m and 300 N*s/m for the 80 mm and the 40 mm foam blocks, respectively.

Appendix B

It is concluded that the reduction in stiffness and damping with increasing thickness of the square blocks of foam of the same material used in this study were consistent with previous research (Zhang *et al*., 2015).

Appendix C INSTRUCTIONS FOR SUBJECTS

C.1 Experiment presented in Chapter 4

EXPERIMENTAL STUDY OF THE DISCOMFORT CAUSED BY VERTICAL WHOLE-BODY VIBRATION AND VERTICAL MECHANICAL SHOCKS

INSTRUCTIONS FOR SUBJECTS

Thank you for agreeing to take part in this study. The experiment has been approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton: Submission Number 8630.

Please read the following instructions carefully. Please ask if you have any queries.

Preparation phase

- Complete the consent form and health questionnaire

Practice with magnitude estimation

- Complete the practice paper exercise to become familiar with magnitude estimation. Your task is to assign values to the lengths of lines.

Experiment with vibration and mechanical shocks

Posture

- Sit on the seat on the vibrator in a comfortable upright posture.
- The experimenter will adjust the belt to a loose comfortable fit.
- Place both feet on the footrest
- An emergency stop button is located beside you.
- Put on the headphones.
- Sit with your eyes closed.
- Keep your head upright and without contact with the headrest.
- Maintain the same comfortable upright body posture without touching the backrest throughout the experiment.

Estimating vibration discomfort

- Before the main experiment starts, you will be presented with a few vibrations and shocks so that you can practice judging the discomfort you experience. Ask for clarification, if you are unclear about the task.
- During the practice, after each motion, judge the DISCOMFORT caused by the motion:
    - For the first motion you can use any number you wish, although people often find 100 a convenient number
- After subsequent motions, give numbers according to the following convention:
    - a motion that causes twice the DISCOMFORT as a previous motion is assigned twice the previous number (e.g., 200),
    - a motion that causes half the DISCOMFORT is assigned half the previous number (e.g., 50).
- After every motion you will also be asked to indicate the LOCATION where you felt most discomfort.
    - Indicate the location using a letter from A to E corresponding to the diagram of the body that will be shown to you.
- Say "Repeat" if you are unsure of your response and would like to experience the motion again.

Sequence of experimental stimuli

- During the main experiment, you will experience 128 vibrations or shocks.
- After each motion, please judge the DISCOMFORT caused by the motion:
    - For the first motion you can use any number you wish. We suggest you continue as during the practice
    - Continue judging DISCOMFORT using the same scale throughout the experiment.
    - Indicate the location using a letter from A to E corresponding to the diagram of the body that will be shown to you.
- Say "Repeat" if you are unsure of your response and would like to experience the motion again.
- After presentation of 128 stimuli, the simulator will be parked. Please remain seated with your lap belt fastened until the experimenter indicates you may leave the platform.
- If you have any queries please ask the experimenter.

C.2 Experiment presented in Chapter 5

EXPERIMENTAL STUDY OF THE DISCOMFORT CAUSED BY UPWARD AND DOWNWARD HIGH MAGNITUDE VERTICAL SHOCKS

INSTRUCTIONS FOR SUBJECTS

This experiment is designed to understand your impression of discomfort caused by mechanical shocks with different magnitudes and directions.

You will be presented with a series of vibration stimuli.

Please read **carefully** and follow the instructions below.

Preparation:

1. **Practice**

- You will be given a brief practice session so as to familiarise you with the stimuli and the procedure before commencing the main experiment. Ask questions if you are unsure.
- During the practice please sit comfortably on the seat **without** touching the backrest. Rest your hands on your lap.
- Wear the pair of headphones and close your eyes.
- **The experimenter will help you to adjust your seat belt. Please, keep your belt fasten and do not touch it during the experiment.**
- Please maintain the same body posture during the entire duration of the exposure.
- After each motion you will be asked to rate the discomfort, indicate the body location of greatest discomfort, and **say whether you left the seat.**
- The first motion experienced during the practice will be your “reference” for all the rest of the experiment.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.

2. **Test**

- You will be presented with **100** mechanical vibrations in the vertical direction.
- The sessions will split into two parts, between which you will have 5 minutes break.
- As in the practice, after each motion you will be asked to rate the discomfort, indicate the body location of greatest discomfort and **say whether you left the seat.**
- Before each part, the experimenter will help you to adjust the seat belt.

- In one part the seat belt will be tight enough that if you tried to stand up with your chest upright, your bottom will be still in contact with the chair.
- In the second part the seat belt will be slightly loose, in a way that if you tried to stand up with your chest upright there will be 1.5 cm space between your buttocks (proximal part) and the seat pan.
- Please, wear the pair of headphones and close your eyes during the test.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.

Please read carefully Part 3 of this sheet, where it is explained how to rate discomfort and body locations.

Rate the discomfort and body location:

- Your task is to say the discomfort caused by each of the **vibration stimuli** using any **positive** number that appears appropriate – whole numbers, decimals, or fractions.
- The first stimulus you will be presented with will be your reference in terms of discomfort. We suggest you start with a rating of 100. This stimulus will be repeated several times so that you become familiar with how it feels.
- Please judge the discomfort caused by the following stimuli relative to the discomfort caused by the first stimulus. For example;
    a. if you feel the discomfort caused by the a stimulus is double the discomfort caused by the first stimulus, you should say ‘200’.
    b. if you feel the discomfort caused by a stimulus is half the discomfort caused by the first stimulus, you should say ‘50’.
- Say ‘Repeat’ if you are unsure and wish to feel a motion again.
- After rating the discomfort, you will be asked to indicate **which part** of the body you feel most uncomfortable. The five parts you will have to take into account are:
    a. head (including the neck)
    b. shoulders
    c. abdomen
    d. lower body (buttocks and thighs)
    e. lower legs and feet.
- You will have a body map in front of you indicating these five parts of the body. You can open your eyes to see the map when stating your decision, and close thee eyes before for the next motion.

C.3 Experiment presented in Chapter 6

EXPERIMENTAL STUDY OF THE EFFECT OF SEAT DYNAMICS ON THE DISCOMFORT CAUSED BY VERTICAL MECHANICAL SHOCKS

INSTRUCTIONS FOR SUBJECTS

This experiment is designed to understand your impression of discomfort caused by mechanical shocks with different magnitudes and frequencies when a soft seat cushion of various thicknesses is used.

You will be presented with a series of vibration stimuli.

Please read **carefully** and follow the instructions below.

Preparation:

1. **Practice**

- You will be given a brief practice session to familiarise you with the stimuli and the procedure before commencing the main experiment. Ask questions if you are unsure.
- During the practice please sit comfortably on the seat **without** touching the backrest. Rest your hands on your lap.
- Wear the pair of headphones and close your eyes.
- **The experimenter will help you to adjust your seat belt. Please, keep your belt fasten and do not touch it during the experiment.**
- Please maintain the same body posture during the entire duration of the exposure.
- After each motion you will be asked to rate the discomfort, indicate the body location of greatest discomfort.**.**
- The first motion experienced during the practice will be your "reference" during the practice session *and* for all the rest of the experiment. During the practice, (but *not* during either part of the experimental session) this stimulus will be repeated several times so that you become familiar with how it feels.
- <u>Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.</u>

2. **Experimental session**

- You will be presented with **117** mechanical vibrations in the vertical direction.
- The session will be split into three parts, between which you will have 2 minutes break.

- As in the practice, after each motion you will be asked to rate your discomfort (relative to your discomfort when exposed to the reference motion during practice), indicate the body location of greatest discomfort..
- Before all parts of the experiment, the experimenter will help you to adjust the seat belt.
- In one part you will sit on a rigid seat.
- In the other two parts you will sit on a soft seat cushion with various thicknesses.
- Please wear the pair of headphones and close your eyes during the test.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.

3. Measure of seat transmissibility

- After being exposed to the 117 vertical shocks, you will attend two short sessions of about 3 minutes each where the experimenter will test the transmissibility of the two cushions used during the test.
- In each session you will be sitting upright on a block of foam and secured by a seat belt.
- You will be exposed to three random signals of 60 seconds of duration each.
- Please do not touch the backrest and maintain the same body posture during the entire duration of the exposure.
- Before both parts, the experimenter will help you to adjust the seat belt.
- You won't need to wear headphones. You won't need to rate discomfort.
- Please find the emergency stop button placed by the seat. You can use this at any time to stop the motion.

Please read carefully Part 3 of this sheet, where it is explained how to rate discomfort and body locations.

Rating the discomfort and body location:

- Your task is to say the discomfort caused by each of the **shock stimuli** using any **positive** number that appears appropriate – whole numbers, decimals, or fractions.
- The first stimulus you will be presented with during practice will be your reference in terms of discomfort. We suggest you start with a rating of 100. This stimulus will be repeated several times at the start of practice so that you become familiar with how it feels.
- Please judge the discomfort caused by all other stimuli relative to the discomfort caused by the first stimulus. For example:

   a. if you feel the discomfort caused by a stimulus is double the discomfort caused by the first stimulus, you should say ‘200’.
   b. if you feel the discomfort caused by a stimulus is half the discomfort caused by the first stimulus, you should say ‘50’.

- Say ‘Repeat’ if you are unsure and wish to feel a motion again.
- After rating the discomfort, you will be asked to indicate **which part** of the body you feel most uncomfortable. The five parts you will have to take into account are:
   a. head (including the neck)
   b. shoulders
   c. abdomen
   d. lower body (buttocks and thighs)
   e. lower legs and feet.
- You will have a body map in front of you indicating these five parts of the body. You can open your eyes to see the map when stating your decision, but please close your eyes before for the next motion.

C.4. Experiment presented in Chapter 7

EXPERIMENTAL STUDY OF THE EFFECT OF POSTURE ON THE DISCOMFORT CAUSED BY VERTICAL WHOLE-BODY VIBRATION

INSTRUCTIONS FOR SUBJECTS – Standing Session

This experiment is designed to understand your impression of discomfort caused by sinusoidal motions in different standing postures.

You will be presented with a series of vibration stimuli.

Please read **carefully** and follow the instructions below.

Preparation:

1. **Part with bent legs**

- With the help of the experimenter wear the harness secured on the frame. DON'T remove it for any reason during the test. Wait for the experimenter at the end of the session to remove it.
- Grip the handrail. Place your feet as far apart as the width of your shoulders.
- Stand comfortably with your knees unlocked so that your legs are slightly bent. Your knees should be vertically above your toes.
- Please find the emergency stop button on the handrail. You can use this at any time to stop the motion.
- Wear the pair of headphones and close your eyes.
- Please maintain your body posture during the entire duration of the experiment.
- You will be given a brief practice session so as to familiarise you with the stimuli and the procedure before commencing the main experiment. Ask questions if you are unsure.
- If you wish to use the emergency stop button for any reason, feel free to open your eyes. The emergency button is on the handrail so is easily available.

5-10 minutes break between part one and part two. During the break the experimenter will adjust your harness.

2. **Part with straight legs**

- With the help of the experimenter wear the harness secured on the frame. DON'T remove it of touch it for any reason during the test. Wait for the experimenter at the end of the session to remove it.
- Stand comfortably with your legs straight and knees unlocked. Put your feet distant as the width of your shoulder. With your hands grip the handrail.
- Wear the pair of headphones and close your eyes.

- Please maintain your body posture during the entire duration of the exposure.
- You will be given a brief practice session so as to familiarise you with the stimuli and the procedure before commencing the main experiment. Ask questions if you are unsure.
- Please find the emergency stop button placed by the handrail. You can use this at any time to stop the motion.
- If you wish to use the emergency stop button for any reason, feel free to open your eyes. The emergency button will be positioned on the handrail in order to be easily available in any time.

Rating vibration discomfort and the location of discomfort:

- During each part of the experiment, you will be presented with series of **128** vertical vibrations.
- Your task is to say the discomfort caused by the **vibration** using any **positive** number that appears appropriate.
- The first stimulus will be your reference in terms of discomfort. We suggest you start with a rating of 100.
- You will judge the following stimuli keeping the proportions comparing with the reference. Let's make the example you rate the discomfort a stimulus as "100". You could feel the next one, for example, one time and half more uncomfortable than the first. In this case you would assign to the latter '150'.
- Say 'Repeat' if you are unsure.
- Just after rating the discomfort you will be asked to indicate **which part** of the body you feel most uncomfortable. The six parts you will have to take into account are: head (including the neck), the shoulders, the abdomen, buttocks, tights), calves and feet.
- If you need, you will have a body map in front of you indicating the parts of the body. During the judgement you can so open your eyes to see the map and close them again for the next motion.

INSTRUCTIONS FOR SUBJECTS– Sitting Session

This experiment is designed to understand your impression of discomfort caused by sinusoidal motions in different sitting postures.

You will be presented with a series of vibration stimuli.

Please read **carefully** and follow the instructions below.

Preparation:

Practice

- You will be given a brief practice session so as to familiarise you with the stimuli and the procedure before commencing the main experiment. Ask questions if you are unsure.
- During the practice, stand comfortably with your legs straight and knees unlocked. Put your feet distant as the width of your shoulder. With your hands grip the handrail.
- Wear the pair of headphones and close your eyes.
- After each motion you will be asked to rate the discomfort cause by that motion and the location of the body where you feel most uncomfortable. (more details in section 3)

1. **Part sitting upright**

- With the help of the experimenter wear the harness secured on the frame. DON'T remove it for any reason during the test. Wait for the experimenter at the end of the session to remove it.
- Sit comfortably, touching the backrest of the seat. Grip the handrail.
- Wear the pair of headphones and close your eyes.
- Please maintain your body posture during the entire duration of the experiment.
- Please find the emergency stop button on the handrail. You can use this at any time to stop the motion.
- If you wish to use the emergency stop button for any reason, feel free to open your eyes. The emergency button is on the handrail so is easily available.
-

5-10 minutes break between part one and part two. During the break the experimenter will adjust your harness.

2. **Part leaning forward**

- With the help of the experimenter wear the harness secured on the frame. DON'T remove it of touch it for any reason during the test. Wait for the experimenter at the end of the session to remove it.
- Sit comfortably, lean slightly forward and place yourself with one's arms folded on the handrail (your elbows should stay on the handrail).

- Wear the pair of headphones and close your eyes.
- Please maintain your body posture during the entire duration of the exposure.
- Please find the emergency stop button placed by the handrail. You can use this at any time to stop the motion.
- If you wish to use the emergency stop button for any reason, feel free to open your eyes. The emergency button will be positioned on the handrail in order to be easily available in any time.

Rating vibration discomfort and the location of discomfort:

- During each part of the experiment, you will be presented with series of **128** vertical vibrations.
- Your task is to say the discomfort caused by the **vibration** using any **positive** number that appears appropriate.
- The first stimulus will be your reference in terms of discomfort. We suggest you start with a rating of 100.
- You will judge the following stimuli keeping the proportions comparing with the reference. Let's make the example you rate the discomfort a stimulus as "100". You could feel the next one, for example, one time and half more uncomfortable than the first. In this case you would assign to the latter '150'.
- Say 'Repeat' if you are unsure.
- Just after rating the discomfort you will be asked to indicate **which part** of the body you feel most uncomfortable. The six parts you will have to take into account are: head (including the neck), the shoulders, the abdomen, buttocks, tights), calves and feet.
- If you need, you will have a body map in front of you indicating the parts of the body. During the judgement you can so open your eyes to see the map and close them again for the next motion.

Appendix D INDIVIDUAL DATA

D.1 Experiment presented in Chapter 4 – Comfort contours in terms of unweighted VDV

Values of the exponent *n* for vibration																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	0.88	0.89	0.40	0.70	0.73	0.73	0.64	0.95	1.24	0.56	0.34	1.02	0.37	0.76	0.52	0.49
Subject 2	1.21	1.26	0.75	1.38	0.91	0.60	0.65	0.93	0.50	0.93	0.51	0.87	0.67	0.47	0.63	0.39
Subject 3	1.33	1.11	0.69	0.73	0.64	1.01	0.87	0.74	0.68	0.74	0.87	0.97	-0.1	0.33	0.11	0.22
Subject 4	1.21	1.17	0.85	0.79	0.69	0.88	0.69	0.76	0.68	0.73	0.67	0.50	0.79	0.65	0.77	0.70
Subject 5	1.04	0.99	0.98	0.61	0.50	0.63	0.63	0.62	0.88	0.82	0.40	0.45	0.65	0.61	0.65	0.77
Subject 6	0.76	1.37	0.82	0.54	0.82	0.55	0.49	0.34	0.43	0.30	0.37	0.12	0.26	0.29	0.29	0.21
Subject 7	1.26	1.17	0.93	0.97	1.19	0.46	1.52	0.63	1.29	1.28	0.83	0.62	0.92	1.04	0.67	0.84
Subject 8	0.72	0.60	0.37	0.34	0.38	0.35	0.74	0.43	0.50	0.64	0.41	0.25	0.23	0.17	0.29	0.09
Subject 9	1.94	1.67	1.39	1.17	0.79	1.06	1.06	1.18	1.10	1.07	0.85	0.94	0.61	0.67	0.47	0.77
Subject 10	0.31	0.33	0.60	0.74	0.36	0.62	0.55	0.62	0.53	0.58	0.48	0.40	0.48	0.33	0.03	0.36
Subject 11	1.13	0.96	0.75	0.52	0.74	0.64	0.66	0.59	0.25	0.69	0.34	0.23	0.44	0.43	0.14	0.13
Subject 12	1.71	1.22	0.90	0.90	0.66	0.84	0.88	1.29	1.00	0.89	0.73	0.77	0.81	0.73	0.67	0.70
Subject 13	1.85	1.67	2.03	1.11	1.14	1.09	0.80	0.89	0.84	1.28	0.35	0.67	0.51	0.79	0.27	1.00
Subject 14	1.86	1.25	1.36	2.16	2.09	1.71	1.49	1.91	1.72	1.09	0.62	1.21	1.49	1.21	1.42	1.55
Subject 15	0.84	0.52	0.54	0.26	0.54	0.53	0.51	0.48	0.42	0.18	0.41	0.34	0.43	0.50	0.25	0.25
Subject 16	2.34	2.11	1.49	0.73	1.11	1.36	0.93	0.98	0.96	1.31	1.07	0.77	0.65	1.05	0.65	0.27
Subject 17	0.56	0.61	0.57	0.26	0.15	0.25	0.25	0.19	0.15	0.22	0.21	0.23	0.16	0.11	0.13	0.14

Values of the constant *k* for vibration																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	63.56	69.49	98.53	67.85	61.88	48.81	56.80	37.77	27.03	83.11	102.71	48.87	89.01	54.57	83.22	74.25
Subject 2	26.57	33.82	64.24	28.07	61.33	76.04	67.04	54.12	91.93	103.38	198.28	132.76	156.29	159.91	148.21	193.27
Subject 3	40.47	43.56	48.56	44.80	37.54	30.63	30.64	48.35	46.15	48.21	66.21	45.12	102.8	103.24	87.44	70.47
Subject 4	40.76	35.77	50.51	44.35	45.15	31.82	43.60	37.43	55.29	82.27	87.39	72.23	68.04	68.43	71.05	81.81
Subject 5	73.75	73.12	61.03	76.29	73.29	59.86	65.63	73.51	64.91	91.11	137.78	112.33	96.97	118.34	118.80	108.41
Subject 6	77.65	52.99	60.42	79.29	54.92	67.27	72.13	84.92	87.21	110.65	106.67	123.73	122.82	133.43	121.08	128.25
Subject 7	56.09	43.20	40.59	35.08	24.73	40.83	15.91	40.77	18.19	36.67	67.72	70.82	67.47	50.31	69.22	83.47
Subject 8	142.99	116.19	137.33	126.29	102.44	85.19	53.76	85.35	84.83	103.53	111.51	107.95	122.29	124.26	109.32	112.89
Subject 9	22.22	24.02	21.72	23.96	44.61	25.51	26.74	23.93	48.66	67.40	50.60	50.02	59.98	91.98	101.99	88.12
Subject 10	51.29	60.99	60.83	46.42	78.14	54.83	64.33	69.76	86.96	99.35	101.22	96.24	85.47	95.67	95.56	95.55
Subject 11	61.87	69.73	70.90	84.62	61.25	53.87	53.55	61.79	97.15	85.43	117.67	127.10	97.42	85.27	102.17	106.30
Subject 12	45.89	56.14	66.16	64.25	46.66	47.56	52.93	35.32	61.26	84.46	112.95	88.15	108.52	119.63	115.52	113.82
Subject 13	14.66	14.52	11.42	26.42	30.14	26.54	39.66	32.51	42.05	36.39	98.92	79.46	65.49	53.74	54.71	48.68
Subject 14	63.56	69.49	98.53	67.85	61.88	48.81	56.80	37.77	27.03	83.11	102.71	48.87	89.01	54.57	83.22	74.25
Subject 15	26.57	33.82	64.24	28.07	61.33	76.04	67.04	54.12	91.93	103.38	198.28	132.76	156.29	159.91	148.21	193.27
Subject 16	40.47	43.56	48.56	44.80	37.54	30.63	30.64	48.35	46.15	48.21	66.21	45.12	102.8	103.24	87.44	70.47

Subject 17	40.76	35.77	50.51	44.35	45.15	31.82	43.60	37.43	55.29	82.27	87.39	72.23	68.04	68.43	71.05	81.81

Values of the exponent n for shocks																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	1.35	0.99	0.54	0.54	0.42	0.28	0.67	0.45	1.28	1.07	1.81	1.94	1.11	1.52	2.05	1.81
Subject 2	1.97	1.62	1.33	0.97	0.59	0.68	0.51	0.48	0.89	0.42	1.08	0.31	0.21	0.45	0.66	0.66
Subject 3	1.63	0.61	1.33	1.40	0.94	0.65	0.91	1.01	1.13	1.05	1.05	1.07	0.65	0.88	0.73	0.86
Subject 4	1.58	1.34	1.02	0.99	0.95	0.65	0.84	0.93	0.88	1.01	0.75	0.80	0.71	0.77	0.93	0.77
Subject 5	1.24	0.89	0.58	0.64	0.69	0.47	0.69	0.73	0.81	0.56	0.43	0.51	0.37	0.38	0.58	0.40
Subject 6	1.08	1.48	0.48	0.59	0.79	0.55	0.76	0.77	0.48	0.49	0.49	0.40	0.49	0.51	0.36	0.63
Subject 7	0.89	2.15	1.35	1.09	0.57	1.69	1.22	1.00	1.29	1.63	0.77	1.12	1.40	1.01	0.84	0.39
Subject 8	0.43	0.97	0.47	0.63	0.51	0.42	0.82	0.48	0.65	0.80	0.58	0.81	0.73	0.78	0.64	0.21
Subject 9	2.10	1.56	1.55	1.40	1.32	1.51	1.36	1.52	1.22	1.03	1.01	1.13	1.38	0.76	0.77	0.96
Subject 10	0.85	0.96	1.18	0.49	0.61	0.89	0.74	0.97	0.90	0.69	0.69	0.63	0.55	0.96	0.64	0.78
Subject 11	1.43	1.15	0.98	0.59	0.93	0.49	0.79	0.28	0.57	0.62	0.74	0.37	0.30	0.23	0.35	0.31
Subject 12	1.56	1.92	1.72	1.42	1.17	1.77	1.30	1.31	1.18	1.15	1.13	1.24	0.92	0.95	1.16	1.25
Subject 13	1.69	2.28	1.98	1.24	1.81	1.14	1.40	0.98	1.13	0.91	0.72	0.81	1.29	0.65	1.58	1.11
Subject 14	3.31	3.82	1.80	1.73	2.08	1.01	2.12	2.46	1.36	2.13	1.62	1.45	1.12	1.10	0.51	1.01
Subject 15	0.77	0.70	0.65	0.75	0.14	0.87	0.61	0.74	0.80	0.67	0.87	0.52	0.49	0.84	0.56	0.60
Subject 16	2.21	2.22	1.96	2.05	0.84	0.99	1.00	1.29	1.26	0.94	0.85	1.33	1.01	0.61	0.46	1.22
Subject 17	0.55	0.58	0.54	0.66	0.55	0.32	0.46	0.58	0.45	0.52	0.31	0.35	0.23	0.28	0.45	0.47

Values of the exponent k for shocks																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	77.69	85.01	116.89	94.67	95.18	108.49	63.29	89.92	22.77	41.55	19.71	16.90	32.32	24.36	17.66	20.33
Subject 2	34.48	35.49	41.23	56.33	64.92	66.93	93.68	121.85	82.59	131.06	85.26	124.69	141.74	135.84	123.67	111.03
Subject 3	43.22	54.74	31.16	27.28	42.69	54.82	36.74	38.43	39.55	47.69	53.37	43.94	69.86	57.39	71.38	49.32
Subject 4	40.56	40.90	39.14	39.23	30.51	48.38	32.65	36.22	44.71	43.03	62.60	56.93	51.78	47.97	48.26	53.11
Subject 5	85.49	83.84	105.40	91.25	71.36	86.11	76.54	77.09	80.02	100.85	114.70	113.67	115.78	126.00	107.40	109.56
Subject 6	78.36	57.60	99.65	66.79	62.92	60.28	95.72	101.25	95.36	108.44	93.64	108.44	93.64	91.60	100.48	87.25
Subject 7	103.78	37.23	32.53	52.71	39.91	14.11	21.35	21.21	17.63	13.77	41.86	21.46	27.66	28.24	21.44	13.31
Subject 8	193.47	116.38	139.22	112.07	113.17	95.23	64.93	89.42	77.42	74.76	79.16	66.38	67.13	65.34	48.39	52.52
Subject 9	18.84	26.14	27.18	19.79	21.11	16.02	22.72	22.49	24.00	38.86	40.02	34.65	29.57	38.72	33.55	24.55
Subject 10	49.26	47.65	38.16	68.45	62.34	44.74	58.88	50.03	58.24	74.17	81.16	66.40	72.52	56.02	63.80	61.93
Subject 11	85.06	87.25	68.12	82.75	48.93	68.38	62.93	96.55	89.40	95.10	71.18	105.11	98.34	90.34	89.74	85.62
Subject 12	65.00	44.18	28.85	32.16	32.95	19.83	26.83	34.33	57.05	64.77	56.79	54.98	71.22	61.65	71.39	60.45
Subject 13	18.01	17.16	14.19	29.97	12.86	31.69	22.38	31.61	38.43	55.62	64.97	56.29	39.14	64.19	27.46	31.35
Subject 14	19.04	7.86	21.86	20.73	5.65	2.41	5.24	5.50	11.54	4.95	11.04	16.60	14.17	10.03	9.06	2.41
Subject 15	98.62	79.68	75.93	49.55	89.95	39.33	57.22	56.45	52.50	62.09	43.30	67.94	60.64	44.69	49.01	51.90
Subject 16	42.21	21.51	14.92	18.53	41.28	41.36	38.65	24.59	29.94	47.71	52.20	34.70	45.73	66.55	42.56	31.93
Subject 17	81.94	73.91	69.17	53.50	54.64	69.25	63.27	61.66	73.73	72.27	87.50	83.48	89.16	81.06	73.05	64.40

D.2 Experiment in Chapter 5- Normalised magnitudes estimates

D.2.1 Tight belt condition

Responses to shocks with fundamental frequencies of 2 Hz										
	Upward shocks					Downward shocks				
	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5
SUBJECT 1	100.00	93.33	100.00	180.00	213.33	46.67	46.67	106.67	80.00	100.00
SUBJECT 2	100.00	200.00	200.00	200.00	300.00	50.00	50.00	50.00	50.00	150.00
SUBJECT 3	88.89	66.67	88.89	133.33	133.33	88.89	100.00	88.89	66.67	44.44
SUBJECT 4	50.00	125.00	125.00	125.00	100.00	150.00	75.00	75.00	75.00	75.00
SUBJECT 5	33.33	66.67	166.67	166.67	200.00	33.33	33.33	133.33	133.33	133.33
SUBJECT 6	40.00	60.00	40.00	100.00	140.00	8.00	120.00	40.00	20.00	60.00
SUBJECT 7	83.33	66.67	166.67	133.33	333.33	33.33	33.33	66.67	83.33	66.67
SUBJECT 8	33.33	166.67	133.33	200.00	250.00	33.33	33.33	83.33	66.67	66.67
SUBJECT 9	84.21	89.47	136.84	115.79	147.37	63.16	68.42	52.63	89.47	100.00
SUBJECT 10	107.69	115.38	153.85	153.85	215.38	46.15	69.23	76.92	138.46	115.38
SUBJECT 11	81.82	100.00	118.18	118.18	154.55	63.64	63.64	81.82	72.73	81.82
SUBJECT 12	88.89	77.78	100.00	122.22	166.67	33.33	77.78	44.44	66.67	88.89
SUBJECT 13	87.50	93.75	125.00	125.00	175.00	100.00	75.00	87.50	93.75	112.50
SUBJECT 14	33.33	166.67	133.33	200.00	250.00	33.33	33.33	83.33	66.67	66.67
SUBJECT 15	50.00	83.33	166.67	166.67	166.67	50.00	116.67	100.00	116.67	133.33
SUBJECT 16	62.50	100.00	125.00	150.00	187.50	62.50	62.50	62.50	62.50	100.00

Responses to shocks with fundamental frequencies of 2.5 Hz										
	Upward shocks					Downward shocks				
	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5
SUBJECT 1	86.67	66.67	120.00	166.67	200.00	46.67	66.67	100.00	66.67	86.67
SUBJECT 2	100.00	100.00	200.00	300.00	300.00	50.00	50.00	50.00	100.00	50.00
SUBJECT 3	100.00	100.00	133.33	200.00	200.00	33.33	66.67	55.56	66.67	100.00
SUBJECT 4	75.00	125.00	75.00	150.00	100.00	125.00	150.00	50.00	100.00	150.00
SUBJECT 5	33.33	100.00	66.67	133.33	200.00	13.33	66.67	100.00	100.00	66.67
SUBJECT 6	60.00	60.00	40.00	160.00	160.00	20.00	40.00	60.00	60.00	80.00
SUBJECT 7	133.33	100.00	100.00	200.00	166.67	50.00	50.00	50.00	83.33	133.33
SUBJECT 8	83.33	133.33	133.33	200.00	266.67	33.33	50.00	33.33	66.67	66.67
SUBJECT 9	100.00	105.26	142.11	147.37	157.89	63.16	52.63	63.16	63.16	73.68
SUBJECT 10	84.62	92.31	115.38	153.85	230.77	61.54	61.54	76.92	76.92	123.08
SUBJECT 11	90.91	118.18	127.27	145.45	136.36	63.64	81.82	63.64	72.73	90.91
SUBJECT 12	88.89	122.22	111.11	144.44	166.67	22.22	22.22	44.44	44.44	88.89
SUBJECT 13	112.50	93.75	125.00	125.00	156.25	93.75	75.00	93.75	93.75	93.75
SUBJECT 14	83.33	133.33	133.33	200.00	266.67	33.33	50.00	33.33	66.67	66.67
SUBJECT 15	83.33	133.33	100.00	100.00	166.67	100.00	83.33	100.00	83.33	116.67
SUBJECT 16	62.50	125.00	125.00	125.00	187.50	25.00	62.50	62.50	100.00	100.00

Responses to shocks with fundamental frequencies of 3.15 Hz										
	Upward shocks					Downward shocks				
	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5
SUBJECT 1	80.00	126.67	140.00	166.67	160.00	66.67	66.67	46.67	93.33	100.00
SUBJECT 2	100.00	100.00	200.00	200.00	300.00	50.00	50.00	100.00	100.00	100.00
SUBJECT 3	77.78	88.89	111.11	166.67	166.67	66.67	33.33	88.89	88.89	77.78
SUBJECT 4	75.00	50.00	50.00	75.00	100.00	50.00	150.00	200.00	50.00	100.00
SUBJECT 5	33.33	133.33	133.33	166.67	200.00	33.33	46.67	33.33	66.67	66.67
SUBJECT 6	80.00	60.00	60.00	180.00	120.00	20.00	40.00	60.00	40.00	80.00
SUBJECT 7	133.33	83.33	133.33	250.00	250.00	50.00	100.00	50.00	100.00	116.67
SUBJECT 8	133.33	133.33	133.33	200.00	250.00	33.33	50.00	83.33	100.00	166.67
SUBJECT 9	84.21	115.79	157.89	157.89	168.42	78.95	89.47	63.16	89.47	126.32
SUBJECT 10	92.31	76.92	153.85	146.15	192.31	38.46	46.15	76.92	92.31	130.77
SUBJECT 11	100.00	100.00	118.18	136.36	154.55	72.73	72.73	63.64	109.09	109.09
SUBJECT 12	33.33	111.11	111.11	100.00	144.44	22.22	88.89	88.89	77.78	122.22
SUBJECT 13	68.75	112.50	125.00	125.00	156.25	93.75	93.75	112.50	112.50	112.50
SUBJECT 14	133.33	133.33	133.33	200.00	250.00	33.33	50.00	83.33	100.00	166.67
SUBJECT 15	50.00	133.33	116.67	133.33	133.33	116.67	66.67	83.33	100.00	133.33
SUBJECT 16	100.00	125.00	125.00	187.50	150.00	100.00	62.50	62.50	62.50	100.00

Responses to shocks with fundamental frequencies of 4.0 Hz										
	Upward shocks					Downward shocks				
	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5
SUBJECT 1	66.67	86.67	153.33	146.67	146.67	53.33	53.33	66.67	73.33	133.33
SUBJECT 2	100.00	100.00	200.00	200.00	200.00	50.00	50.00	50.00	200.00	150.00
SUBJECT 3	133.33	111.11	111.11	111.11	166.67	55.56	66.67	111.11	100.00	77.78
SUBJECT 4	175.00	75.00	175.00	125.00	100.00	50.00	100.00	100.00	50.00	75.00
SUBJECT 5	66.67	66.67	133.33	133.33	166.67	13.33	13.33	66.67	100.00	66.67
SUBJECT 6	40.00	100.00	60.00	180.00	200.00	20.00	60.00	60.00	60.00	60.00
SUBJECT 7	83.33	116.67	100.00	150.00	216.67	83.33	83.33	83.33	100.00	166.67
SUBJECT 8	100.00	133.33	100.00	200.00	250.00	83.33	66.67	66.67	100.00	133.33
SUBJECT 9	84.21	84.21	115.79	126.32	168.42	63.16	73.68	105.26	100.00	136.84
SUBJECT 10	115.38	92.31	138.46	123.08	169.23	69.23	76.92	69.23	76.92	146.15
SUBJECT 11	100.00	90.91	127.27	136.36	127.27	54.55	72.73	90.91	109.09	109.09
SUBJECT 12	88.89	66.67	122.22	133.33	133.33	88.89	100.00	100.00	88.89	88.89
SUBJECT 13	112.50	125.00	137.50	156.25	175.00	93.75	93.75	112.50	112.50	112.50
SUBJECT 14	100.00	133.33	100.00	200.00	250.00	83.33	66.67	66.67	100.00	133.33
SUBJECT 15	66.67	100.00	133.33	66.67	150.00	33.33	66.67	133.33	100.00	166.67
SUBJECT 16	100.00	100.00	100.00	125.00	125.00	62.50	62.50	62.50	100.00	100.00

Responses to shocks with fundamental frequencies of 5.0 Hz										
	Upward shocks					Downward shocks				
	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5
SUBJECT 1	100.00	80.00	80.00	126.67	140.00	46.67	66.67	73.33	93.33	93.33
SUBJECT 2	100.00	200.00	200.00	200.00	200.00	50.00	100.00	200.00	200.00	200.00
SUBJECT 3	66.67	111.11	133.33	122.22	166.67	66.67	66.67	88.89	111.11	88.89
SUBJECT 4	75.00	100.00	150.00	100.00	100.00	100.00	50.00	50.00	125.00	125.00
SUBJECT 5	13.33	33.33	66.67	100.00	133.33	33.33	33.33	66.67	100.00	66.67
SUBJECT 6	40.00	60.00	80.00	60.00	160.00	100.00	40.00	40.00	40.00	80.00
SUBJECT 7	83.33	166.67	183.33	116.67	200.00	50.00	83.33	83.33	100.00	200.00
SUBJECT 8	83.33	66.67	100.00	100.00	166.67	100.00	83.33	66.67	133.33	100.00
SUBJECT 9	84.21	100.00	73.68	131.58	152.63	63.16	78.95	89.47	100.00	147.37
SUBJECT 10	92.31	115.38	115.38	146.15	153.85	69.23	69.23	53.85	92.31	115.38
SUBJECT 11	81.82	109.09	136.36	118.18	145.45	90.91	81.82	118.18	109.09	118.18
SUBJECT 12	77.78	100.00	88.89	122.22	122.22	66.67	77.78	100.00	111.11	122.22
SUBJECT 13	62.50	125.00	112.50	175.00	156.25	62.50	87.50	93.75	93.75	125.00
SUBJECT 14	83.33	66.67	100.00	100.00	166.67	100.00	83.33	66.67	133.33	100.00
SUBJECT 15	33.33	66.67	133.33	100.00	100.00	66.67	66.67	33.33	100.00	116.67
SUBJECT 16	62.50	100.00	100.00	150.00	100.00	25.00	62.50	62.50	100.00	100.00

D.2.2 Loose belt condition

Responses to shocks with fundamental frequencies of 2.0 Hz										
	Upward shocks					Downward shocks				
	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5
SUBJECT 1	93.33	106.67	146.67	106.67	193.33	73.33	80.00	106.67	100.00	146.67
SUBJECT 2	50.00	150.00	100.00	200.00	200.00	50.00	50.00	50.00	50.00	100.00
SUBJECT 3	100.00	88.89	100.00	133.33	166.67	77.78	88.89	100.00	100.00	111.11
SUBJECT 4	50.00	75.00	150.00	125.00	175.00	50.00	50.00	75.00	100.00	75.00
SUBJECT 5	100.00	66.67	100.00	173.33	233.33	26.67	133.33	100.00	166.67	133.33
SUBJECT 6	100.00	120.00	240.00	220.00	200.00	40.00	200.00	60.00	40.00	100.00
SUBJECT 7	50.00	83.33	133.33	166.67	133.33	83.33	33.33	100.00	50.00	83.33
SUBJECT 8	50.00	100.00	166.67	250.00	283.33	33.33	33.33	50.00	100.00	133.33
SUBJECT 9	89.47	115.79	126.32	147.37	157.89	52.63	68.42	78.95	52.63	84.21
SUBJECT 10	69.23	130.77	153.85	161.54	230.77	61.54	30.77	61.54	107.69	153.85
SUBJECT 11	81.82	109.09	109.09	118.18	154.55	81.82	72.73	63.64	81.82	63.64
SUBJECT 12	122.22	66.67	144.44	166.67	166.67	11.11	11.11	55.56	66.67	133.33
SUBJECT 13	75.00	100.00	112.50	125.00	125.00	62.50	93.75	81.25	93.75	93.75
SUBJECT 14	50.00	100.00	166.67	250.00	283.33	33.33	33.33	50.00	100.00	133.33
SUBJECT 15	133.33	100.00	133.33	166.67	166.67	66.67	100.00	83.33	100.00	133.33
SUBJECT 16	125.00	100.00	125.00	100.00	187.50	37.50	62.50	62.50	100.00	125.00

Responses to shocks with fundamental frequencies of 2.5 Hz										
	Upward shocks					Downward shocks				
	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5
SUBJECT 1	93.33	133.33	146.67	160.00	200.00	46.67	73.33	93.33	66.67	126.67
SUBJECT 2	100.00	100.00	100.00	200.00	200.00	50.00	50.00	50.00	50.00	100.00
SUBJECT 3	88.89	100.00	122.22	144.44	133.33	55.56	66.67	77.78	88.89	100.00
SUBJECT 4	75.00	100.00	150.00	150.00	175.00	50.00	75.00	50.00	75.00	100.00
SUBJECT 5	66.67	100.00	100.00	200.00	200.00	33.33	13.33	66.67	66.67	100.00
SUBJECT 6	100.00	240.00	220.00	240.00	260.00	40.00	60.00	100.00	200.00	160.00
SUBJECT 7	33.33	83.33	133.33	183.33	166.67	66.67	100.00	66.67	50.00	150.00
SUBJECT 8	83.33	166.67	166.67	200.00	200.00	16.67	33.33	33.33	50.00	116.67
SUBJECT 9	115.79	94.74	126.32	147.37	178.95	63.16	63.16	73.68	78.95	63.16
SUBJECT 10	92.31	100.00	153.85	153.85	230.77	23.08	30.77	38.46	76.92	138.46
SUBJECT 11	72.73	90.91	118.18	136.36	145.45	72.73	72.73	72.73	72.73	90.91
SUBJECT 12	88.89	100.00	122.22	133.33	166.67	22.22	111.11	44.44	88.89	122.22
SUBJECT 13	100.00	93.75	112.50	112.50	175.00	81.25	50.00	75.00	106.25	112.50
SUBJECT 14	83.33	166.67	166.67	200.00	200.00	16.67	33.33	33.33	50.00	116.67
SUBJECT 15	83.33	100.00	133.33	100.00	166.67	66.67	100.00	83.33	100.00	100.00
SUBJECT 16	100.00	100.00	125.00	125.00	187.50	37.50	62.50	62.50	100.00	100.00

Responses to shocks with fundamental frequencies of 3.15 Hz										
	Upward shocks					Downward shocks				
	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5
SUBJECT 1	126.67	113.33	126.67	140.00	213.33	53.33	86.67	73.33	86.67	100.00
SUBJECT 2	100.00	150.00	100.00	150.00	200.00	50.00	50.00	100.00	50.00	150.00
SUBJECT 3	111.11	100.00	122.22	133.33	122.22	77.78	66.67	88.89	77.78	111.11
SUBJECT 4	75.00	100.00	125.00	150.00	200.00	75.00	75.00	50.00	100.00	125.00
SUBJECT 5	66.67	100.00	133.33	133.33	166.67	13.33	13.33	33.33	66.67	100.00
SUBJECT 6	100.00	120.00	140.00	160.00	240.00	80.00	120.00	80.00	220.00	200.00
SUBJECT 7	133.33	150.00	116.67	133.33	166.67	83.33	66.67	66.67	116.67	150.00
SUBJECT 8	133.33	133.33	166.67	200.00	266.67	83.33	83.33	100.00	133.33	166.67
SUBJECT 9	100.00	126.32	136.84	152.63	168.42	68.42	52.63	84.21	84.21	94.74
SUBJECT 10	100.00	100.00	115.38	153.85	169.23	15.38	38.46	53.85	84.62	84.62
SUBJECT 11	90.91	100.00	109.09	145.45	154.55	72.73	81.82	81.82	100.00	109.09
SUBJECT 12	88.89	88.89	155.56	144.44	155.56	111.11	66.67	88.89	122.22	144.44
SUBJECT 13	93.75	100.00	93.75	143.75	156.25	75.00	93.75	112.50	100.00	112.50
SUBJECT 14	133.33	133.33	166.67	200.00	266.67	83.33	83.33	100.00	133.33	166.67
SUBJECT 15	100.00	133.33	133.33	133.33	133.33	100.00	66.67	100.00	100.00	133.33
SUBJECT 16	100.00	125.00	125.00	125.00	187.50	62.50	62.50	62.50	100.00	100.00

Responses to shocks with fundamental frequencies of 4.0 Hz										
	Upward shocks					Downward shocks				
	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5
SUBJECT 1	66.67	86.67	153.33	166.67	133.33	80.00	46.67	93.33	100.00	113.33
SUBJECT 2	100.00	100.00	150.00	150.00	200.00	50.00	50.00	100.00	100.00	100.00
SUBJECT 3	100.00	122.22	111.11	111.11	122.22	55.56	77.78	88.89	88.89	88.89
SUBJECT 4	50.00	100.00	125.00	100.00	150.00	50.00	75.00	100.00	100.00	125.00
SUBJECT 5	33.33	66.67	133.33	166.67	166.67	66.67	33.33	100.00	100.00	100.00
SUBJECT 6	220.00	140.00	120.00	240.00	200.00	120.00	80.00	100.00	200.00	100.00
SUBJECT 7	83.33	83.33	166.67	133.33	200.00	66.67	83.33	116.67	50.00	166.67
SUBJECT 8	133.33	166.67	100.00	200.00	250.00	50.00	100.00	133.33	166.67	133.33
SUBJECT 9	84.21	105.26	126.32	147.37	147.37	63.16	73.68	105.26	94.74	94.74
SUBJECT 10	84.62	115.38	92.31	130.77	192.31	30.77	69.23	53.85	84.62	115.38
SUBJECT 11	100.00	100.00	109.09	127.27	136.36	90.91	90.91	90.91	100.00	118.18
SUBJECT 12	66.67	133.33	133.33	122.22	155.56	77.78	66.67	111.11	122.22	122.22
SUBJECT 13	93.75	125.00	112.50	156.25	156.25	81.25	112.50	93.75	81.25	93.75
SUBJECT 14	133.33	166.67	100.00	200.00	250.00	50.00	100.00	133.33	166.67	133.33
SUBJECT 15	66.67	100.00	66.67	133.33	133.33	66.67	83.33	66.67	100.00	66.67
SUBJECT 16	100.00	62.50	125.00	125.00	125.00	37.50	100.00	62.50	62.50	62.50

Responses to shocks with fundamental frequencies of 5.0 Hz										
	Upward shocks					Downward shocks				
	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5	MAGNITUDE 1	MAGNITUDE 2	MAGNITUDE 3	MAGNITUDE 4	MAGNITUDE 5
SUBJECT 1	80.00	113.33	106.67	146.67	160.00	66.67	86.67	113.33	113.33	126.67
SUBJECT 2	100.00	100.00	200.00	150.00	200.00	50.00	100.00	100.00	150.00	150.00
SUBJECT 3	88.89	88.89	100.00	133.33	133.33	77.78	55.56	88.89	111.11	111.11
SUBJECT 4	75.00	100.00	125.00	125.00	125.00	50.00	50.00	100.00	100.00	150.00
SUBJECT 5	66.67	66.67	133.33	133.33	100.00	6.67	13.33	33.33	100.00	100.00
SUBJECT 6	200.00	120.00	220.00	400.00	200.00	40.00	140.00	60.00	240.00	160.00
SUBJECT 7	83.33	66.67	100.00	116.67	133.33	66.67	50.00	83.33	83.33	133.33
SUBJECT 8	83.33	166.67	133.33	83.33	200.00	66.67	83.33	133.33	133.33	200.00
SUBJECT 9	89.47	115.79	115.79	147.37	147.37	78.95	105.26	105.26	126.32	136.84
SUBJECT 10	84.62	100.00	100.00	123.08	146.15	46.15	84.62	61.54	115.38	107.69
SUBJECT 11	81.82	109.09	118.18	127.27	136.36	72.73	72.73	100.00	100.00	118.18
SUBJECT 12	44.44	100.00	133.33	88.89	155.56	77.78	55.56	44.44	133.33	133.33
SUBJECT 13	93.75	100.00	81.25	106.25	125.00	50.00	81.25	56.25	112.50	112.50
SUBJECT 14	83.33	166.67	133.33	83.33	200.00	66.67	83.33	133.33	133.33	200.00
SUBJECT 15	66.67	100.00	66.67	100.00	133.33	66.67	66.67	100.00	116.67	100.00
SUBJECT 16	62.50	100.00	100.00	125.00	125.00	62.50	37.50	62.50	62.50	100.00

D.3 Experiment presented in Chapter 6 – subjective SEAT values based on normalised magnitude estimates

40 mm FOAM – Magnitude 1													
Frequency (Hz)	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	62.5	66.7	150.0	88.9	93.3	114.3	170.0	116.7	100.0	94.4	77.8	55.6	150.0
Subject 2	50.0	40.0	100.0	40.0	200.0	100.0	42.0	100.0	50.0	100.0	50.0	50.0	100.0
Subject 3	40.0	100.0	50.0	120.0	300.0	100.0	250.0	300.0	100.0	500.0	250.0	50.0	100.0
Subject 4	50.0	72.2	220.0	20.0	166.7	166.7	25.0	133.3	100.0	500.0	66.7	100.0	200.0
Subject 5	100.0	100.0	120.0	50.0	116.7	71.4	62.5	100.0	120.0	83.3	200.0	125.0	60.0
Subject 6	166.7	121.4	62.5	230.0	83.3	100.0	100.0	160.0	120.0	175.0	100.0	50.0	50.0
Subject 7	100.0	100.0	100.0	100.0	100.0	200.0	200.0	100.0	100.0	100.0	100.0	100.0	100.0
Subject 8	50.0	100.0	33.3	200.0	50.0	33.3	66.7	100.0	100.0	100.0	66.7	150.0	50.0
Subject 9	33.3	66.7	66.7	50.0	50.0	100.0	150.0	100.0	100.0	33.3	50.0	150.0	100.0
Subject 10	37.5	55.6	10.0	20.0	12.5	70.6	11.1	80.0	44.4	25.0	12.5	50.0	50.0
Subject 11	80.0	100.0	100.0	200.0	400.0	200.0	50.0	50.0	600.0	100.0	200.0	20.0	100.0
Subject 12	25.0	100.0	40.0	100.0	83.3	100.0	66.7	37.5	100.0	80.0	60.0	100.0	100.0
Subject 13	66.7	150.0	83.3	100.0	200.0	100.0	100.0	200.0	100.0	150.0	200.0	4.0	100.0
Subject 14	60.0	100.0	133.3	160.0	100.0	71.4	85.7	120.0	71.4	120.0	83.3	100.0	60.0
Subject 15	80.0	100.0	100.0	200.0	400.0	200.0	50.0	50.0	600.0	100.0	200.0	20.0	100.0
Subject 16	200.0	160.0	100.0	100.0	100.0	100.0	100.0	100.0	50.0	100.0	100.0	40.0	40.0
Subject 17	40.0	20.0	100.0	200.0	500.0	40.0	100.0	250.0	140.0	100.0	40.0	100.0	100.0
Subject 18	90.9	66.7	110.0	111.1	125.0	111.1	111.1	112.5	100.0	100.0	100.0	88.9	72.7

40 mm FOAM – Magnitude 2													
Frequency (Hz)	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	107.1	100	122.2	109.1	120	83.3	71.4	125	81.8	166.7	100	105.3	123.1
Subject 2	83.3	66.7	80	40	100	75	33.3	100	100	100	50	50	100
Subject 3	66.7	150	120	178.6	166.7	75	93.8	250	200	200	50	80	33.3
Subject 4	111.1	153.8	200	100	300	90.9	36.4	33.3	66.7	116.7	25	300	100
Subject 5	100	107.1	100	100	61.5	166.7	166.7	100	100	90	33.3	80	50
Subject 6	102.9	187.5	104.2	68.2	106.7	257.1	62.5	133.3	160	116.7	85.7	150	150
Subject 7	100	400	100	50	100	100	100	100	200	100	400	200	400
Subject 8	66.7	60	100	80	100	100	100	100	100	75	75	150	66.7
Subject 9	88.9	57.1	133.3	62.5	66.7	166.7	75	66.7	60	50	50	150	100
Subject 10	22.2	28.6	36.4	57.1	47.6	45.5	75	55.6	71.4	55.6	16.7	50	100
Subject 11	175	87.5	100	250	200	250	350	100	100	50	100	50	50
Subject 12	60	66.7	100	75	53.3	100	80	20	60	80	20	100	200
Subject 13	142.9	100	83.3	75	100	100	200	200	200	100	100	100	100
Subject 14	100	125	150	125	150	100	150	66.7	40	71.4	50	66.7	46.7
Subject 15	175	87.5	100	250	200	250	350	100	100	50	100	50	50
Subject 16	100	100	100	100	300	100	100	50	80	50	50	50	100
Subject 17	66.7	100	250	50	200	250	50	40	100	100	100	100	250
Subject 18	90	112.5	91.7	120	136.4	100	150	100	100	100	120	108.3	91.7

40 mm FOAM – Magnitude 3													
Frequency (Hz)	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	109.5	95.2	125	115	105.3	102.6	82.4	100	100	93.3	85.7	127.3	76.9
Subject 2	100	100	85.7	100	83.3	66.7	80	50	50	60	33.3	100	66.7
Subject 3	160	100	133.3	133.3	133.3	83.3	100	166.7	80	125	50	200	80
Subject 4	100	100	100	150	100	120	100	75	83.3	30.8	57.1	35.7	50
Subject 5	100	90	100	111.1	133.3	117.6	100	125	83.3	76.9	66.7	53.3	70
Subject 6	100	110	111.1	137.5	146.7	115.4	113.6	158.3	150	62.5	188.9	138.5	142.9
Subject 7	166.7	100	125	133.3	300	150	200	100	100	200	100	100	100
Subject 8	87.5	85.7	37.5	87.5	116.7	85.7	100	66.7	57.1	66.7	66.7	83.3	50
Subject 9	80	81.3	55.6	100	66.7	75	62.5	57.1	87.5	166.7	100	150	100
Subject 10	106.3	121.4	100	106.7	91.7	78.6	88	69.6	63.6	38.1	27.3	27.3	11.1
Subject 11	166.7	227.3	120	115.4	109.1	125	162.5	71.4	120	40	333.3	150	80
Subject 12	100	125	100	60	66.7	133.3	25	66.7	150	75	37.5	25	100
Subject 13	100	100	125	83.3	125	87.5	150	100	100	125	200	125	200
Subject 14	150	150	100	100	100	100	100	100	100	75	60	80	100
Subject 15	166.7	227.3	120	115.4	109.1	125	162.5	71.4	120	40	333.3	150	80
Subject 16	100	100	125	80	100	100	100	150	80	66.7	66.7	66.7	66.7
Subject 17	100	100	66.7	66.7	166.7	200	70	50	70	200	100	100	200
Subject 18	100	125	100	100	100	111.1	133.3	100	100	123.1	93.8	83.3	115.4

80 mm FOAM – Magnitude 1													
Frequency (Hz)	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	106.3	105.6	150	88.9	133.3	128.6	180	133.3	120	55.6	77.8	55.6	125
Subject 2	100	60	100	40	200	50	100	50	50	100	50	50	100
Subject 3	40	150	20	100	100	100	83.3	100	100	250	50	50	50
Subject 4	50	55.6	80	60	266.7	83.3	75	66.7	100	200	33.3	100	200
Subject 5	66.7	100	160	70	83.3	114.3	125	140	100	83.3	100	75	60
Subject 6	100	171.4	100	240	83.3	87.5	200	120	240	50	85.7	75	50
Subject 7	100	100	200	100	100	100	200	100	100	100	100	100	100
Subject 8	100	150	133.3	200	200	100	100	100	100	50	100	100	50
Subject 9	50	133.3	200	200	300	100	150	100	100	66.7	50	100	100
Subject 10	87.5	100	180	30	62.5	58.8	55.6	10	77.8	50	12.5	150	10
Subject 11	40	14.3	50	100	200	200	50	50	200	100	50	20	20
Subject 12	50	100	30	50	133.3	100	266.7	62.5	80	40	40	33.3	50
Subject 13	83.3	150	50	33.3	500	200	200	100	100	50	100	100	100
Subject 14	80	100	116.7	160	160	71.4	114.3	160	71.4	100	83.3	166.7	100
Subject 15	40	14.3	50	100	200	200	50	50	200	100	50	20	20
Subject 16	160	100	100	200	100	100	100	100	20	40	40	40	40
Subject 17	100	50	500	40	500	100	250	250	200	100	40	50	150
Subject 18	136.4	73.3	100	133.3	162.5	122.2	111.1	100	111.1	55.6	120	22.2	81.8

80 mm FOAM – Magnitude 2													
Frequency (Hz)	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	85.7	140	144.4	127.3	120	100	85.7	125	72.7	150	100	100	123.1
Subject 2	83.3	16.7	80	100	100	100	66.7	100	50	50	50	50	100
Subject 3	133.3	100	80	142.9	66.7	30	93.8	62.5	60	40	20	40	20
Subject 4	55.6	76.9	160	91.7	250	72.7	90.9	83.3	83.3	25	62.5	400	100
Subject 5	100	64.3	170	150	76.9	166.7	166.7	80	50	40	41.7	60	30
Subject 6	129.4	225	208.3	109.1	146.7	57.1	100	300	240	166.7	71.4	100	400
Subject 7	200	200	100	50	100	100	200	200	200	50	200	100	100
Subject 8	66.7	100	140	100	150	100	100	50	100	50	50	200	66.7
Subject 9	111.1	114.3	133.3	62.5	83.3	133.3	150	133.3	60	50	175	50	166.7
Subject 10	100	164.3	118.2	104.8	104.8	72.7	131.3	22.2	42.9	66.7	33.3	300	50
Subject 11	62.5	87.5	87.5	500	300	150	150	200	100	25	25	50	50
Subject 12	40	50	50	50	53.3	150	50	33.3	30	50	13.3	40	20
Subject 13	85.7	75	100	62.5	33.3	100	100	200	150	50	50	50	50
Subject 14	66.7	187.5	150	100	150	150	50	125	100	142.9	80	66.7	100
Subject 15	62.5	87.5	87.5	500	300	150	150	200	100	25	25	50	50
Subject 16	100	100	150	150	300	100	200	50	50	50	50	50	100
Subject 17	100	200	500	150	200	750	150	100	350	500	100	100	250
Subject 18	100	125	133.3	120	136.4	150	130	120	100	100	100	108.3	50

80 mm FOAM – Magnitude 3													
Frequency (Hz)	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	114.3	61.9	115	110	100	92.3	94.1	92.3	100	66.7	89.3	118.2	100
Subject 2	100	114.3	100	116.7	100	83.3	80	75	75	40	16.7	100	66.7
Subject 3	120	75	133.3	100	86.7	100	80	100	40	30	25	100	40
Subject 4	83.3	95.5	100	100	125	80	100	150	20.8	23.1	57.1	57.1	75
Subject 5	125	100	125	138.9	100	117.6	100	125	166.7	61.5	46.7	33.3	60
Subject 6	106.7	110	133.3	160	116.7	115.4	118.2	183.3	83.3	66.7	200	123.1	71.4
Subject 7	133.3	50	75	100	200	100	200	200	200	100	100	50	25
Subject 8	100	100	100	87.5	133.3	114.3	116.7	100	71.4	66.7	33.3	116.7	83.3
Subject 9	80	75	55.6	116.7	83.3	100	87.5	71.4	50	100	225	125	350
Subject 10	125	85.7	146.2	120	108.3	78.6	96	91.3	90.9	47.6	81.8	36.4	33.3
Subject 11	108.3	109.1	100	115.4	118.2	58.3	100	71.4	30	64	166.7	50	60
Subject 12	100	100	60	80	100	100	50	83.3	50	50	20	20	40
Subject 13	100	120	150	100	100	100	150	66.7	125	50	100	150	50
Subject 14	150	150	150	125	100	80	100	133.3	50	50	48	48	100
Subject 15	108.3	109.1	100	115.4	118.2	58.3	100	71.4	30	64	166.7	50	60
Subject 16	100	100	125	100	125	133.3	100	100	66.7	66.7	66.7	66.7	33.3
Subject 17	150	166.7	133.3	133.3	100	150	100	150	150	200	150	200	40
Subject 18	100	100	150	125	138.9	111.1	120	100	100	115.4	112.5	83.3	92.3

D.4 Experiment presented in Chapter 7 - Comfort contours in terms of unweighted VDV

Values of the exponent n for standing straight legs																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	1	1,14	1,04	0,51	0,73	0,57	0,58	0,85	0,81	0,86	0,65	0,49	0,3	0,42	0,57	0,46
Subject 2	1,2	0,86	0,68	0,73	0,6	0,55	0,71	0,38	0,55	0,43	0,42	0,28	0,28	0,39	0,33	0,33
Subject 3	1,33	0,94	1,28	1,05	1,34	0,83	0,78	0,73	0,72	0,7	0,89	0,5	0,4	0,77	0,5	0,66
Subject 4	1,3	0,73	0,85	1,09	0,99	0,78	0,96	0,68	0,16	1,22	0,67	0,5	0,64	1,11	0,85	0,55
Subject 5	2,03	1,7	2,14	1,1	1,27	1,1	1,19	0,86	1,22	1,06	1,02	0,44	0,56	1,33	0,93	0,66
Subject 6	0,1	0,1	0,19	0,18	0,09	0,13	0	0,15	0,1	0,21	0,12	0,12	0,11	0,13	0,07	0,08
Subject 7	2,46	1,37	1,17	0,84	0,48	0,6	0,7	0,8	1,03	0,9	0,62	0,94	0,72	0,66	1,01	0,91
Subject 8	0,51	0,27	0,31	0,44	0,41	0,48	0,56	0,42	0,39	0,56	0,6	0,36	0,47	0,38	0,43	0,43
Subject 9	0,48	0,51	0,68	0,47	0,43	0,63	0,55	0,28	0,3	0,54	0,38	0,22	0,25	0,23	0,44	0,17
Subject 10	0,71	1,15	0,93	0,9	0,53	0,4	0,49	0,59	0,44	0,36	0,4	0,21	0,2	0,3	0,27	0,37
Subject 11	0,55	1,48	1,01	1,36	1,48	0,75	1,67	1,32	1,47	1,01	1,09	0,65	0,93	1,09	0,98	1,12
Subject 12	0,77	0,89	0,63	0,47	0,66	0,68	0,15	0,5	0,58	0,65	0,58	0,54	0,45	0,5	0,39	0,43
Subject 13	0,65	0,62	0,83	0,8	0,62	0,39	0,44	0,34	0,2	0,28	0,26	0,21	0,4	0,35	0,37	0,08
Subject 14	0,31	0,39	0,15	0,28	0,16	0,20	0,23	0,38	0,29	0,30	0,24	0,33	-	0,19	0,15	0,25

Values of the exponent k for standing straight legs																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	51,93	35,51	32,54	56,67	43,89	52,11	51,56	42,18	52,33	58,92	80,26	100,89	129,09	95,64	79,16	77,45
Subject 2	52,36	65,06	63,62	53,12	54,62	57,79	53,38	80,29	69,12	82,36	86,77	109,08	107,22	108,8	110,96	110,63
Subject 3	46,96	48,36	32,96	42,08	28,62	41,07	60,41	65,56	68,47	103,3	135,96	131,97	139,3	144,15	148,46	124,54
Subject 4	37	68,96	56,3	49,33	44,29	52	41,87	60,29	93,58	70,65	96,71	100,13	81,23	75,97	59,64	74,05
Subject 5	22,71	23,28	8,09	32,98	28,13	31,88	32,81	52,19	44,26	87,98	126,01	120,04	98,85	62,35	59,35	61,94
Subject 6	100,48	108,18	95,19	97,98	98,83	99,28	113,74	101,84	98,55	103,06	104,22	108,3	113,33	115,9	108,21	107,17
Subject 7	8,88	22,9	21,96	28,37	49,75	39,67	43,31	43,31	45,33	59,03	89,04	71,35	65,63	67,43	52	53,03
Subject 8	61,59	75,02	80,12	72,52	83,97	77,13	64,3	92,52	101,61	95,01	112,15	122,88	106,74	112,43	105,93	105,17
Subject 9	97,66	93,64	60,43	75,44	66,34	55,88	59,59	77,67	81,54	83,71	99,44	96,7	94,59	96,2	80,54	98,18
Subject 10	41,78	28,42	32,07	33,28	59,25	63,25	69,71	63,1	93,13	100,61	100,66	125,14	103,86	124,05	114,96	120,89
Subject 11	51,37	26,5	35,41	24,91	15,86	51,44	17,36	34,98	45,72	110,81	94,81	112,18	94,85	138	113,06	120,91
Subject 12	89,34	73,46	85,86	89,9	61,75	48,8	84,04	65,56	64,52	88,12	117,81	127,71	118,67	118,03	124,81	112,64
Subject 13	75,01	66,5	49,8	45,48	52,41	69,76	52,84	74,9	95,9	87,41	99,06	97,6	95,55	94,52	94,98	101,19
Subject 14	95,75	84,69	97,91	79,46	84,04	86,90	82,44	73,46	83,91	109,63	108,31	98,28	96,00	98,34	88,05	81,60

Values of the exponent n for standing bent legs																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	1,23	0,93	0,56	0,84	0,76	0,96	0,42	0,42	0,71	0,61	0,22	0,67	0,83	0,62	0,64	0,55
Subject 2	1,53	1,82	0,78	1,23	1,13	0,5	0,42	0,28	0,17	0,24	0,87	0,81	0,96	0,45	0,3	0,28
Subject 3	1,26	1,01	1,41	1,1	1,54	1,26	0,93	0,8	1,04	0,6	0,72	0,73	0,68	0,6	0,74	1,17
Subject 4	1,79	1,32	0,72	0,69	0,65	0,62	0,53	0,56	0,46	0,52	0,46	0,49	0,92	0,52	0,89	0,43
Subject 5	2,18	2,05	1,88	1,27	0,81	0,61	0,77	0,76	0,74	0,79	0,95	0,94	0,99	1,12	0,65	0,74
Subject 6	0,08	0,08	0,15	0,07	0,07	0,09	0,02	0,10	0,07	0,09	0,09	0,06	0,04	0,17	0,08	0,03
Subject 7	0,24	1,08	0,97	1,09	0,36	0,65	0,57	0,33	0,18	0,32	0,26	0,23	0,78	0,39	0,56	0,28
Subject 8	0,28	0,32	0,37	0,45	0,5	0,54	0,42	0,35	0,38	0,31	0,22	0,32	0,25	0,31	0,25	0,3
Subject 9	0,66	0,53	0,73	0,26	0,28	0,7	0,23	0,27	0,31	0,77	0,42	0,49	0,29	0,37	0,71	0,14
Subject 10	0,82	0,62	0,85	0,34	0,56	0,53	0,36	0,62	0,41	0,14	0,19	0,02	0,25	0,22	0,2	0,27
Subject 11	0,98	0,81	1,49	1,55	1,46	0,58	1,19	0,92	0,94	0,83	0,78	0,71	1,17	0,74	1,19	0,63
Subject 12	0,8	0,94	0,82	0,53	0,52	0,5	0,46	0,6	0,76	0,23	0,47	0,41	0,3	0,55	0,44	0,48
Subject 13	0,41	0,62	0,63	0,46	0,24	0,43	0,52	0,37	0,23	0,31	0,35	0,15	0,3	0,07	0,38	0,49
Subject 14	0,49	0,23	0,3	0,19	0,23	0,2	0,28	0,31	0,16	0,27	0,17	0,1	-0,01	0,23	0,32	0,18

Values of the exponent k for standing bent legs																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	41,82	46,12	62,67	45,56	36,34	30,37	63,04	77,18	62,27	84,22	87,57	70,12	68,29	84,36	72,54	77,99
Subject 2	30,15	18,81	40,85	21,45	26,23	71,5	84,93	95,69	99,03	82,5	50,76	56,15	56	76,61	77,91	78,85
Subject 3	38,45	49,41	28,61	39,35	26,81	27,25	49,55	81,13	80,6	120,28	161,57	150,4	162,13	145,36	152,98	78,09
Subject 4	28,55	33,74	53,70	48,22	61,32	60,73	70,41	80,78	137,70	121,25	106,11	88,00	78,44	83,87	73,92	94,06
Subject 5	25,26	18,57	14,7	28,44	60,12	82,12	69,72	77,58	105,79	101,44	85,89	69,05	72,02	54,76	67,6	51,41
Subject 6	94,57	94,22	85,71	95,61	90,88	90,02	96,89	92,71	97,33	98,48	99,06	94,43	96,16	99,49	97,73	98,21
Subject 7	78,62	40,07	35,79	25,6	87,77	47,75	66,89	102,61	98,85	71,44	84,85	98,75	63,8	77,57	69,54	92,19
Subject 8	69,97	65,53	77,14	83,5	75,16	66,16	94,66	115,04	119,62	118,83	101,12	94,1	79,67	89,86	89,25	84,44
Subject 9	76,47	91,52	57,34	94,73	92,19	52,12	84,26	92,4	92,63	76,36	81,13	59,1	42,98	64,19	61,35	56,45
Subject 10	18,5	28,25	32,92	62,5	53,07	62,65	97,64	72,74	123,61	124,56	100,22	94,55	102,3	106,64	110,03	103,02
Subject 11	44,31	55,19	28,28	23,7	25,94	76,92	53,88	120,69	143,66	172,95	102,06	106,31	54,1	97,37	85,55	149,33
Subject 12	78,92	64,67	48,11	62,53	58,44	59,63	63,01	65,13	80,71	142,31	113,33	90,1	89,36	91,36	106,18	99,92
Subject 13	78,48	69,01	60,61	68,86	71,04	58,41	55,96	75,84	92,44	89,79	85,4	73,26	76,69	81,23	79,82	64,74
Subject 14	78,65	104,72	87,09	97,4	85,44	90,45	89,07	91,51	100,04	83,49	99,7	96,56	98,26	94,26	81,18	76,99

Values of the exponent n for sitting upright																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	1,51	1,32	0,81	0,76	0,89	0,75	0,63	0,39	0,69	0,76	-0,37	0,56	0,76	0,87	0,95	0,72
Subject 2	1,78	1,24	1,25	1,02	1,11	1,26	1,01	0,74	1,18	0,96	0,76	0,6	1,29	0,78	1,17	1
Subject 3	1,74	1,11	1,29	0,82	0,73	0,57	0,44	0,66	0,68	0,9	0,81	0,73	0,19	0,51	0,52	0,7
Subject 4	1,48	1,41	1,43	1,32	1,22	1,18	0,95	1,1	0,56	0,85	1,11	0,76	0,38	1,6	0,5	1,13
Subject 5	1,66	1,44	1,23	0,64	0,98	0,57	0,69	0,74	0,87	0,71	0,63	0,62	0,52	0,58	0,63	0,36
Subject 6	1,3	1,47	0,93	1,12	0,8	0,94	0,8	1,5	1,46	1,31	1,02	0,79	1,15	0,91	0,91	0,38
Subject 7	0,23	0,12	0,2	0,2	0,24	0,22	0,18	0,24	0,23	0,32	0,15	0,24	0,21	0,01	-0,09	0,15
Subject 8	0,16	0,14	0,15	0,12	0,12	0,11	0,12	0,04	0,05	0,11	0,1	0,12	0,1	-0,04	0,06	0,08
Subject 9	0,33	1,5	1,14	1,4	0,99	1,13	0,94	0,61	1,07	1,2	0,7	0,99	0,62	1,32	0,68	0,51
Subject 10	0,29	0,05	0,12	0,16	0,47	0,27	0,22	0,4	0,39	0,57	0,41	0,36	0,33	0,17	0,4	0,64
Subject 11	2,25	2,51	1,6	1,17	1,44	1,48	1,26	0,89	1,4	1,92	1,72	1,63	1,3	0,97	1,82	1,54
Subject 12	0,98	0,39	0,51	0,54	0,35	0,43	0,38	0,38	0,36	0,32	0,30	0,24	0,32	0,27	0,27	0,26

Values of the exponent k for sitting upright																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	27,13	28,44	42,24	36,46	25,9	33,56	40,4	44,62	40,21	56,67	105,53	69,75	65,48	74,11	65,27	74,72
Subject 2	32,4	48,5	39,47	41,14	24,87	26,13	45,12	62,31	40,02	74,06	96,45	117,04	102,51	143,22	136,02	150,62
Subject 3	26,51	41,03	24,28	37,2	46,81	50,63	67,01	51,67	59,75	54,23	63,28	71,43	95,81	88,74	77,47	81,83
Subject 4	37,38	24,51	23,77	22,06	30,06	29,77	38,94	37,67	83,33	128,49	103,69	99,49	120,99	81,82	134,37	116,06
Subject 5	21,62	22,78	22,94	46,06	28,02	58,2	47,64	53,01	49,43	73,34	83,76	80,32	89,53	78,52	73,98	83,33
Subject 6	44,86	22,72	34,48	31,60	38,68	38,24	41,84	24,66	39,50	78,54	115,72	107,57	99,56	111,22	131,02	226,09
Subject 7	93,01	94,75	83,48	78,61	78,51	81,05	82,53	80,96	87,79	90,36	98,24	87,19	92,05	87,56	87,81	86,21
Subject 8	92,75	94,1	87,67	90,15	87,87	87,48	87,68	93,6	93,98	93,09	95,21	95,82	99,23	102,43	103,13	104,74
Subject 9	22,44	13,34	20,39	13,26	19,98	18,42	29,34	42,78	26,54	44,13	79,61	43,54	51,37	42,96	74,04	81,91
Subject 10	58,11	64,71	82,23	79,45	62,61	78,42	85,77	73,12	82,02	89,54	86,02	94,28	87,16	91,43	88,16	69,71
Subject 11	14,15	7,87	18,69	31,91	17,71	11,83	19,65	35,92	23,77	19,17	28,78	26,09	39,5	60,02	26,64	40,59
Subject 12	44,60	59,50	62,17	53,10	65,97	52,93	60,13	66,52	71,13	76,22	74,25	79,62	70,07	78,25	78,05	77,36

Values of the exponent n for sitting leaning forward																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	1,06	0,75	0,43	0,67	0,43	0,43	0,37	0,48	0,43	0,99	0,48	0,21	0,4	0,31	0,42	0,39
Subject 2	1,39	1,41	1,36	0,61	0,31	0,99	0,61	0,28	0,62	0,94	0,68	0,41	0,94	0,72	0,81	0,91
Subject 3	1,74	1,48	0,74	0,87	0,73	0,58	0,64	0,39	0,35	0,88	0,85	0,43	0,64	0,95	0,76	0,60
Subject 4	1,54	1,52	1,21	1,17	1,04	1,08	0,54	0,52	0,26	0,96	0,98	0,66	1,16	0,78	0,79	1,02
Subject 5	1,32	1,17	1,24	1,17	0,69	0,51	0,89	0,7	0,6	0,84	0,82	0,73	0,62	0,61	0,52	0,42
Subject 6	1,32	1,44	1,37	2,04	1,41	1,29	0,7	0,77	0,76	1,69	1,51	0,96	1,01	1,07	1,12	1,09
Subject 7	0,23	0,17	0,1	0,17	0,13	0,24	0,11	0,08	0,13	0,23	0,13	0,09	0,05	0,12	0	0,06
Subject 8	0,22	0,18	0,16	0,1	0,15	0,11	0,09	0,06	0,05	0,07	0,05	0,03	0,06	0,07	0,08	0,1
Subject 9	1,83	1,1	1,46	0,75	0,65	0,8	0,68	0,94	1,01	0,87	1,06	1,18	1	1,05	0,98	0,26
Subject 10	0,19	0,01	0,24	0,32	0,44	0,23	0,53	0,3	0,49	0,53	0,34	0,42	0,5	0,2	0,26	0,28
Subject 11	2,37	2,05	0,98	1,14	0,93	1,35	0,82	0,8	1,2	0,84	1,57	0,89	1,12	0,94	0,99	0,62
Subject 12	0,57	0,53	0,49	0,49	0,45	0,37	0,26	0,35	0,28	0,54	0,41	0,28	0,42	0,11	0,17	0,19

Values of the exponent k for sitting leaning forward																
Frequency (Hz)	**0.5**	**0.63**	**0.8**	**1.0**	**1.25**	**1.6**	**2.0**	**2.5**	**3.15**	**4.0**	**5.0**	**6.3**	**8.0**	**10.0**	**12.5**	**16.0**
Subject 1	50,35	55,59	67,47	48,08	61,89	58,69	62,85	61,55	71,47	47,34	89,73	93,35	95,89	97,2	93,32	100,21
Subject 2	45,14	38,48	29,53	53,88	91,25	45,43	69,74	84,39	72,19	71,04	107,36	121,25	102,91	127,17	99,94	111,85
Subject 3	41,21	37,71	63,49	40,11	44,55	59,88	48,26	72,41	77,23	61,00	77,33	98,52	84,10	71,29	73,03	70,81
Subject 4	23,57	25,56	30,38	28,44	35,41	35,57	78,77	76,28	90,81	61,08	84,16	132,93	122,71	127,47	127,51	111,68
Subject 5	26,52	34,36	26,87	24,42	42,41	58,14	37,14	50,2	58,12	57,92	71,53	78,05	85,51	82,49	82,81	68,16
Subject 6	26,13	22,82	23,55	8,6	19,28	25,76	59,69	67,97	59,74	45,95	75,04	116,17	95,64	105,92	99,29	132,22
Subject 7	98,69	96,19	103,08	86,46	93,86	84,58	97,98	101,39	95,33	96,94	106,48	96,86	102,6	104,88	101,79	100,9
Subject 8	88,34	87,34	89,11	90,64	84,84	87,6	93,86	95,17	98,7	100,29	98,81	99,72	103,68	100,77	106,52	105,34
Subject 9	13,58	24,69	17,74	43,61	50,1	44,09	49,3	38,09	49,5	72,31	69,07	62,84	63,02	50,21	54,41	84,09
Subject 10	63,41	66,42	67,73	61,55	62,06	82,73	59,24	84,06	72,32	82,9	94,11	90,87	90,64	92,96	85,45	87,09
Subject 11	12,26	12,58	35,14	25,53	25,29	16,02	36,69	40,09	26,57	50,95	36,09	70,07	46,88	54,81	60,3	64,63
Subject 12	69,28	63,39	61,62	55,49	61,4	66,29	75,6	69,49	71,42	64,98	80,3	85,65	77,42	90,16	82,95	82,67

Appendix E PARAMETER OF THE MODEL DESCRIBED IN CHAPTER 6

Table E.1 Parameters when a block of foam 40 mm thick was used

Subject	k_1	k_2	k_3	c_1	c_2	c_3	m_1	m_2	m_3	Total seated weight m(kg)
Subject 1	122800,6	25640,7	105761,9	445,3	613,8	2138,9	0,5	35,4	11,4	47,3
Subject 2	102126,9	26939,4	34892	516	783,5	2696,1	0,5	34,5	11,0	46
Subject 3	115271	50282	130501	445	516	1516	3,8	41,5	10,0	55,3
Subject 4	124998	15104	38444	999,8	237,6	591,2	9,6	57,2	9,5	76,3
Subject 5	120993	30795	11091	50	568	1137	0,5	33,6	18,4	52,5
Subject 6	118388	12963	73868	619	543	2259	0,6	37,6	12	50,2
Subject 7	120615	33710	68692	610	796,1	2728,5	0,5	39,3	12,6	52,4
Subject 8	117130,6	47012,1	43193,4	1000	594	2750,8	12,6	47,2	3,2	63
Subject 9	124932,6	20295,4	18804,5	53,6	513	564,3	4,0	34,9	11,9	50,8
Subject 10	96271,9	13801,5	19319,1	999,9	408,8	2999,3	11,6	43,4	2,9	57,9
Subject 11	105026,5	36854,8	51171,9	132,1	634,1	1318,5	1,2	37,7	11,3	50,3
Subject 12	38322,3	128704,7	150261,8	999,9	2999,9	1557,1	0,5	33,4	18,3	52,2
Subject 13	132312,8	57299,4	106943,9	973,2	1238,8	2999,9	5,5	40,6	8	54,1
Subject 14	117126,7	47010,3	43193,2	564,3	633,2	2796,8	0,9	33,1	10,1	44,1
Subject 15	114030,8	14499,9	109486,9	802,2	343,95	2132,2	0,7	51,1	16,4	68,2
Subject 16	124999,9	12000,1	61956,5	999,9	493,1	2999,9	0,6	50,2	16,1	66,9
Subject 17	110860,2	28305	14560,8	772,9	660,2	1730,3	10,4	38,9	2,6	51,9
Subject 18	121824,2	42632,4	65915,5	217,5	1056,7	2198,8	0,6	45,0	14,4	60

Table E.2 Parameters when a block of foam 80 mm thick was used

Subject	k_1	k_2	k_3	c_1	c_2	c_3	m_1	m_2	m_3	Total seated weight m(kg)
Subject 1	55394,9	25383,2	81847,2	227,7	278,1	1284,4	9,4	27,1	10,8	47,3
Subject 2	50523,3	26872,7	143255,1	140	665,2	1791,8	0,4	34,4	11,2	46
Subject 3	66860	37432	25384	50	589	1436	4,9	36,8	13,6	55,3
Subject 4	114451	38729	118326	169	686	1439	0,7	57,6	18	76,3
Subject 5	60611	40771	33100	54	810	2790	0,5	39,3	12,7	52,5
Subject 6	58906	13819	22691	470	294	1881	9,9	22	17	50,2
Subject 7	59230,2	47338,9	33552,7		816,2	2238,5	0,5	39,3	12,6	52,4
Subject 8	71301,9	49258,2	41575,2	248,9	1038,96	2117,4	0,6	47,2	15,2	63
Subject 9	46250,7	13322,1	18895,8	50	1613,9	201,8	0,5	33,2	17,1	50,8
Subject 10	67067,5	44424,8	32593,4	119,7	913,1	2163,5	0,6	42,7	14,6	57,9
Subject 11	45096,0	31669,8	60033,3	159,7	795,5	2999,2	0,5	36,9	12,8	50,3
Subject 12	25624,5	25426,2	26480,9	799,5	169,9	2498,3	0,5	39,2	12,5	52,2
Subject 13	57390,7	23172,6	85160,2	549,2	579,1	2999,3	10,8	25,7	17,6	54,1
Subject 14	65160	25016,9	73309,9	263,1	370,1	2433,4	2,6	26,1	15,4	44,1
Subject 15	62744,1	39411,6	127138,7	244,9	1172	2440	0,7	51,1	16,4	68,2
Subject 16	80919,3	20041,2	22974,1	50,0	1395,1	274,2	0,7	42,8	23,4	66,9
Subject 17	62721,7	39410,8	127138,7	212,5	610,2	2336,4	5,3	38,9	7,7	51,9
Subject 18	62715,1	39420,7	127138,7	364,3	370,1	2347,6	11,7	27,3	21,0	60

List of References

Ahn S.J. and Griffin M.J. (2008). Effects of frequency, magnitude, damping, and direction on the discomfort of vertical whole-body mechanical shocks. Journal of Sound and Vibration, 311, 485-497.

Ashley C. (1970). Equal annoyance contours for the effect of sinusoidal vibration on man. The Shock and Vibration Bulletin, 41, 13-20.

Basri B. and Griffin M.J. (2011). The vibration of inclined backrests: perception and discomfort of vibration applied normal to the back in the x-axis of the body. Journal of Sound and Vibration, 330, 4646-4659.

Basri B. and Griffin M.J. (2012). Equivalent comfort contours for vertical seat vibration: effect of vibration magnitude and backrest inclination. Ergonomics; 55, 8; 909-922.

Basri B. and Griffin M.J. (2013). Predicting discomfort from whole-body vertical vibration when sitting with an inclined backrest. Applied Ergonomics, 44, 423-434.

Basri B. and Griffin M.J. (2014). The application of SEAT values for predicting how compliant seats with backrests influence vibration discomfort. Applied ergonomics, 45, 6, 1461-1474.

Beard G.F. and Griffin M.J. (2013). Discomfort during lateral acceleration: Influence of seat cushion and backrest. Applied Ergonomics, 44, 4, 588-594.

Beard G.F. and Griffin M.J. (2016). Discomfort of seated persons exposed to low frequency lateral and roll oscillation: Effect of backrest height. Applied Ergonomics, 54, 51-61.

Bovenzi M. and Hulshof C. T. J. (1999). An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain (1986–1997). International archives of occupational and environmental health 72, 6, 351-365.

British Standards Institution (1987). Guide to Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock. BS 6841-1:1987.

Brumaghim S.H. (1967). Subjective reaction to Dual Frequency Vibration, The Boeing Co., Wichita, Kansas, TR D3-7562, AD 664 510.

Cameron B., Morrison J., Robinson D., Roddan G. and Springer M. (1997). Development of a Standard for the Health Hazard Assessment of Mechanical Shock and Repeated Impact in Army Vehicles.

Chaney R.E. (1964). Subjective Reaction to whole-body vibration. The Boeing Co., Wichita, Kansas, Report D3-6474, (AD 607 462).

Chaney R.E. (1965). Whole-body vibration of standing subjects. The Boeing Co., Wichita, Kansas, Report D3-6779, (AD 472 912).

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

Constant H. (1932). Aircraft Vibration. J. Roy. Aero. Soc., Vol. 36, 1932, pp. 205-250.

Corbridge C. and Griffin M. J. (1986) vibration and comfort: vertical and lateral motion in the range 0.5 to 5 Hz. Ergonomics, 29, 2, 249-272.

Dobie, T. G. (2000). The importance of the human element in ship design. Presented at the Ship Structure Symposium, Arlington VA.

Donohew B.E. and Griffin M.J. (2010). Motion sickness with combined lateral and roll oscillation: effect of percentage compensation. Aviation, Space and Environmental Medicine, 81:22-29.

Dupuis H., Hartung E. and Louda L. (1972) The effect of random vibration of a limited frequency band compared with sinusoidal vibrations on human beings. R.A.E. Library Translation 1603 (of report from Max-Planck Institute for Agricultural Work and Techniques, bad Kreuznach).

Ebe K. and Griffin, M.J. (2000a) Quantitative prediction of overall seat discomfort. Ergonomics, 43, 6, 791-806.

Ebe K. and Griffin M.J. (2000b). Qualitative models of seat discomfort including static and dynamic factors. Ergonomics, 43, 6, 771-790.

Ensign W., Hodgdon J.A., Prusaczyk W.K., Ahlers S., Shapiro D. and Lipton M. (2000). A Survey of Self-Reported Injuries Among Special Boat Operators. Tech Report 00-48, Naval Health Research Centre, San Diego.

Fairley T.E. and Griffin M.J. (1986). A test method for the prediction of seat transmissibility. Society of Automotive Engineers International Congress and Exposition, Detroit, February 24-28, SAE Paper 860046.

Fairley T.E. and Griffin M.J. (1989). The apparent mass of the seated human body: vertical vibration. Journal of Biomechanics, 22, 2, 81-94.

Ferguson G. (1976). Statistical analysis in psychology and education – Fourth Edition. New York: Mc Graw-Hill.

Fothergill L.C. and Griffin M.J. (1977a). The use of an intensity matching technique to evaluate human response to whole-body vibration. Ergonomics, 20, 249-261.

Fothergill L.C. and Griffin M.J. (1977b). The subjective magnitude of whole-body vibration. Ergonomics, 20, 521-533.

Gescheider G. (1997). Psychophysics: The Fundamentals. Psychology Press, Third edition.

Gorrill R.B. and Snyder F.W. (1957). Preliminary study of aircrew tolerance to low-freuency vertical vibration, Boeing Airplane Co., Doc. No. D3-1189, (AD 155 462).

Goldman D.E. (1948). A review of subjective responses to vibrating motion of the human body in the frequency range 1-70 cycle4s per second. U.S. Naval Medical Research Institute. Project NM 004/01 Rept. No. I.

Grant D. S. and Wilson P. A. (2005). The development of a design tool for rigid inflatable boats. Proceedings of the Conference on High speed marine vehicles (HSMV 1905), Naples, Italy, 1–6.

Griffin M.J. (1976). Subjective equivalence of sinuisoidal and random whole-body vibration. The Journal of the Acoustical Society of America, 60, 1140-1145.

Griffin M.J. (1990). Handbook of human vibration. Published: Academic Press, London, ISBN: 0-12-303040-4.

Griffin M.J. (1998). Predicting the hazards of whole-body vibration - considerations of a standard. Industrial Health, 36, 2, 83-91.

Griffin M.J. (2007). Discomfort from feeling vehicle vibration. Vehicle System Dynamics, 45, 679-698.

Griffin M.J. and Whitham E.M. (1980a). Discomfort produced by impulsive whole-body vibration. The Journal of the Acoustical Society of America, 68, 5, 1277-1284.

Griffin M.J. and Whitham E.M. (1980b). Time dependency of whole-body vibration discomfort. The Journal of the Acoustical Society of America, 68, 5, 1522-1523.

Griffin M. J., Whitham E.M. and Parsons K.C. (1982) Vibration and comfort. I. Translational seat vibration. Ergonomics, 25, 7, 603-630.

Hanes R.M. (1970). Human sensitivity to whole-body vibration in urban transportation systems: a literature review. Transportation Programs Report, APL/JHU TPR 004. Applied Physics Laboratory, The Johns Hopkins University, Maryland.

Harris C. and Piersol A. (2001). Harris' shock and vibration handbook. McGraw-Hill.

Helberg W. and Sperling E. (1941). Verfahren zur beurteilung der laufeigenschaften von eisenbahnwesens, Volume 96, 177-187.

Hinz B. and Seidel H. (1987). The Nonlinearity of the Human Body's Dynamic Response during Sinusoidal Whole Body Vibration. Industrial Health, Vol. 25, No. 4, 169-181.

Howarth H.V.C. (1986). A review of experimental investigations of the time dependency of subjective reaction to whole-body vibration. United Kingdom Informal Group Meeting on Human Response to Vibration, University of Technology, Loughborough.

Howarth H.V.C. and Griffin M.J. (1991). Subjective reaction to vertical mechanical shocks of various waveforms. Journal of Sound and Vibration, 147, 3, 395-408.

Howarth H.V.C. and Griffin M.J. (2003). Effect of roll oscillation frequency on motion sickness. Aviation, Space, and Environmental Medicine, 74, 4, 326-331.

Huang, Yu and Griffin, M.J. (2014). Comparison of absolute magnitude estimation and relative magnitude estimation for judging the subjective intensity of noise and vibration. Applied Acoustics, 77, 1-7.

International Organization for Standardization (1978). Guide to the evaluation of human exposure to whole-body mechanical vibration and shock. ISO 2631. International Organization for Standardization, Geneva.

International Organization for Standardization (1997). Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1. BS ISO 2631:1997.

International Organization for Standardization (2005). Human response to vibration -- Measuring instrumentation. ISO 8041:2005.

International Organization for Standardization (2009). Mechanical vibration, shock and condition monitoring – Vocabulary. BS ISO 2041: 2009.

Jacklin H.M. and Liddell G.J. (1933). Riding Comfort Analysis, Engng. Bull., Purdue University, Volume XVII, 3.

Jalil N.A.A. and Griffin M.J. (2008) Fore-and-aft apparent mass of the back: Nonlinearity and variation with vertical location. Journal of Sound and Vibration, 318, 1348-1363.

Jones A.J. and Saunders D.J. (1972). Equal comfort contours for whole body vertical, pulsed sinusoidal vibration, 23, 1-14.

Jones A.J. and Saunders D.J. (1974). A scale of human reaction to whole-body, vertical sinusoidal vibration. Journal of Sound and Vibration, 35, 503-520.

Kato K. and Hanai T. (1998). The effect of backrest angles on discomfort caused by fore-and-aft back vibration. Industrial Health, 36, 107-111.

Kitazaki S. and Griffin M. J. (1998). Resonance behaviour of the seated human body and effects of posture. Journal of biomechanics 31, 2, 143-149.

Lawther A. and Griffin M.J. (1986). The motion of a ship at sea and the consequent motion sickness amongst passengers. Ergonomics, 29, 4, 535-552.

Lewis C.H. and Griffin M.J. (2002). Evaluating vibration isolation of soft seat cushions using an active anthropodynamic dummy. Journal of Sound and Vibration, 253, 1, 295-311.

Loeb M., Barron T. and Burda E. a preliminary investigation of the effects of whole-body vibration and noise. Army Medical research Lab., Fort Knox, Ky., Proj. 6 95 20 001, Report 145, AD 47142.

Mandel M.J. and Lowry R.D. (1962). One-minute tolerance in man to vertical sinusoidal vibration in the sitting position¸ USAF Biomedical Lab., Wright-Patterson AFB, Ohio, AMRL-TDR-62-121, (AD 292 704).

Mansfield N.J. and Griffin M.J. (2000). Non-linearities in apparent mass and transmissibility during exposure to whole-body vertical vibration. Journal of Biomechanics, 33, 933-941.

Mansfield N.J. and Griffin M.J. (2002). Effects of posture and vibration magnitude on apparent mass and pelvis rotation during exposure to whole-body vertical vibration. Journal of Sound and Vibration, 253, 1, 93-107.

Mansfield N.J. and Maeda S. (2005). Comparison of the apparent mass of the seated human measured using random and sinusoidal vibration. Industrial Health, 43, 1, 233-240.

Matsumoto Y. and Griffin M.J. (1998). Dynamic response of the standing human body exposed to vertical vibration: influence of posture and vibration magnitude. Journal of Sound and Vibration, 212, 1, 85-107.

Matsumoto Y. and Griffin M.J. (2000) Comparison of biodynamic responses in standing and seated human bodies. Journal of Sound and Vibration 238, 4, 691-704.

Matsumoto Y. and Griffin M. J. (2002a). Non-Linear Characteristics in the Dynamic Responses of Seated Subjects Exposed to Vertical Whole-Body Vibration. Journal of Biomechanical Engineering. Vol. 124, 527-532.

Matsumoto Y. and Griffin,M.J. (2002b) Effect of phase on human responses to vertical whole-body vibration and shock - analytical investigation. Journal of Sound and Vibration, 250, 5, 813-834.

Matsumoto Y. and Griffin M.J. (2005). Nonlinear subjective and biodynamic responses to continuous and transient whole-body vibration in the vertical direction. Journal of Sound and Vibration, 287, 4-5, pp. 919-937.

McIlraith M.L.L., Serrao K.M. and Paddan G.S. (2012). Variation in vibration during repeat measures in an offshore raiding craft. 47th UK conference on Human Responses to Vibration, University of Southampton, Southampton.

Meister F.J. (1935). Die empfindlickeit des menschen gegen erschutter-ungen Forschung auf dem Gebiet des Ing. Wesens. Volume 6, 116-1200.

Miwa T. (1967) Evaluation methods for vibration effect. Part 1. Measurements of threshold and equal sensation contours of whole-body for vertical and horizontal vibrations. Industrial Health, 5, 183-205.

Miwa T. (1968). Evaluation methods for vibration effect, Part 7. The vibration greatnessof the pulses. Ind Health, 6,143–164.

Morioka M. and Griffin M.J. (2006a). Magnitude-dependence of equivalent comfort contours for fore-and-aft, lateral and vertical whole-body vibration. Journal of Sound and Vibration, 298, 755-772.

Morioka M. and Griffin M.J. (2006b). Magnitude-dependence of equivalent comfort contours for fore-and-aft, lateral and vertical hand-transmitted vibration. Journal of Sound and Vibration, 295, 633-648.

Van Niekerk J.L., Pielemeier W.J. and Greenberg J.A. (2003). The use of seat effective amplitude transmissibility (SEAT) values to predict dynamic seat comfort. Journal of Sound and Vibration, 260, 5, 867-888.

Oborne D.J. and Boarer P.A. (1982).Subjective response to whole-body vibration. The effects of posture. Ergonomics, 25, 673-681.

Oborne D.J. and Clarke M.J. (1974). The determination of equal comfort zones for whole-body vibration. Ergonomics, 17, 769-782.

Olley M. (1934). Indipendent Wheel Suspension-Its whys and therefores. SAE J., 77-81.

Pethybridge R. J. (1982). Sea sickness incidence in Royal Navy Ships (No. INM Report 37/82). Gosport, England: Institute of Naval Medicine.

Paddan G.S. (2012). Effect of direction of travel on vibrations in a Swedish military combat boat. 47th UK conference on Human Responses to Vibration, University of Southampton, Southampton.

Paddan G.S. and Griffin M.J. (1988a). The transmission of translational seat vibration to the head - 1. Vertical seat vibration. Journal of Biomechanics, 21, 3, 191-197.

Paddan G.S. and Griffin M.J. (1988b). The transmission of translational seat vibration to the head - II. Horizontal seat vibration. Journal of Biomechanics, 21, 3, 199-206.

Paddan G.S. and Griffin M.J. (1993). The transmission of translational floor vibration to the heads of standing subjects. Journal of Sound and Vibration, 160, 3, 503-521.

Paddan G.S. and Griffin M.J (1998) A review of the transmission of the translational seat vibration to the head. Journal of Sound and Vibration. 215, 4, 863-882.

Paddan G.S. and Griffin M.J. (2002). Evaluation of whole-body vibration in vehicles. Journal of Sound and Vibration, 253, 1, 195-213.

Parks DL and Snyder FW (1961). Human Reaction to low frequency vibration, the Boeing Co., Wichita, Kansas, Technical Report no. 1, D3-3512-1, (AD 261 330).

Parsons K.C. and Griffin,M.J. (1978). The effect of rotational vibration in roll and pitch axes on the discomfort of seated subjects. Ergonomics, 21, 8, 615-625.

Parsons K.C. and Griffin M.J. (1982). Vibration and comfort. II Rotational seat vibration. Ergonomics, 25, 7, 631-644.

Parsons K.C. and Griffin M.J. (1988). Whole-body vibration perception thresholds. Journal of Sound and Vibration, 121, 2. 237-258.

Parsons K.C., Griffin M.J. and Whitham E.M. (1982). Vibration and comfort. III. Translational vibration of the feet and back. Ergonomics, 25, 8, 705-719.

Pike D. (2003). Inflatable tubes offer advantage for small craft. Ship and Boat Int., 78–82.

Rakheja S., Stiharu I., Zhang H. and Boileau P.É. (2002). Seated occupant apparent mass characteristics under automotive postures and vertical vibration. Journal of Sound and Vibration 253, 57–75.

Reiher H. and Meister F.J. (1931). The sensitiveness of the human body to vibrations (Empfindlichkeit des menschen gegen erschutterung). Forschung (VDI) 2: 381-386. Translation, Report No. F-TS-616-RE (1946). Headquarters Air Material Command, Wright Field, Dayton, Ohio.

Rutherford K. (2011) Whole Body vibration exposure on marine high speed craft – A military perspective. 46th UK Conference on Human Response to Vibration, Buxton, united Kingdom.

Shoenberger R.W. and Harris C. S. (1971) Psychophysical assessment of whole-body vibration. Human factors, 13, 41-50.

Siegel S. and Castellan N. J. (1988). Non parametric Statistics for the behavioural Sciences – Second Edition. McGraw-Hill Humanities/Social Sciences/Languages.

Stevens S. S. (1956) The direct estimation of sensory magnitude-loudness. American Journal of Psychology, 69, 1-25.

Stevens S. S. (1957) On the psychophysical law. Psychological Review, 64, 153-181.

Steven S.C. and Parsons M. G. (2002). Effects of Motion at Sea on Crew Performance: A Survey. Marine Technology, 39, 1, 29-47.

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

Thuong O. and Griffin M.J. (2011). The vibration discomfort of standing persons: 0.5 - 16 Hz fore-and-aft, lateral, and vertical vibration. Journal of Sound and Vibration 330 (2011) 816-826.

Toward M. G. R. and Griffin M.J. (2009). Apparent mass of the human body in the vertical direction: effect of seat backrest. Journal of Sound and Vibration 327, 657–69.

Toward M. G. R. and Griffin M. J. (2010a). Apparent mass of the human body in the vertical direction: Effect of a footrest and a steering wheel. Journal of Sound and Vibration 329, 1586–96.

Toward M. G. R. and Griffin M. J. (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, 5, 654-662

Toward M.G.R. and Griffin M.J. (2011a). Apparent mass of the human body in the vertical direction: Inter-subject variability. Journal of Sound and Vibration 330, 827-841.

Toward M.G.R. and Griffin M.J. (2011b). The transmission of vertical vibration though seats: Influence of the characteristics of the human body. Journal of Sound and Vibration 330, 6526-6543.

Townsend N.C., Wilson P.A. and Austen S. (2008). Sea-keeping characteristics of a model RIB. Proceedings of the Conference on High speed marine vehicles (HSMV 1908), Naples, Italy.

Tufano S. and Griffin M.J. (2013) Nonlinearity in the vertical transmissibility of seating: the role of the human body apparent mass and seat dynamic stiffness. Vehicle System Dynamics 51, 122-138.

Wei L. and Griffin,M.J. (1998a). Mathematical models for the apparent mass of the seated human body exposed to vertical vibration. Journal of Sound and Vibration, 212, 5, 855-874.

Wei L. and Griffin M.J. (1998b). The prediction of seat transmissibility from measures of seat impedance. Journal of Sound and Vibration, 214, 1, 121-137.

Whitham E.M. and Griffin,M.J. (1977). Measuring vibration on soft seats. Society of Automotive Engineers, SAE Paper 770253, International Automotive Engineering Congress and Exposition, Detroit.

Whitham E. M. and Griffin M. J. (1978). The effects of vibration frequency and direction on the location of areas of discomfort caused by whole-body vibration. Applied Ergonomics, 9, 4, 231-239.

Wikström B. O. (1993) Effects from twisted postures and whole-body vibration during driving. International Journal of Industrial Ergonomics, 12, 1, 61-75.

Wyllie I.H. and Griffin M.J. (2007) Discomfort from sinusoidal oscillation in the roll and lateral axes at frequencies between 0.2 and 1.6 Hz. Journal of the Acoustical Society of America, 121, 5, 2644-2654.

Wyllie I.H. and Griffin M.J. (2009). Discomfort from sinusoidal oscillation in the pitch and fore-and-aft axes at frequencies between 0.2 and 1.6 Hz. Journal of Sound and Vibration, 324, 453-467.

Zhang X (2014) Measurement and modelling of seating dynamics to predict seat transmissibility, PhD Thesis, University of Southampton.

Zhang X., Qiu Y. and Griffin M.J. (2015). Transmission of vertical vibration through a seat: Effect of thickness of foam cushions at the seat pan and the backrest. International Journal of Industrial Ergonomics, 48, 36-45.

Zhou Z. and Griffin M.J. (2014a) Response of the seated human body to whole-body vertical vibration: discomfort caused by sinusoidal vibration. Ergonomics, 57, 5, 714-732.

Zhou Z. and Griffin M.J. (2014b). Response of the seated human body to whole-body vertical vibration: biodynamic responses to sinusoidal and random vibration. Ergonomics, 57, 5, pp.693-713.

Zhou Z. and Griffin M.J. (2016a) Response of the seated human body to whole-body vertical vibration: discomfort caused by mechanical shocks. Unpublished paper.

Zhou Z. and Griffin M.J. (2016b) Response of the seated human body to whole-body vertical vibration: biodynamic responses to mechanical shocks. Unpublished paper.

Ziegenruecker G.H. and Magid E.B. (1959) Short time human tolerance to sinusoidal vibrations. Aerospace Medical Research Labs., Wright-Patterson AFB, Ohio, Project 7231, Task 71 786, WADC TR 59 391, (AD 22734).

Zwislocki J.J. and Goodman D. A. (1980). Absolute scaling of sensory magnitudes: A validation. Perception and Psychophysics, 28, 28-38.