UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

INSTITUTE OF SOUND AND VIBRATION RESEARCH

DISCOMFORT CAUSED BY MULTIPLE-INPUT VIBRATION AT THE HANDS, THE SEAT AND THE FEET

by

Nikolaos Pamouktsoglou

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

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Ride quality in vehicles can be influenced by multiple-input vibration: vibration simultaneously transmitted to the body via multiple vibrating surfaces, such as steering wheels, seats, and floors. Standardised methods of predicting the discomfort of multiple-input vibration (ISO 2631-1, 1997) do not take into account vibration of the hands or the phase between vibration input to the hands, the feet, and the seat. This research seeks to understand the mechanisms associated with discomfort caused by multiple-input vertical vibration, examining the effect of vibration frequency, vibration magnitude, input location, and phase between vibration at the hands, the seat, and the feet, at frequencies between 2 and 12.5 Hz.

A total of four psychophysical laboratory experiments were conducted. Three studies were designed to expand knowledge of the absolute and relative sensitivity to vibration at the inputs, or between the three inputs, by determining: (i) absolute thresholds for perception of vibration (minimum levels of vibration that can be detected) at the hands and at the feet (Experiment 1); (ii) equivalent comfort contours for vibration (levels of vibration that produce similar discomfort across the range of frequencies) at the hands and at the feet (Experiment 2); and (iii) the equivalence of vibration sensation (vibration magnitudes required to produce equivalent discomfort) between the hands and the feet (from 2 to 12.5 Hz), between the hands and the seat (from 4 to 12.5 Hz), and between the seat and the feet (from 4 to 12.5 Hz) (Experiment 3). The findings indicate similar absolute thresholds at the hands and the feet between 2 and 5 Hz, with the thresholds having constant velocity. At frequencies between 5 and 12.5 Hz, absolute thresholds have constant acceleration at the feet while continuing to have constant velocity at the hands: an indication that different mechanisms may be involved in the detection of threshold levels of vibration at the hands and the feet between 5 and 12.5 Hz. Contours of equivalent comfort at the hands and the feet between 2 and 12.5 Hz resemble the shapes of the absolute thresholds, with little dependence in vibration magnitude. The relative magnitudes of vibration required to produce equivalent discomfort at the hands and the feet, or at the hands and the seat, depend on the frequency of vibration and indicate greater sensitivity to vertical vibration at the seat than at the hands and the feet over the frequency range investigated. A clear difference in the frequency-dependence of sensitivity to vertical vibration at the seat from those at the hands and the feet suggests a separate mechanism for detecting supra-threshold vibration of the seat.

The final study (Experiment 4) concerned the perception and discomfort of multiple-input vertical vibration with various phases between vibration at pairs of inputs, so as to determine: (a) difference thresholds (just noticeable differences, JNDs) for the detection of phase differences, (b) the effect of phase on discomfort, and (c) the localisation (i.e. body location) at which phase differences are detected. The results suggest that phase differences between the hands and the feet at frequencies greater than 5 Hz are unlikely to be detected, and that any phase differences between the hands and the feet over the range 2 to 12.5 Hz are unlikely to influence discomfort. Phase differences between the seat and the hands, or between the seat and the feet, over the range 4 to 12.5 Hz were detected by some subjects and increased discomfort up to 50% (when changing phase only, with no change in vibration magnitude). Over the three inputs (i.e. the hands, the feet, and the seat) sensitivity to vertical vibration was greatest at the seat and least at the hands. The phase between the inputs can affect discomfort, but only when vibration is applied at the seat. Changes in discomfort due to vibration frequency, vibration magnitude, or phase differences between the inputs may be partly associated with changes in the body locations experiencing greatest discomfort, due to different paths for the transmission of vibration into the body. The research has increased understanding of how multiple-input vibration applied simultaneously at the hands, the seat, and the feet contribute to produce an overall sensation of discomfort.

Contents

List of Figures

List of Tables

Declaration Of Authorship

I, NIKOLAOS PAMOUKTSOGLOU

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

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I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;

2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;

3. Where I have consulted the published work of others, this is always clearly attributed;

4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;

5. I have acknowledged all main sources of help;

6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

7. parts of this work have been published as:

Pamouktsoglou, N. and Morioka, M. (2008) *Absolute thresholds for perception of vertical vibration at the hands and the feet at low frequencies.* Proceedings of the 43rd United Kingdom Conference on Human Responses to Vibration, held at Caterpillar Inc, Leicester, England, 15 - 17 September 2008

Pamouktsoglou, N. and Morioka, M. (2009) *Effect of vibration magnitude on equivalent comfort contours for vertical low frequency vibration of the hands.* Proceedings of the 44th UK Conference on Human Responses to Vibration, Loughborough, UK, 07 - 09 Sep 2009.

Pamouktsoglou, N. and Morioka, M. (2010) *Equivalence of sensations caused by vertical vibration of the hands and the seat at frequencies from 4 to 12.5 Hz.* Proceedings of the 45th United Kingdom Conference on Human Responses to Vibration, held at Institute of Naval Medicine, Alverstoke, Gosport, PO12 2DL, England, 6 - 8 September 2010

Pamouktsoglou, N. and Morioka, M. (2012) *Equivalence of sensations caused by vertical vibration of the hands and the feet at frequencies from 2 to 12.5 Hz.* Proceedings of the 47 United Kingdom Conference on Human Responses to Vibration, held at ISVR, University of Southampton, Southampton, England, 17 - 19 September 2012

Date: November, 2015

Signed:

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To my Grandmother Anastasia . . .

Chapter 1

Introduction

Exposure to vibration is something very common and frequent, it happens to the majority of the people. A task that involves exposure to vibration that most people experience is the transportation with a vehicle in order to move from one place to another. We, as drivers or passengers, the vibration exposure can influence our comfort during the travel. Drivers and passengers experience discomfort not only from the vibration of seats but also from the vibration of their hands (e.g., steering wheels) and their feet (e.g., pedals or floor). Standardised methods of predicting the discomfort caused by whole-body vibration are based on few studies, which do not include vibration of the hands and do not take into account the phase between motions at the seat, the hands, and the feet that are likely to influence overall discomfort, particularly with low-frequency vibration less than about 10 Hz.

Multiple-input vibration can cause out of phase motions when two vibration inputs (i.e. the seat and the feet, the hands and the seat, the hands and the feet) are in contact with different vibration surfaces (i.e. via a suspension seat, a foam seat, a steering wheel, etc.). Discomfort of a passenger may be altered depending on the magnitude, frequency, and phase of multiple-input vibration. This research seeks to understand how the discomfort caused by vertical vibration at the hands, the seat, and the feet is influenced by the frequency, the magnitude and the phase between vibration at these inputs. The thesis consists of a review of the literature, Chapter 2, related to vertical transmitted vibration at the hands, the feet and the seat, next Chapter 3 presents the experimental design as well as the objectives and the hypotheses of this study. Chapter 4 is a presentation of the apparatus and the vibration measuring systems that were used in order to conduct the experiments. Chapters 5 to 8 are reporting the four experiments that were designed for this study and chapter 9 is general discussion about the findings of all four experiments. Finally Chapter 10 concludes the thesis.

Chapter 2

Review of literature

2.1 Introduction

Multiple-input vibration can occur in many forms of transport (i.e. driver or passenger in a transport by road, air and sea) where vibration can enter to multiple parts of the human body via vibrating surfaces (i.e. floor, seat and handle/steering wheel). Such multiple-input vibration can be evaluated if the vibration experienced at each of the input locations in contact with the human body (i.e. hands, seat and feet) are quantified. Each input location (i.e. hands, seat and feet) presents a series of different characteristics in terms of vibration sensitivity, such as vibration perception thresholds and vibration discomfort. There are many studies that investigated and predicted the sensitivity, the thresholds and the comfort contours of each input separate or as pair with another input (i.e. equivalence of sensation between two inputs). Also there are well documented standards providing detailed information about the evaluation of vibration exposure at each input. The majority of cases involving vibration exposure on a human inside a transport vehicle are categorised as whole-body vibration exposure. This means that the calculation of the vibration exposure at the feet the seat and the back are the main inputs of interest.

Although there are separate standards for hand transmitted vibration there is no method at the moment proposing an overall calculation of the vibration exposure and vibration discomfort due to multiple-input vibration at the hands the seat and the feet. It is known that body location like the hands, the seat and the feet are more sensitive to vertical transmitted vibration compared to vibration transmitted at other axis. With respect of the frequency content of multiple-input vibration there is not much knowledge in terms of combining three inputs at the same time, but there is some relative new research done by Morioka (2007) that examined the equivalence between hands seat and feet at 12.5, 50 and 100 Hz. So in order to broaden the knowledge of discomfort due to multiple input motions the present study is focusing on low frequency (i.e. 2 to 12.5 Hz) vertical vibration transmitted at the hands the seat and the feet.

2.2 Psychophysics for quantifying vibration perception and discomfort

2.2.1 Psychophysical quantities

2.2.1.1 Absolute threshold

According to Griffin (1990), an absolute threshold is defined as ″the value of a stimulus which is justified for its presence to be detected″. Psychophysical thresholds can only be defined by statistics indicating the probability of detection for some value of the stimulus. Absolute threshold is also called 'detection threshold' or just 'perception threshold' and usually the thresholds are expressed as a function of frequency.

2.2.1.2 Difference threshold

Difference threshold is the smallest amount of change in a stimulus that can be detected. It is also known as just noticeable difference (JND) and it is expressed as the difference in value of two stimuli which is just sufficient for their difference to be detected according to Griffin (1990).

2.2.1.3 Masked threshold

Masking is a phenomenon in which the perception of a normally detectable stimulus is impeded by a second stimulus (masker) according to Griffin (1990). The normally detectable stimulus has an elevated threshold due to the presence of the second stimulus. The second stimulus may be presented or at a different point in the same sensory system and cause lateral masking or it may be presented at a different time, either before (for forward masking), or after (for backward masking) of the test stimulus.

2.2.1.4 Equal sensation levels

Equal sensation levels are the magnitudes of the stimuli that produce similar degrees of sensation, with vibration stimuli. They are normally expressed as a function of frequency and they represent the equivalent comfort contours

2.2.1.5 Sensation magnitudes

The sensation magnitudes for vibration stimuli can be used to determine the rate of growth in sensation (n). The rate of growth in sensation is expected to be constant for each type of stimulus. According to the values it takes as vibration magnitude increases across vibration frequencies, it can indicate the relative discomfort between frequencies (i.e. comfort contours).

2.2.2 Psychophysical methods

2.2.2.1 Method of constant stimuli

With the method of constant stimuli, the subjects compare the sensation produced by each stimulus in a set of 'test' stimuli. The test stimulus vary in terms of magnitude and it is presented in random order. With this method it can be determined the percentage of detections as a function of stimulus intensity. It must be taken into account that this method is time consuming. In order to conduct this method, a set of preliminary tests must be acquired to determine a required range of the test stimuli.

2.2.2.2 Method of limits

In the method of limits, the subjects are presented with a series of 'test' stimuli in ascending and descending steps and they report back whether each stimulus was larger, smaller, or equal to a comparison of a 'reference' stimulus or a defined sensation. Since the 'test' stimuli are not presented in random order there is a possibility of fatigue and learning effects.

2.2.2.3 Method of adjustment

In the method of adjustment the subjects' task is to adjust a 'test' stimulus so that it produces sensations with a required ratio (often the required ratio is unity) to the sensations of a 'reference' stimulus. The ability of the subjects to 'dial' the preferred magnitude may produce a bias or unreliable data.

2.2.3 Procedures

2.2.3.1 Yes-no

With the 'yes-no' procedure, the subjects are presented with a series of trials and they are asked to judge the presence or absence of a stimuli. The receiver operating curve (ROC curve) is affected by the variation of the signal detection probability.

2.2.3.2 Forced choice

When the 'forced choice' procedure is used the subjects are presented with a trial of two or more observations in random order and their task is to report which observation contains a required signal. An example of a force-choice method is the two-interval forced-choice procedure (2IFC).

2.2.3.3 Scaling

The scaling procedure is often used for judgement of large number of stimuli with or without referencing to a fixed standard stimulus. The subjects are asked to scale their judgements reflecting some attribute of the signal or signals. Often ratio scaling system (i.e. 50%, 100%, 200% e.t.c) in order to identify the sensation of signal compared to a reference signal (i.e. 50% = half the sensation, 100%= the same sensation, 200% = double the sensation).

2.2.4 Variation of method

2.2.4.1 Up-down (staircase) method

Up-down method is a variation of the method of limits and it is often used to determine sensory thresholds. Subjects are presented with a sequence of stimuli trials that increase or decrease in some attribute by small steps depending on their response. The value of the stimuli at each trial is recorded and depending on the response of the subject, the sequence is reversed from ascending or vice-versa. The procedure is complete when a sufficient number of reversal points are collected. The threshold levels are calculated by averaging the reversal points. This method is considered to be less time consuming in comparison with other methods because the presented stimuli are always close to threshold levels. An example of the Up-down method is shown in Figure 2.1 where a series of phase stimuli (i.e. File 100 to 112) are presented in order to determine the threshold of phase between two vibration inputs (e.g. right and left hands). The rule presented in this example is 3-down 1-up rule; the sequence is descended after three consecutive correct responses and the sequence is ascended after each incorrect response.

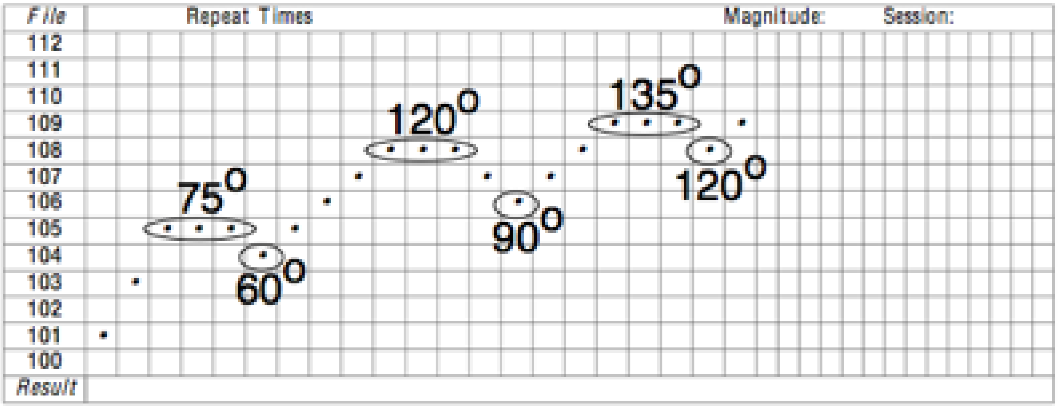

FIGURE 2.1: Example of the staircase method (each increment of stimulus file corresponds to 15-degree increment of phase difference between two inputs of vibration stimuli).

2.2.4.2 Magnitude estimation

Magnitude estimation method combines the constant stimuli method and the scaling procedure. The subjects are asked to make numerical estimations of vibration sensation on the randomly presented stimuli. Magnitude estimation method sometimes involves 'reference' stimuli which corresponds to a fixed number (e.g. 100). The task of the subjects can be to give a numerical estimation of the second stimuli (i.e. test) in terms of sensation (e.g. discomfort, greatness, etc) in comparison with the 'reference' stimuli. If the 'test' stimuli produced double the vibration sensation compared to the reference (equivalent to 100) then the subject should reply with '200'.

2.2.5 Phychoplysical laws

2.2.5.1 Weber's law

Weber law suggests that the 'JND' (Just noticeable difference) in a stimulus magnitude is proportional to the magnitude of the stimulus

$$\Delta l = C \tag{2.1}$$

where

Δl is the just detectable change of the intensity l

l is the intensity of the stimulus

C is a constant

2.2.5.2 Fechner's law

This law suggests that the growth of the strength of the sensation is proportional to the logarithm of the stimulus intensity.

$$\psi = k * log\phi \tag{2.2}$$

where

ψ is the sensation magnitude of the stimulus

k is a constant depending on the units employed

ϕ is the physical magnitude of the stimulus

2.2.5.3 Steven's power law

The law suggests that the relationship between the sensation magnitude and the physical magnitude of a stimulus is a function of power

$$\psi = k * \phi^n \tag{2.3}$$

where

ψ is the sensation magnitude of the stimulus

k is a constant depending on the units employed

ϕ is the physical magnitude of the stimulus

n is the constant that determines the growth in sensation for each type of stimulus

2.3 Vertical transmitted vibration

2.3.1 Vertical vibration at the hands

2.3.1.1 Absolute thresholds

Absolute thresholds for hand-transmitted vertical vibration have been determined by Miwa (1967a) for a frequency range between 2 to 300 Hz and Morioka and Griffin (2008) and Morioka and Griffin (2009) as shown in Figure 2.2. It can be seen that absolute thresholds for vertical vibration at the hand differs between the three studies. This may occur due to different phycophysical methods and the experimental conditions (e.g. hand posture, hand orientation, etc). Miwa (1967a) employed the method of paired comparisons, whereas Morioka and Griffin (2008) and Morioka and Griffin (2009) employed the staircase method with yes-no procedure. At low frequencies (i.e. 2 to 12.5 Hz) there is an increment of thresholds as frequency increases, whereas between 12.5 and 100 Hz there is a decrement of thresholds as frequency increases. The thresholds increase with increasing frequencies from about 100 Hz.

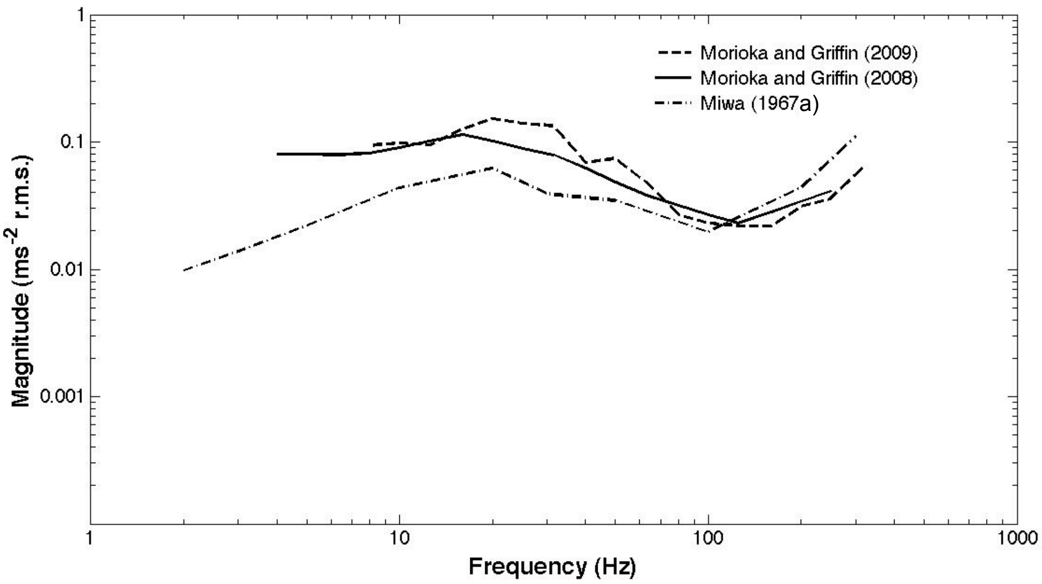

FIGURE 2.2: Absolute thresholds at the hands for vertical vibration. Data reproduced from Miwa (1967a) and Morioka and Griffin (2008, 2009)

2.3.1.2 Comfort contours

Equivalent comfort contours for hand-transmitted vibration were determined by Miwa (1967a), Morioka and Griffin (2009) and Morioka and Griffin (2006b) Selected contours from each study are overlaid in Figure 2.3. Miwa (1967a) investigated the equal sensation contours for vertical and horizontal vibration at the hand over the frequency range from 3 to 300 Hz with the magnitude range from 0.012 to 9 ms^{-2} r,m,s, and the reference vibration was set at 20 Hz. Morioka and Griffin (2006b) determined comfort contours for hand-transmitted vibration in each of the three translational axes (fore-and-aft, lateral and vertical axes) for frequencies between 8 and 400 Hz, with varied velocity from 0.002 to 0.126 ms^{-1} r.m.s. in 3 dB steps, and reference motion at 50 Hz with acceleration 5 ms^{-2} in the axis being investigated. Morioka and Griffin (2009) determined the equivalent comfort contours for vertical vibration at the hands holding a rigid steering wheel over a range of frequencies from 4 to 250 Hz and magnitude range from 0.1 to 1.58 ms^{-2}.

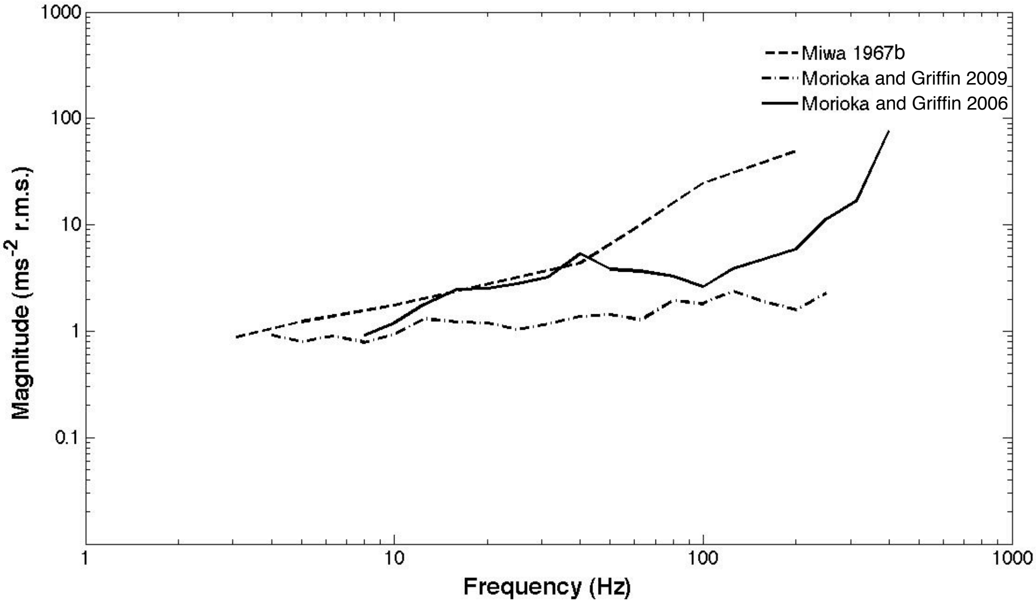

FIGURE 2.3: Comfort contours for vertical vibration transmitted at the hands. Data reproduced from Miwa (1967b) and Morioka and Griffin (2009, 2006)

Figure 2.3 presents a single comfort contour from each of the three studies that were determined from similar vibration magnitudes (about 1 ms^{-2} r.m.s. at 10 Hz) so as to allow comparison in the shape of the contours between the studies. Please note that comfort contours determined by the three studies shown in Figure 2.3 do not produce the same sensation level due to the use of different reference stimuli. It can be observed that as frequency increases the vibration magnitude in order to produce the same discomfort increases, except for Morioka and Griffin (2009).

2.3.2 Vertical vibration at the feet

2.3.2.1 Absolute thresholds

Morioka and Griffin (2008) determined the vibration thresholds for vertical vibration at the foot from 8 to 315 Hz and the results are presented in Figure 2.4. Little research has investigated the thresholds for vibration at the feet, there are no published thresholds for vertical vibration at the feet at low frequencies less than 8 Hz.

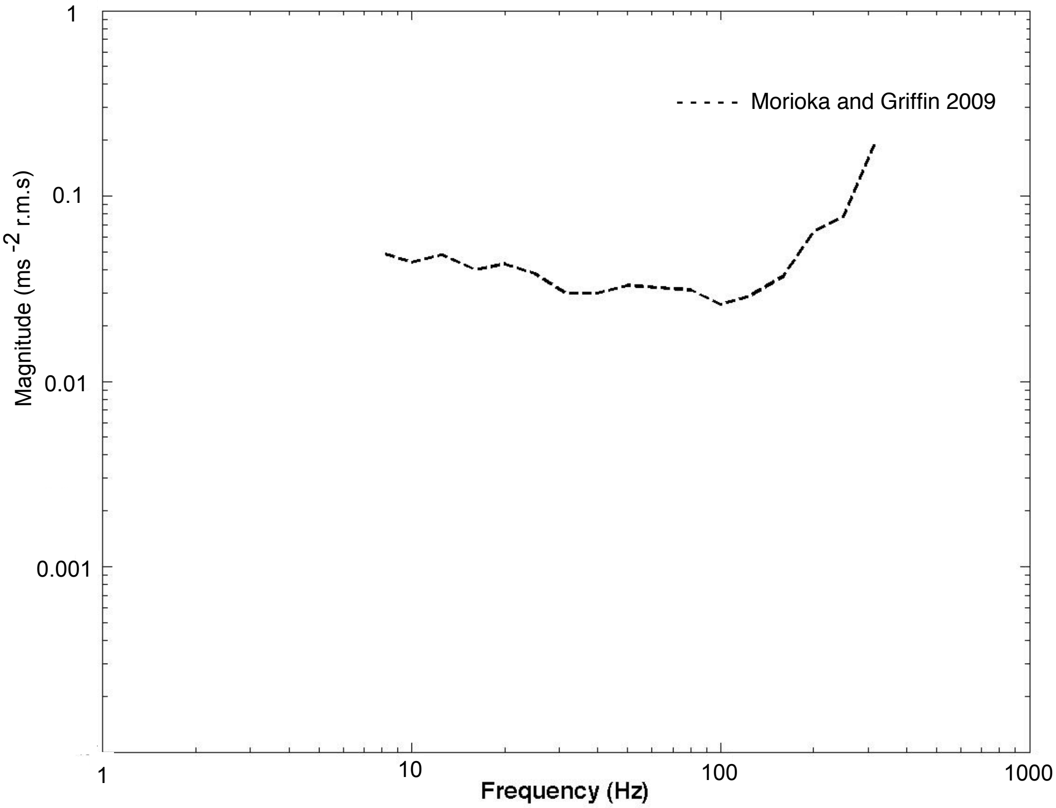

FIGURE 2.4: Vibration thresholds for vertical vibration transmitted at the foot. Data reproduced from Morioka and Griffin (2008)

2.3.2.2 Comfort contours

A study by Morioka and Griffin (2010) determined the equivalent comfort contours for vibration at the foot for each of the three axes over the frequency range from 8 to 315 Hz, and investigated the effect of frequency and magnitude. The method of magnitude estimation was employed using the reference motion at 50 Hz of 5 ms^{-2}. Another study by Parsons et al. (1982) determined the equivalent comfort contours for translational vibration of the feet for frequency range from 2.5 to 63 Hz relative to vertical vibration at the seat at 0.8 ms^{-2} r.m.s at 10 Hz. Also Miwa (1987) determined the equal sensation for vibration at the foot at frequencies from 8 to 400 Hz, the reference and the test motion was changed for each tested frequency.

Equivalent comfort contours from the three studies are overlaid in Figure 2.5. It becomes apparent that the three studies present similar shapes of comfort contours: independent of frequency (when expressed in terms of acceleration) at low frequencies between about 2.5 and 40 Hz and decreased sensitivity as increasing frequencies from about 40 to 400 Hz indicating a greater vibration magnitude is needed to produce the same discomfort. Because the three studies used different reference stimuli, the plotted data in Figure 2.5 does not present equivalent sensation between the three studies.

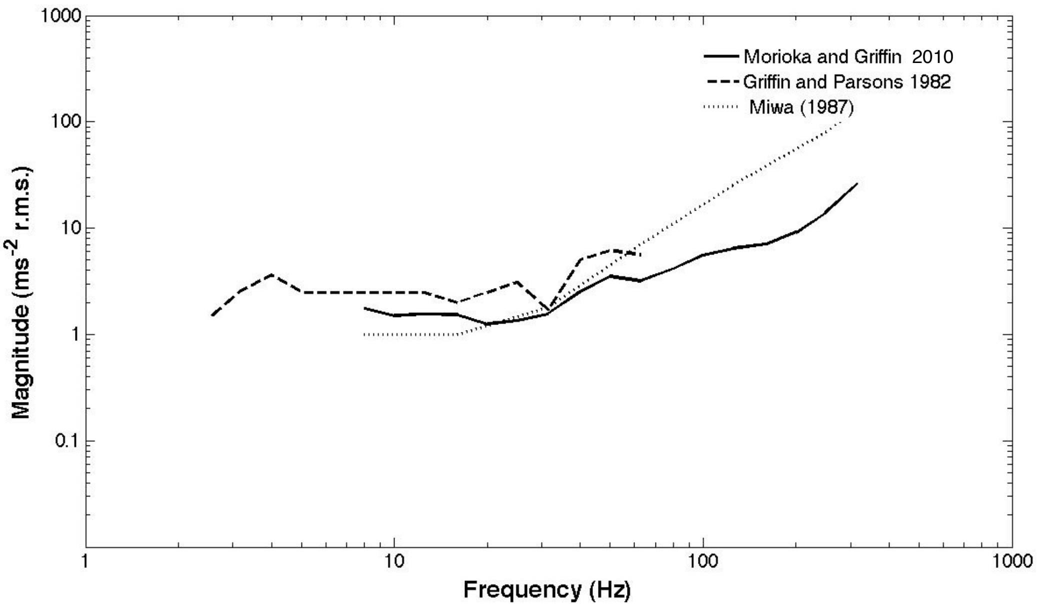

Figure 2.5: Comfort contours for vertical vibration at the foot. Data reproduced from Morioka and Griffin (2010); Griffin and Parsons(1982); Miwa (1987)

2.3.3 Vertical vibration at the seat

2.3.3.1 Absolute thresholds

Several studies investigated absolute thresholds for perception of vertical vibration at the seat since it is considered as the most sensitive input, in most frequencies, when whole-body vibration transmitted at the human body when seated in a vehicle. Absolute thresholds for vertical vibration at the seat determined by some studies are overlaid in Figure 2.6. McKay (1971) used a stationery footrest whereas Benson and Dilnot (1981) used a rather shorter stimuli compared with the other studies.

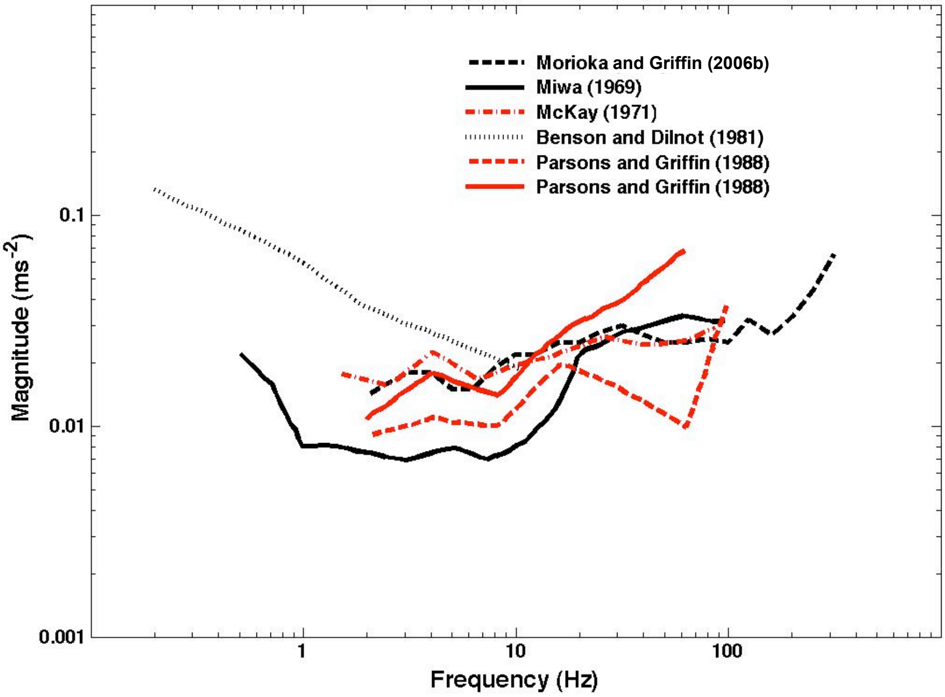

FIGURE 2.6: Vibration thresholds for vertical vibration at the seat. (Data reproduced from the figure by Griffin (1990) p.p 70 Figure 3.14 and from Morioka and Griffin (2006b)

The two studies by Parsons and Griffin (1988) used different psychophysical methods, the lower curve (in Figure 2.6) used the method of signal detection and the higher curve used the method of adjustment. The thresholds obtained by McKay (1971) present similarities with the study by Parsons and Griffin (1988), partly because the experiment was conducted in the same laboratory but using a different method. The variations in the thresholds are possibly due to the different experimental methods and the laboratory equipment but an overall trend can be proposed to describe the vertical vibration thresholds at the seat. The thresholds (expressed in terms of acceleration) at lower frequencies from 1 to 10 Hz present less variations with frequency (i.e. frequency independent) whereas the thresholds above 10 Hz increase as frequency increases (i.e. frequency dependent).

2.3.3.2 Comfort contours

Figure 2.7 presents equivalent comfort contours for vertical vibration at the seat from previous studies over the frequency range from 0.01 to 100 Hz. Most of the studies present an increase in sensitivity to vibration acceleration between 2 to 6 Hz whereas at higher frequencies (above 10 Hz) sensitivity decreased. Although there are not many studies that investigated comfort contours for lower frequencies apart from studies by Dupuis et al. (1972) and Shoenberger (1975), it is suggested by Griffin (1990) (Section 7.3.1) that the increase of sensitivity with increasing frequencies from 0.5 to 1 Hz is opposite to the increase of sensitivity in perception thresholds (as shown in Figure 2.6) due to the increased susceptibility to motion sickness at low frequencies (i.e. 0.5 to 2 Hz).

Because each study employed different experimental procedure, different psychophysical methods, different seating geometry, various footrests and backrest conditions there were some differences between the obtained contours. These differences show that the conditions of the experiment (i.e. sitting posture, seat and foot position) can influence the obtained data.

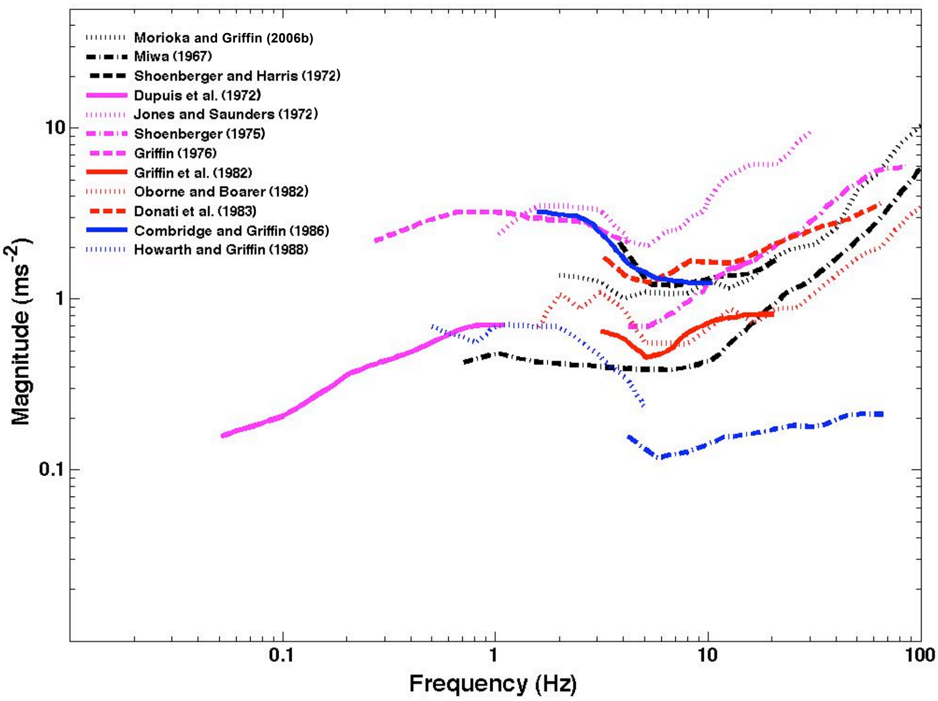

Figure 2.7: Comfort contours for vertical transmitted at the seat. (Data reproduced according to Griffin (1990) p.p 55 Figure 3.2 and Morioka and Griffin (2006b)

2.4 Factors influencing vibration perception and discomfort

Comfort in vehicles can be influenced by many factors including vibration, noise, vision, smell, consumption of food/drink, seating, privacy, e.t.c. as mentioned by Griffin (1990), (Figure 3.1). Vibration can be identified as one of the important factors influencing comfort, since 'vibration transmission' in vehicles occurs from the engine and the road/sea surface (i.e. road-wheels, tracks-wheels, sea-boat). Different magnitudes, frequencies and orientation of vibration can cause the vibration to transmit different parts of the human body, which may result in producing various scales of discomfort (i.e. Noticeable but not uncomfortable, Mildly uncomfortable, Uncomfortable, Very uncomfortable), as mentioned by Griffin (1990) (Table 3.3). In order to measure, evaluate and assess the feeling of vibration it is important to identify the factors influencing vibration discomfort.

2.4.1 Vibration frequency

The sensation of discomfort, caused by a constant velocity vibration magnitude, varies with vibration frequency. When the human body is exposed to whole body vibration, the amount of discomfort caused by low frequency vibration (i.e. 1-2Hz) would differ from those caused by vibration at high frequencies. Vehicle vibration can be perceptible from the passengers in a frequency range from 0.5 Hz to 1000 Hz as mentioned by Griffin (1990). Vibration at frequencies lower than 1 Hz is likely to yield motion sickness, which refers to different evaluation methods from vibration discomfort. Vibration discomfort due to vibration at frequencies greater than 300 Hz can be influenced by audible noise generated from the vibration source.

Earlier studies investigated the equivalent comfort contours that present the relationship between the vibration frequency and vibration magnitude. It was found by Corbridge and Griffin (1986) that as frequency increases from 0.5 to 5 Hz the acceleration magnitude of the vibration must be increased in order to produce the same discomfort. This means that at higher frequencies the human body is less sensitive to vibration acceleration than at lower frequencies. It should be taken into consideration that shapes of the comfort contours between the studies may vary due to different body postures (see Section 2.4.7) and experimental conditions employed.

2.4.2 Vibration magnitude

It is intuitively obvious that discomfort is increased with increasing magnitude of vibration up to a certain level of vibration magnitude (above that level may associate with annoyance and hazardous). The relationship between the vibration discomfort and the vibration magnitude is often expressed with Stevens power law as shown in equation (2.3). Generally in the frequency range between 8-400 Hz, in each of three axes, the frequency-dependence of comfort contours is dependent on vibration magnitude. At low magnitudes the equivalent comfort contours present similar shapes to the perception threshold. As increasing the vibration magnitudes, the equivalent comfort contours are approximated by the constant velocity. The magnitude-dependence of the equivalent comfort contours suggest that different psychological channels may be responsible for discomfort at different vibration magnitudes, which leads to the conclusion that no single frequency weighting can provide accurate predictions of subjective judgments of discomfort.

2.4.2.1 Hands

Equivalent comfort contours for hand-transmitted vibration for various magnitudes were determined by Miwa (1967a), Morioka and Griffin (2009) and Morioka and Griffin (2006b), which are presented in Figure 2.8. All the three studies show an increased discomfort with increasing vibration magnitude. The rate of growth of sensation is independent from vibration magnitude since most of the trend present to be parallel across the frequencies. The comfort contours from the three studies lead to suggest that low frequency vibration (i.e. 2 to 12.5 Hz) may present similar comfort contours in terms of magnitude dependence as well as rate of growth of sensation.

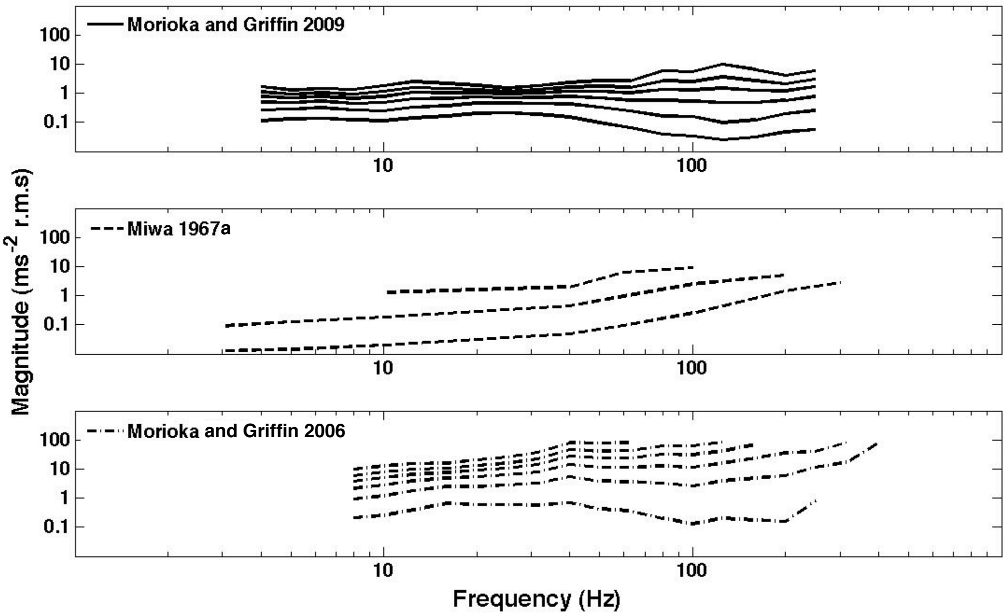

Figure 2.8: Comfort contours for vertical vibration at the hand. (Effect of vibration magnitude on equivalent comfort contours for vertical vibration at the hand determined by Miwa,1967a; Morioka and Griffin, 2006; 2009)

2.4.2.2 Feet

The effect of magnitude on discomfort caused by vibration at the foot was examined by Morioka and Griffin (2010) for each of three axes, and the equivalent comfort contours for vertical vibration at the foot are shown in Figure 2.9. The rate of growth of sensation is independent from vibration magnitude since no significance difference was found between the frequencies, all the trends are parallel in any given magnitude. Although this study helps to predict discomfort at different magnitudes between 8 and 315 Hz there is little research investigating the effect of vibration magnitude on discomfort caused by low frequency vibration (i.e. below 8 Hz) at the feet. This study aims to investigate the effect of vertical vibration magnitude on discomfort below 8 Hz, the findings can broad the knowledge of how the rate of growth of sensation depends from vertical vibration magnitude below 8 Hz. This will help to understand how the feet can interact when other vibration inputs are applied in a complex motion (i.e. the hands and the seat)

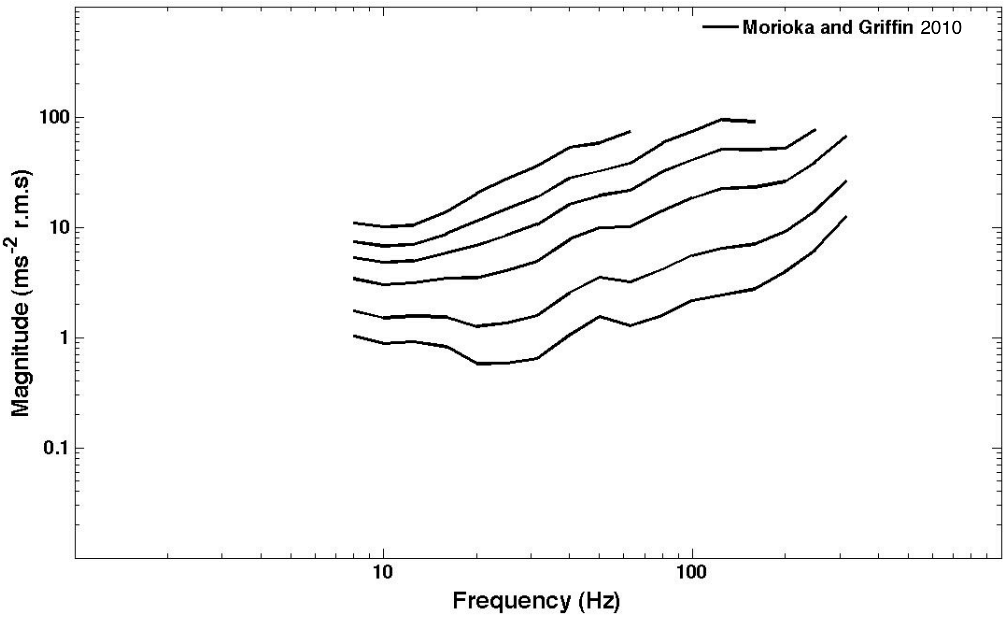

FIGURE 2.9: Equivalent comfort contours for vertical vibration at the foot relative to 5 ms^{-2} r.m.s. at 50 Hz (Data reproduced from Morioka and Griffiin (2010)

2.4.2.3 Seat

Morioka and Griffin (2006a) examined the effect of magnitude on discomfort caused by vibration at the seat for frequencies between 2 and 315 Hz in each of the three axes. The equivalent comfort contours for vertical seat vibration are shown in Figure 2.10.

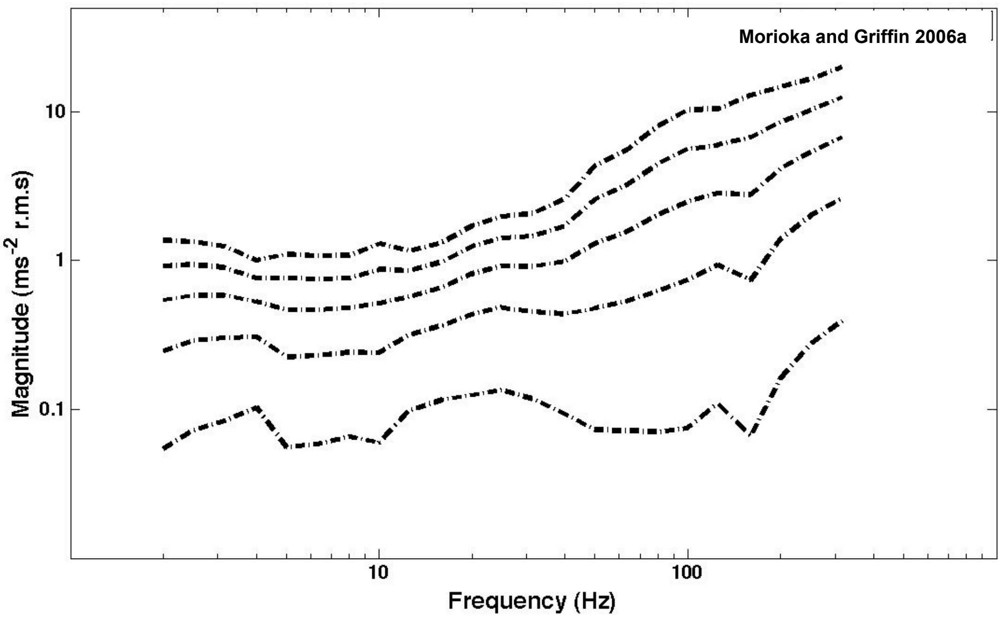

FIGURE 2.10: Equivalent comfort contours for vertical vibration at the seat relative to 0.5 ms^{-2} r.m.s. at 20 Hz. (Data reproduced from Morioka and Griffin (2006a)

2.4.3 Vibration duration

According to Griffin (1990), a study by Griffin and Whitham (1977a) and later studies by Kjellberg and Wickström (1985) as well as Kjellberg et al. (1985) concluded that the relation between discomfort and duration varies between frequencies and between subjects. It was suggested that a simple averaging method, root-mean-quad (r.m.q.), as shown in equation (2.4), was used later as the basis for the derivation of the expression of Vibration Dose Value (V.D.V) as shown in equation (2.5)

$$\alpha^4 t = constant \tag{2.4}$$

where
α is the acceleration in ms^{-2}
t is the time duration in s

$$V.D.V = [\int_{t=0}^{t=T} a^4(t)dt]^{1/4} \tag{2.5}$$

where
$V.D.V$ is the Vibration Dose Value
T is the time period of exposure in s

2.4.4 Vibration direction (axis)

Morioka and Griffin (2006a) found that when subjects are seated on a rigid surface with no backrest, absolute thresholds for the perception of whole-body vibration in each of three axes were highly dependent on vibration frequency. At frequencies greater than 10 Hz, thresholds for vertical vibration were lower than those for horizontal vibration, whereas for frequencies less than 4 Hz thresholds for vertical vibration were higher than those for horizontal vibration. Fore-and-aft and lateral vibration thresholds were similar over the frequency range investigated. It was found that the rates of growth sensation, within each of three axes of vibration, were also dependent on vibration frequency. At low frequencies of fore-and-aft and vertical vibration the greatest exponent n was obtained at the resonance frequency of the body (i.e 1.5 and 3 Hz for lateral and 5 Hz for vertical), while at high frequencies (16-315 Hz) the dependence was similar to that for hand transmitted vibration.

The general conclusion is that in the frequency range between 2-315 Hz, the equivalent comfort contours showed maximum sensitivity to acceleration between 5-10 Hz for vertical vibration, and at 2 Hz for both fore-and aft and lateral vibration. At low vibration magnitudes, the equivalent comfort contours have a similar frequency-dependence to perception thresholds. With increasing vibration magnitude, the equivalent comfort contours correspond to constant velocity in frequency range 2-315 Hz for horizontal vibration and in frequency range 16-315 Hz for vertical vibration. Morioka and Griffin (2008) found that when the hand is grasping a horizontal cylindrical handle, the greatest sensitivity (the lowest in perception threshold) to vibration acceleration was in the frequency range of 80-160 Hz in each of the three axes. For frequencies less than 50 Hz, perception thresholds are lowest for fore-and-aft vibration among the three axes, while at frequencies greater than 125 Hz thresholds for vertical vibration are lower than those for lateral vibration.

2.4.5 Body location

In various transport, drivers and passengers detect vibration which can cause discomfort at various locations of the body where vibration is transmitted from the vibrating surface (e.g. steering wheels, seats, floors). When the human body is exposed to more than one vibration input, the vibration perception threshold from multiple input vibration is assumed to be determined by the location with the lowest threshold. Morioka and Griffin (2008) compared frequency dependence of perception thresholds for vibration between the hand, the seat and the foot for each of the three axes in order to understand the mechanisms involved in the detection of vibration. With vertical axis of vibration it was found that sensitivity at the hand was the greatest at the frequency range from 100 to 160 Hz, while sensitivity at the seat decreased as the frequency increased (the frequency range of the experiment was 2 to 315 Hz). Sensitivity of the foot was less than that of the hand or the seat at frequencies greater than 125 Hz.

It was concluded that the only frequency range that all three locations have the same contribution in perception for vertical vibration is around 100Hz, at other frequencies perception at the seat was greater than those at the foot and the hand. In the study by Morioka and Griffin (2008), the area of contact and forces between the body and the source of vibration were inevitably differed between the three body locations investigated (i.e. at the hand, the seat, and the foot). Based on the knowledge of the effect of contact area and contact force on the vibrotactile perception presented by Morioka and Griffin (2008), it seems likely that variations in force or contact area between the body locations cannot solely explain the variations in perception thresholds between the body locations. It seems apparent that vibration discomfort is partially dependent on the location of the body where vibration is transmitted to, and the biodynamic responses to vibration at the hands, the feet, and the seat.

2.4.6 Biodynamic responses to vibration

2.4.6.1 Hands

Transmission of vibration at the hands can be influenced by factors such as grip forces on a handle, push force and variation of the arm angle. Reynolds et al. (1977) found that the apparent mass of the hand depends on frequency and axes of vibration. As the frequency of vibration increases from 7 to 1000 Hz the apparent mass of the hand decreases in all three axes (i.e. horizontal (x), axial (y) and vertical (z)) and for the vertical axis the apparent mass remains constant (around 0.4 kg) between 40 and 100 Hz. Altering the grip force can increase coupling between the hand and the handle resulting an increase of the impedance and the apparent mass. Variations in the arm angle can also change the impedance at the hand but the effect depends on the axis of vibration since the greater increase occurs at low frequencies.

2.4.6.2 Feet

Suggs et al. (1976) examined the apparent mass of the feet between 1 and 32 Hz. It was found that the apparent mass of the feet for vertical vibration present the maximum value of 27.2 kg at 8 Hz and as frequency increase the apparent mass decrease. The apparent mass did not differ between the two magnitudes tested (i.e. 0.1 and 0.2 g) with the maximum value at 8 Hz. This leads to the conclusion that the feet and lower legs present a linear response between 1 and 32 Hz with the resonance frequency at about 8 Hz.

2.4.6.3 Seat

Transmission of vibration to the body can be influenced by the non-linear response of the body. Fairley and Griffin (1989a) investigated the apparent mass of subjects exposed to four magnitudes of vertical vibration (i.e. 0.25, 0.5 1.0 and 2 ms^{-2}) up to 20 Hz. It was found that the resonance frequency was decreased from 6 to 4 Hz as magnitude increased, which was partly explained by the non-linear response of the body flesh (and other soft tissue) and the involuntary loss of muscle tone.

2.4.7 Posture

Sitting posture of the human body can vary due to different seat designs and operating positions in vehicles (i.e. car, boat, motorcycles). Change of seating posture is known to alter transmission of vibration to the body, which would result in altering discomfort. Some of the biodynamic studies are summarised below.

Griffin et al. (1979) demonstrated an increased head motion at frequencies above 6 Hz and decreased at lower frequencies when the subjects adopted a stiff posture, while they were sitting on the rigid seat. Kitazaki and Griffin (1997) examined the effect of posture on the resonance behaviour of the seated human body and found that when subjects changed posture from erect to slouched, the natural frequency of the entire body mode decreased, resulting in a decrease in the principal resonance frequency (i.e. 5 Hz with an erect posture). With the effect of a footrest, for seated subjects exposed to vertical vibration, on the biodynamic response, Fairley and Griffin (1989a) found that varying the height of a footrest can greatly alter the apparent mass of the person at low frequencies (below 2 Hz) and that different results are obtained when the feet are stationary as opposed to vibrating in phase with the seat.

Nawayseh and Griffin (2004) investigated the non-linear dual-axis biodynamic response to fore-and-aft whole body random vibration between 0.25 to 20 Hz. It was found that when the height of the footrest was increased the vertical forces on the seat increased at low frequency, but when a backrest was used, the vertical forces on the footrest decreased at low frequencies. The changes of the transmissibility of vibration to the body and the resonance frequency due to the change in body posture can alter the vibration sensation, resulting in increase of decrease the discomfort.

2.4.8 Complex vibration

In real cases, the human body is exposed to vibration with multiple frequencies and random vibration in multiple axes. It is therefore vital that laboratory research should simulate real conditions as best as it can.

2.4.8.1 Multiple frequency and random vibration

Fothergill and Griffin (1977) investigated the discomfort produced by multiple frequency whole-body vertical vibration and compared the results with the procedures for assessing multiple frequency motions defined in the International Standard on the evaluation of human exposure to whole-body vibration (A: Separate evaluation of the r.m.s. acceleration at more than one discrete frequencies, B: Evaluation of the r.m.s. acceleration at the centre frequency for a narrow-band vibration, C: In case of a broadband vibration the r.m.s. acceleration is to be evaluated at the centre frequency for each band). Three experiments took place; the first experiment was designed to compare the accuracy of three alternative methods of predicting the discomfort of a motion consisting of two sinusoids; the second was conducted to determine whether the two more successful prediction methods (from the first experiment) are successful with other combinations of vibration frequencies, motions containing two similar frequencies which produced noticeable beats; the third experiment investigated the accuracy of the two main prediction methods when four frequencies of vibration are presented.

The results suggested that the discomfort due to multiple frequency motions can be well expressed in terms of the equivalent sensation level of a single frequency vibration. The whole procedure for this transformation must be done by weighting the components of the complex motion according to their individual equivalent sensation level and then calculating the root mean square of the weighted components. In comparison with the 'recommended' ISO techniques for evaluating the discomfort of multiple frequency motions it can be said that the present experimental findings were more consistent for the specific investigated frequencies.

2.4.8.2 Multi-axis vibration

A study by Fairley and Griffin (1988) investigated the best procedure for predicting the discomfort caused by simultaneous vertical and fore-and -aft whole body vibration at frequencies in the range of 2.5 to 10 Hz. The study was consisted by two experiments, in the first experiment the vibration in each axis was at the same frequency and the ratio between the two axis varied, while in the second experiment the vibration in both axes was not at the same frequency. I was assumed that in order to predict the discomfort of two-axis vibration a formula of $(H^n + V^n)^{1/n}$, where H and V are the weighted values of the fore-and-aft and the vertical vibration, is the most appropriate formula. The results showed that the root-sums-of-squares (n=2) procedure was better than either the linear sum (n=1) or the worst component (n= ∞) for both experiments.

For multi-axis vibration, the proposed evaluation method includes the 'worst component method', the linear sum of the components, the sum of the second power and the sum of the tenth power of the components in each axis. Griffin and Whitham (1977b) investigated the discomfort caused by multi-axis vibration. The experiment was conducted in two parts: A and B. In part A, a vertical vibration followed by a lateral vibration of 3.15 Hz was presented and the subjects adjusted the level until they felt discomfort similar to that produced by ten dual-axis set of motions. The ten dual-axis set of motions were produced by combining five pairs of 3.15 Hz horizontal and vertical motions with two different phases.

When the motions were in phase, it resulted in an "up-right down left" translational motion, and when there was 90 degrees phase lag in one stimulus, it resulted in circular anti-clockwise motion. In part B a vertical followed by a lateral vibration of 3.15 Hz was presented again and the subjects adjusted the level until they felt discomfort similar to that produced by seven standard levels of lateral and vertical vibration (0.4, 0.52, 0.7, 1.0, 1.4, 2.1, and 2.5 ms^{-2}). It was concluded that discomfort caused by dual-axis vibration at 3.15 Hz is independent of phase difference and it also can be determined from the level of a reference motion occurring in a single axis. The method for evaluating combined vertical and lateral vibration offers an improved method for predicting the total discomfort of multi axis motions.

2.4.8.3 Vibration Phase

The relative motions between various parts of the body (i.e. seat and backrest, hands and feet, seat and hands, feet and seat) can influence the discomfort. However, there is little understanding of how differential phase between motions at pairs of inputs influence the perception and discomfort.

A study by Entrekin et al. (1976) evaluated the differential vibration of the feet and the seat as a factor affecting affecting the ride quality of seated human subjects for frequencies from 1 to 32 Hz as well as examined the dynamic characteristics of the legs and trunk of seated human subjects. It was found that for frequencies greater than 4 or 5 Hz subjects preferred to have a stationary footrest despite the fact that differential motion of the seat with respect to the stationary footrest. For frequencies below 4 Hz subjects indicated a preference for the footrest to vibrate at the same amplitude and in phase with the seat. This distinction of the differential motion preference at 4 Hz between the two inputs corresponds to the first major resonance of the whole body at 5 Hz. Due to the fact that phase motions between the feet and the seat can be distinguished up to 4 Hz, while at higher frequencies the ability to detect phase between the feet and the seat became worse, it can be concluded that vibration at the feet at frequencies lower than 4 Hz can produce greater discomfort if the two inputs (i.e. feet and seat) are not vibrate at the same phase.

Jang and Griffin (2000) and Jang and Griffin (1999) investigated the effect of phase, frequency, magnitude and posture on discomfort associated with differential vertical vibration at the seat and the feet. Jang and Griffin (1999) found that at the lower vibration magnitudes (less than about 1.0 ms^{-2} r.m.s.) at 4 Hz, an increase in phase difference increased discomfort, whereas no difference in discomfort with change of phase at magnitudes greater than 1.0 ms^{-2} r.m.s. This finding was explained by different sensations involved when detecting vibration at low magnitudes and high magnitudes judgements of low magnitudes of vibration are influenced by relative motion at the upper legs (thighs) and hips, whereas judgements of high-magnitude vibration are more affected by vibration in the torso of the body.

This was supported by the finding that the subjects were slightly more sensitive to the effect of phase with thigh contact than without thigh contact. With increasing vibration frequencies from 2.5 to 6.3 Hz, the effect of phase on the discomfort judgements decreased particularly at frequencies greater than 5 Hz, indicating that the subjects are unable to detect phase differences between the seat and the feet as the frequency increases as it was found by Jang and Griffin (2000). The rates of increase in discomfort with increasing vibration magnitude was greater with in-phase motion than those with 180 phase difference. This means that although the subjects felt the out of phase motion to be more uncomfortable, increments in the magnitude of this motion resulted in a slower rate of increase in discomfort.

Pamouktsoglou (2008) determined detection thresholds of vibration phase between vibration at the hands and the feet over the range of frequency from 2 to 12.5 Hz. It was found that vibration threshold expressed in terms of phase degree was frequency de-pendent (the threshold of phase increased with increasing vibration frequency). The findings also suggested that for frequencies greater than 10 Hz phase motions are unlikely to be detectable and influence judgement of vibration discomfort.

Dupuis et al. (1972) investigated the differential vibration of the feet and the trunk of humans in transport environments at low frequencies (i.e. 1 to 30 Hz). It was found that at high frequencies the subjects preferred motions with the stationary footrest, while the seat was vibrating. As frequency decreased, below 5 Hz, there was a preference for most of the subjects of having the footrest vibrating with the seat due to the large amount of relevant motion between the seat and the feet, if the feet were stationary. The biodynamic response was also investigated in the same study, and it was found that the whole body response was mass like at frequencies up to about 6 Hz and for frequencies higher than 6 Hz the spring and damping properties predominated. Subjects could not detect in-phase motions between 6 to 8 Hz, but they could detect phase motions of 180 degrees below 6 Hz. It was reported that the major sensation of discomfort was due to vibration of the trunk therefore any sensation from the feet could only be traceable if the foot vibration magnitude was greater than the vibration at the trunk.

2.4.8.4 Inter-subject variability

The perception and discomfort of vibration can vary between the individuals and the extent of the differences may be partly attributed to the variability in characteristics of the individuals such as body size, age and gender. Griffin and Whitham (1978a) reported that the subjective responses presented little correlation with various measures of body size, no significant correlation between the subjective responses and age. There was no statistically significant difference in the subjective responses between male and female subjects.

2.5 Conclusions

It became apparent that extensive research have been conducted to understand how the discomfort depends on vibration (e.g. the frequency, the magnitude, the direction, the duration) at the hands, the seat, and the feet and how each of these inputs contribute to produce an overall discomfort. When considering discomfort caused by multiple-input vibration, relative motions (i.e. differential motions caused by phase) between the inputs will play a significant role for influencing the discomfort. Relative motions between the seat and the feet are known to alter the discomfort of vibration at frequencies less than 5 Hz.

So factors as vibration frequency at low range, as mentioned in section 2.4.1, indicates that human are more sensitive at lower frequencies, vibration magnitude, as mentioned in section 2.4.2, where it is profound that as magnitude increases the level of discomfort increases. Also the vibration direction, see section 2.4.4 has a significant role in this study since the sensitivity at vertical vibration for low frequency vibration is greater. In terms of vibration input, see section 2.3, it became apparent that each vibration input (i.e. the hands, the feet and the seat) present individual thresholds and comfort contours, this means that this study needs to address first each input in a separate experimental (i,.e thresholds, contours) investigation where appropriate (some previous knowledge concerning the seat, see section 2.3.3 will be used) and then investigate their interaction (i.e. equivalence of sensation). Phase motions at multiple-input motions as presented in section 2.8.4.3 may be related with the alteration of discomfort levels when compared to in-phase multiple-input motions.

There is little understanding of how the phase between the motions at multiple input positions are detected by seated persons. Moreover, there is no known published research on discomfort caused by the phase between vibration at the hands and the seat and also the hands and the feet. Having completed the literature review, the following research questions are raised to increase understandings of mechanisms associated with discomfort caused by multiple-input vibration at the hands, the seat and the feet:

(i) How does the sensitivity to vibration differ between the hands, the seat and the feet?

(ii) What are the mechanisms involved in detection of phase between vibration at multiple inputs?

(iii) Does the detectable phase alter the discomfort? If so, how the discomfort is influenced by the phase differences?

Chapter 3

Objectives, Hypotheses and plan of experiments

3.1 Introduction

A series of experiments are proposed in order to examine the hypotheses identified for the research. This chapter presents an analytical approach of the adapted model, main research questions, main objectives, a summary of the hypotheses and organisation of the experiments.

3.2 Model

According to the review of literature, discomfort caused by vibration at the hands, the seat, and the feet can be evaluated based on the knowledge of human sensitivity to vibration which depends on frequency, magnitude, body location, and possibly phase between the body locations. The adapted model for this research is shown in Figure 3.1 where a complex vibration is quantified in three individual inputs: at the hands (A), the seat (B) and the feet (C).

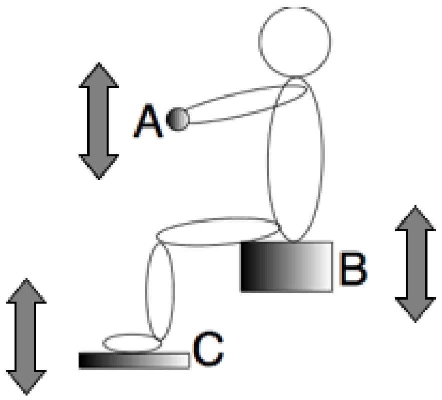

FIGURE 3.1: Schematic model of multiple-input complex motion. [A: Hands B: Seat, and C: Feet]

3.3 Common Experimental Design

In order to design a series of experiments for examining the hypotheses identified in Section 3.2.1, we must take into account and control factors (other than independent variables) which may influence the dependent variables (e.g. subjective judgement of vibration). These factors include:

a) Vibration variability (e.g. duration, prior exposure to vibration)

b) Inter-subject variability (e.g. age, gender)

c) Intra-subject variability (e.g. body posture, closing)

d) Environmental variability (e.g. noise, vision)

e) Experimental procedure (e.g. practice on subjective judgement,

familiarisation of vibration stimuli)

3.3.1 Vibration variability

3.3.1.1 Vibration duration

The duration of the vibration stimuli employed for each experiment were 2 seconds for Experiments 1 and 2 (Chapters 5 and 6) and 4 seconds for Experiments 3 and 4 (Chapters 7 and 8), ensuring the subjects receive each vibration stimulus with sufficient duration for making judgement. The 2-second stimulus was considered as the minimum duration, considering the frequency range (from 2 to 12.5 Hz) investigated in this research. The 2-second stimulus provided a minimum of full 3 cycles of waveform (excluding the taper of 0.25 ms at each end) for each stimulus. The stimulus duration of 2-4 seconds were employed in the previous research with the minimum frequency of 2 Hz as reported by Morioka and Griffin (2006b) and Morioka and Griffin (2008)

The duration of a single session for each experiment was limited up to 60 minutes, in order to minimise fatigue or loss of concentration by the subjects. A short break was provided to the subject when appropriate.

3.3.1.2 Prior exposure to vibration

Prior exposure to hand-transmitted vibration can cause an increased perception threshold of vibration, known as temporary threshold shifts (TTS) . TTS is likely to occur and increase if the prior exposure vibration and the perception threshold for vibration were excited by the same tactile channel as reported by Harada and Griffin (1991). Since it is not certain whether multiple tactile channels would be excited by the vibration stimuli employed in the present research, the order of presenting frequency or magnitude of vibration stimuli were randomised to minimise any possible TTS.

3.3.2 Inter-subject variability

3.3.2.1 Age

With whole-body vibration, judgement of vibration discomfort has little effect of age Griffin and Whitham (1978a). With hand-transmitted vibration, vibrotactile thresholds progressively increase with advancing age at high frequencies (greater than 50 Hz) mediated by Pacinian channel as reported by Verrillo (1979b). In the present research, age of the subjects who took part in Experiments 1-4 were restricted within the range between 23 and 41 years.

3.3.2.2 Body size

It is reported that sensitivity to whole-body vibration decrease with increasing body size for some conditions by Parsons et al. (1982) and Griffin et al. (1982), which may be associated with larger subjects being less transmission of vibration to the upper-body parts. With hand-transmitted vibration, the elevation of vibrotactile thresholds found from 10 to 23 years of age was suggested to be due to the increase in the hand size, causing less dense distribution of the receptors Verrillo (1977). The trends seem to fit in the fact that taller subjects have longer impulse conduction from the distal parts of the body.

3.3.2.3 Gender

With whole-body vibration, females tended to show increased sensitivity than males, but the differences were relatively small as found by Griffin and Whitham (1978b) and Griffin et al. (1982). In the similar manner, females were found to be more sensitive to vibrotactile stimuli than males as reported by Maser et al. (1997), although some studies did not find significant gender effect as reported by Verrillo (1979a). Interestingly, Maser et al. (1997) reported that the gender effect disappeared when sensoty thresholds were normalised for height, which can be explained by increased neuron length with taller subjects (males). In order to minimise the gender effect (and the possible effect of the body size) on the measured subjective responses to vibration, only male subjects were employed in the present research.

3.3.3 Intra-subject variability

3.3.3.1 Body posture

The change of sitting posture are known to alter the transmission of vibration to the body as reported by Griffin et al. (1979) and Kitazaki and Griffin (1997), (also see section 2.4.7). The presence of the footrest and backrest can also affect the transmissibility of the vibration to the body as reported by Fairley and Griffin (1989b) and by (Nawayseh and Griffin (2005). It has been reported that greater transmission of vibration to the head is associated with greater sensitivity as reported by Griffin and Whitham (1978b) and by Griffin et al. (1982). These findings lead to the conclusion that all experiments of the present research must control the body posture so as to ensure all subjects adopt the same sitting posture. In the present research, the subjects were instructed to grip the handlebars with light grip, knowing the change of the grip force can alter the subjective judgement of perceived discomfort as it was found by Reynolds et al. (1977) and Morioka and Griffin (2009).

3.3.3.2 Clothing

In the same manner, the outfit (trousers, shirts) of the subjects must not obstruct, amplify or act as a clue of vibration stimuli altering the subjective judgement. In the present research, all the subjects were instructed to roll up their trousers and wear a short-sleeve shirt, ensuring no loose clothes would come in contact with their legs and the arms during the exposure to vibration.

3.3.4 Environmental variability

3.3.4.1 Noise

The discomfort caused by whole-body vibration can be affected by the presence of noise and the discomfort caused by noise can be affected by the presence of vibration. Huang and Griffin (2012) and Huang and Griffin (2014) reported the higher levels of noise masked discomfort of lower magnitudes of vibration. In the present research, all the subjects were presented with white noise through a pair of headphones, so as to ensure all the subjects receive constant levels of noise (to mask any unwanted or unexpected noise in the laboratory) during the vibration exposure.

3.3.4.2 Vision

It is intuitive to assume that vibration can be detected by seeing the movement relative to the surrounding environment. With horizontal whole-body vibration, no statistically significant effects of vision on perception thresholds were found at frequencies from 1 to 16 Hz by Moxley et al. (2012). It is not known how the vision influence the perception caused by vertical vibration at the hands, the seat or the foot. In the present research, the subjects wore a blindfold or a pair of goggles taped around the lower edge to prevent them from seeing the moving handles or footrests.

3.3.5 Experimental procedure

Hiramatsu and Griffin (1984) emphasised the importance of providing a practice session to provide subjects an opportunity to experience the range of vibration stimuli and to familiarise how to make subjective judgement using the method of magnitude estimation. For the reason above, all the experiments always provided a practise session followed by the main test.

3.4 Objectives and Hypotheses

The main objective of this research is to investigate how perception and discomfort caused by multiple-input vertical vibration (applied simultaneously at the hands, the seat and the feet) depends on vibration frequency, vibration magnitude, input location, and phase between vibration at the three inputs, at frequencies between 2 and 12.5 Hz. In order to accomplish this, three main research questions are raised:

Q1: How the sensitivity of detecting vibration or judging discomfort differ between the hands, the seat, and the feet?

Q2: What mechanisms are involved in detecting or judging discomfort caused by vibration at the hands, seat and feet?

Q3: How the amount of discomfort caused by phases between vibration at pairs of inputs is associated with the ability of detecting the phases?

A set of four experiments were designed to seek answers to these questions Specific hypotheses (H1 to H11) are tested over the four experiments (see Figure 3.2), with justifications/rationales for each hypothesis are also provided in Section 3.4.

HYPOTHESES

H1. Perception thresholds for vibration at the hands and the feet are frequency dependent. (If they share the same tactile channels)

H2. Perception thresholds for vibration at the hands and the feet are similar.

H3. Comfort contours for vibration at the hands and the feet are frequency dependent.

H4. Comfort contours for vibration at the hands and the feet are magnitude dependent.

H5. Relative magnitudes of vibration required to produce the equivalent sensation at the hands, the feet and the seat are frequency-dependent.

H6. Relative sensation of vibration between the hands and the feet is magnitude-independent.

H7. Relative sensation of vibration between the hands and the seat is magnitude-dependent.

H8. Phase differences between vibration at pairs of inputs are undetectable at frequencies over 10 Hz.

H9. Thresholds for the detection of phase differences depend on pair of input locations (i.e. Hands, Seat, and Feet)

H10. Discomfort caused by change of phase differences of multiple-input vibration depends on the vibration magnitude

H11. Discomfort caused by change of phase differences of multiple-input vibration depends on the vibration frequency

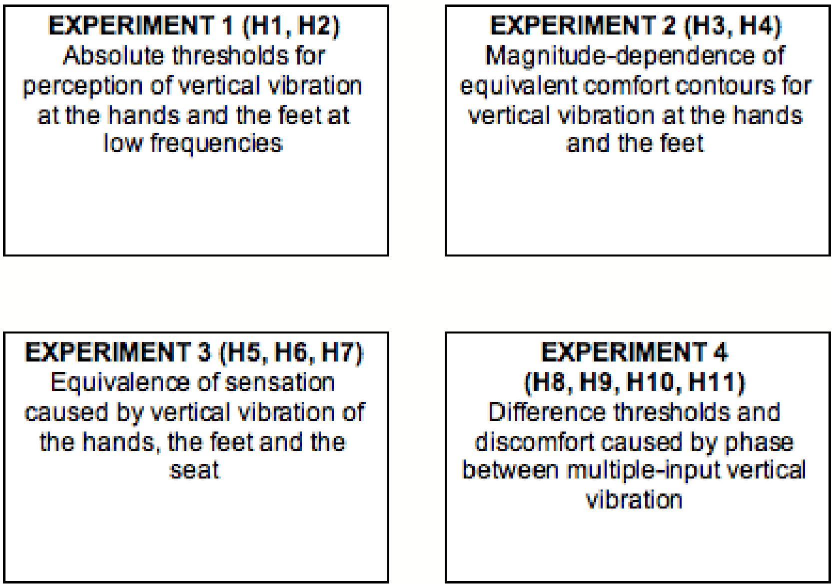

FIGURE 3.2: Description of the four experiments linked with specific hypotheses

3.5 Experiment 1 - Absolute thresholds for perception of vertical vibration at the hands and the feet at low frequencies

The objective of the first experiment is to determine perception thresholds for vertical vibration at the hands and the feet at low frequencies (i.e., 2 to 12.5 Hz). It is hypothesised that the frequency-dependence (H1) of perception vibration thresholds would be similar at the hands and the feet (H2), assuming that the same tactile channel mediates perception of vibration at the hands and the feet.

3.6 Experiment 2 - Magnitude-dependence of equivalent comfort contours for vertical vibration at the hands and the feet

The objective of the second experiment is to determine equivalent comfort contours for vertical vibration transmitted at the hands and the feet at low frequencies (2 to 12.5 Hz), so as to examine the effects of the frequency and the magnitude of vibration on the sensitivity of the hands and the feet. It is hypothesised that comfort contours at the hands and the feet are frequency dependent (H3) (the sensitivity to vibration decreases as the frequency increases) and magnitude dependent (H4) (the vibration discomfort increase as magnitude increase).

3.7 Experiment 3 - Equivalence of sensation caused by vertical vibration of the hands, the feet and the seat

The objective of the third experiment is to determine magnitudes of vertical vibration that produce similar degrees of vibration discomfort at the hands and the feet for frequencies from 2 to 12.5 Hz, at the hands and the seat, and at the feet and the seat for frequencies from 4 to 12.5 Hz. Also the effects of vibration frequency and vibration magnitude on the relative sensitivity between the hands and the feet, the hands and the seat, and the feet and the seat are examined. It is hypothesised that the equivalence of sensations at the hands the feet and the seat would be frequency-dependent (H5) due to the different shapes of equivalent comfort contours at the hands and the feet and with the ratio of acceleration at the seat to acceleration at the hands decreasing with increasing frequency of vibration, especially from 4 to 6.3 Hz. It is also hypothesised that relative sensitivity at the hands and the feet would not be magnitude-dependent (H6), since equivalent comfort contours at the hands and the feet are not magnitude-dependent over the frequency range 2 to 12.5 Hz but the relative sensitivity at the hands and the seat would be magnitude-dependent (H7), assuming the rate of growth of discomfort differs between the hands and the seat.

3.8 Experiment 4 - Difference thresholds and discomfort caused by phase between multiple-input vertical vibration

The objective of the fourth experiment is to determine the difference thresholds (just noticeable difference, JND) for the detection of phase between vertical motions at pairs of inputs (i.e. the hands and the feet, the hands and the seat, the seat and the feet) at frequencies from 2 to 12.5 Hz (i.e. hands-seat, feet-seat between 4 to 12.5 Hz, hands-feet between 2-12.5 Hz) and examine the effects of the phase motions on discomfort. The localisation (i.e. body location) at which phase differences are detected was also investigated. It was hypothesised that out-of phase motions can influence discomfort and alter the overall vibration sensation due to vibration detection from the most sensitive input. A series of hypotheses are made (H8 to H11) in order to examine and analyse in detail the steps that the experiment will be conducted.

Chapter 4

Apparatus and vibration measurement

4.1 Apparatus

The equipment set-up employed for the experiment is illustrated in Figure 4.1

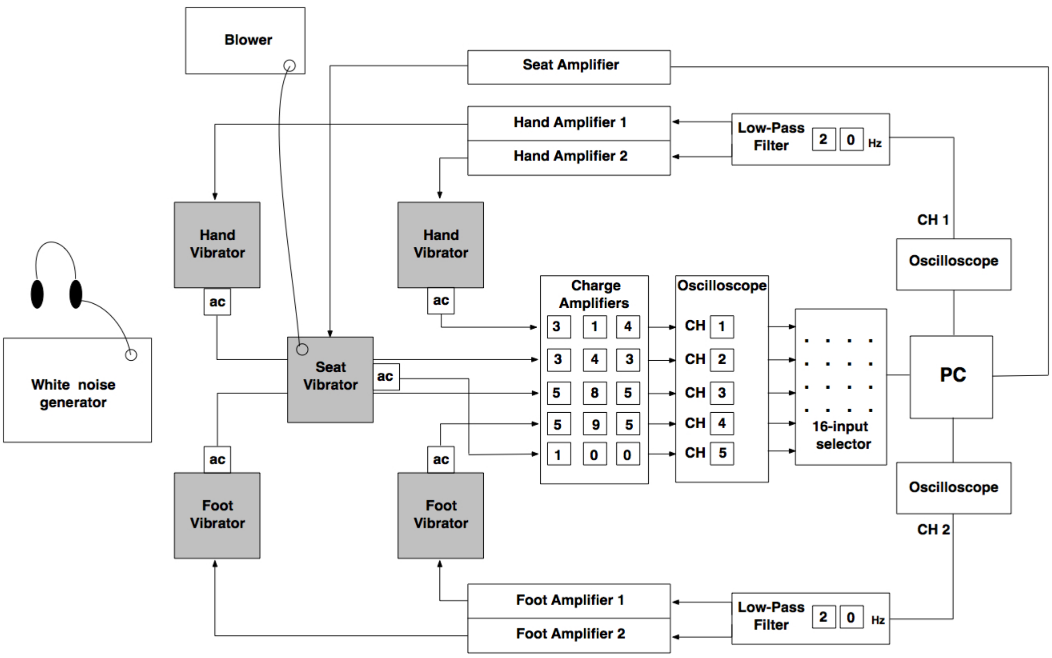

FIGURE 4.1: Equipment set-up.

The equipment used for each experiment (four in total) is shown in Table 4.1 and Table 4.2.

Table 4.1: Equipment used for each experiment

Experiment	*Channel* 1	*Channel* 2	*Amplifier No*	*Accelerometer*	*Masking Noise*
1	*R. Hand*	*L. Hand*	1 2	1 2	70 *dB*
2	*R. Foot*	*L. Foot*	3 4	3 4	70 *dB*
3	*Hands*	*Feet*	1 2 3 4	1 2 3 4	70 *dB*
4	*Hands*	*Seat*	1 2 5	1 2 5	70 *dB*
4	*Feet*	*Seat*	3 4 5	3 4 5	70 *dB*

[Note: R:Right, L:Left]

Table 4.2: Equipment employed for all four experiments

Equipment	**Brand**	**Quantity**
Vibrators	*MB Dynamics*	*Four*
Accelerometer	*DJB/ Endevco/ Bruel Kjaer*	*Four*
Noise Source Generator	*ISVR Laboratories*	*One*
Amplifier	*MB Dynamics*	*Four*
ChargeAmplifier	*Bruel Kjaer*	*Four*
Low – Pass filter	*Kemo*	*One*

4.1.1 Vibrators

Two of the vibrations systems provided vibration inputs to the rigid metallic handlebars and another two (from MB Dynamics) provided vibration inputs at the rigid wooden foot pedals. Also there was a rigid wooden seat attached on a vibrator (Derritron, VP75) in order to provide an upright sitting posture. Each of the four vibration systems comprises an electrodynamic vibrator, an external flexure, an air spring and a cooling system. Figure 4.2 presents an exterior view of the vibration system and dimensions of the handlebars (rigid cylindrical handles), the feet pedals (rigid footrests with 10-degree inclination) and the seat (rigid contoured seat 250 mm x 150 mm)

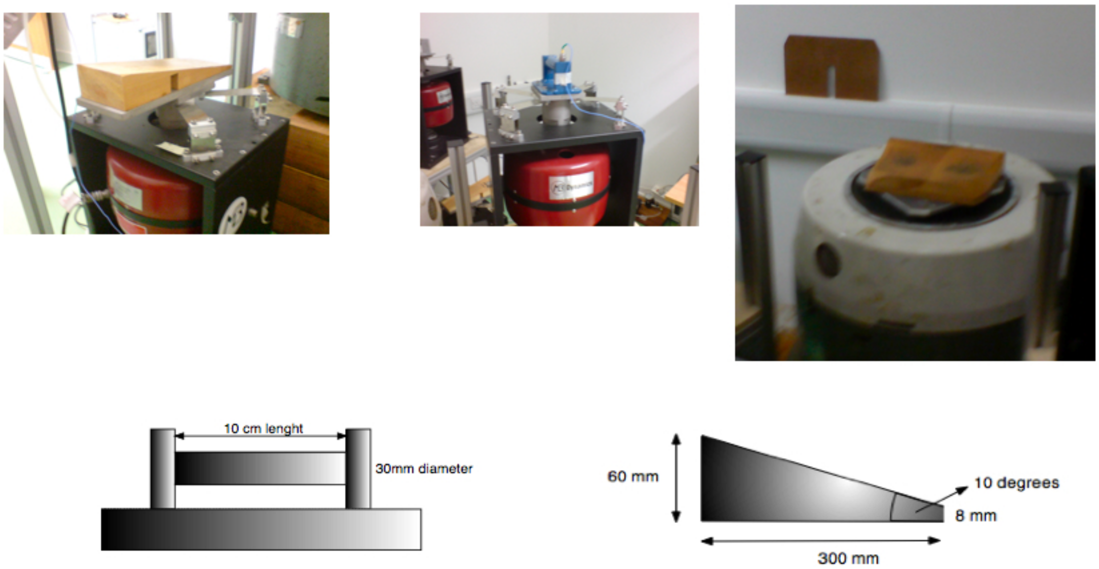

Figure 4.2: Exterior view of the MB Dynamics vibration systems.

The vibration systems are capable of supporting the static load of the hand or the foot and operate with the performance as specified in Table 4.3.

TABLE 4.3: Specifications for the handlebar and foot pedal vibration systems

Specifications	**Vibration System**
Vibration Direction	*Vertical*
Frequency Range	2 *to* 500 *Hz*
Maximum Static Load	100 *N*
Total Moving Mass	130 *N*
Max Acceleration (without static load)	118 ms^{-2} *r.m.s*
Max Acceleration (with static load)	27 ms^{-2} *r.m.s*
Maximum Displacement	10 *mm, peak − to − peak*
Maximum Force	500 *N pk* (355 *N RMS*)
Background Vibration	$<$ 0.01 ms^{-2} *r.m.s*
Acoustic Noise Level	$<$ 65 *dB(A), within* 1 *m of the package*

4.1.2 Accelerometer

The vibration stimuli were acquired using five piezoelectric accelerometers attached on the contractor surface. The types of the accelerometers used for the experiment are shown in Table 4.4.

TABLE 4.4: Accelerometer

Accelerometer	**Brand**	**Type**
1 (*R.HAND*)	*DJB*	*A20/T*
2 (*L.HAND*)	*DJB*	*A20/T*
3 (*R.FOOT*)	*Endevco*	
4 (*L.FOOT*)	*Bruel Kjaer*	2635
5 (*SEAT*)	*B&K*	4371

4.1.3 Noise generator

During all the experiments, the subjects were exposed to white noise via a pair of headphones in order to minimise any audible noise that may generated from the vibration systems and environmental noise. The white noise level was no more than 75 dB(A), which does not exceed the unusual exposure limit of 85 dB(A) for 60 minutes as defined in Table of the ISVR Technical Memorandum No 808 (1996).

4.1.4 Amplifier for the vibrator system

Five amplifiers were used, one for each vibrator system, allowing the experimenter to control the vibration magnitudes independently and to ensure that the stimuli were presented with the same acceleration values. The type of the amplifiers used for the experiment is shown in Table 4.5.

TABLE 4.5: Amplifier

Input	**Amplifier**	**Type**
$Seat$	$Derritron$	$VP75$
$Hands, Feet$	$MB\ Dynamics$	$SL500VCF$

4.1.5 Charge amplifier for the accelerometer

Five charge amplifiers were used, one for each accelerometer, in order to ensure that the output recorder signals were correct. The type of the charge amplifiers used for the experiments is shown in Table 4.6.

TABLE 4.6: Charge Amplifier

Charge Amplifier	**Type**
$Bruel\ Kjaer$	2635

4.1.6 Low-Pass filter

The generated signals passed through a low pass filter with cut-off frequency at 200 Hz . The type of the Low-Pass filter used for the experiments is shown in Table 4.7.

TABLE 4.7: Low-Pass filter

Low – Pass Filter	**Type**
$Kemo$	$VBF/8$

4.2 Vibration Measurement

4.2.1 Direction of vibration

The vibration transmitted to the hands and the feet was defined with the basicentric coordinate systems and all the experiments were performed with vibration in the vertical direction. (Vertical vibration at the hands is defined as x-axis and vertical vibration at the feet is defined as z-axis).

4.2.2 Magnitude of vibration

The vibration magnitude is expressed in terms of acceleration ms^{-2}. For the magnitude of vibration to which humans are exposed, is generally adopted the root-mean-square (r.m.s) acceleration.

4.2.3 Calibration of accelerometer

Before the experiment the vibration magnitude was calibrated using a Rion Calibration Exciter type VE-10 (Serial No: 00880928), which produce an r.m.s acceleration of 10.0 ms^{-2} at a frequency of 159.2 Hz.

4.2.4 Software

The vibration stimuli was created and acquired by HVLab Data Acquisition and Analysis Software (version 3.81) via a personal computer. All the stimuli parameters (magnitude, frequency, duration and sampling) were programmed and controlled using the software. The computer was fitted with anti-aliasing filters (TechFilter) and the signals were digitised by analogue to digital converter (PCL-818) at a fixed sample rate.

Chapter 5

Absolute thresholds for perception of vertical vibration at the hands and the feet at low frequencies

5.1 Introduction

Discomfort caused by multiple-input vibration can influence ride quality in many transport environments. When vibration is transmitted to the human body at more than one vibration input (e.g., the hands, the seat and the feet), a person is likely to experience the vibration at a body location where the perception threshold is the lowest. Knowledge of relative differences in the thresholds of perception for vibration between the body locations will assist the identification of sources of disturbance or discomfort caused by vibration.

A study by Morioka and Griffin (2008) determined perception thresholds for vibration at the hand, the foot and the seat in each of the three axes over the frequency range from 8 to 12.5 Hz at the hand and foot and from 2 to 315 Hz at the seat; the study allowed comparison of the perception thresholds between different input locations without being influenced by the use of different psychophysical methods or other methodological factors. At frequencies less than 10 Hz, there are no known studies of perception thresholds at the feet and only by Morioka and Griffin (2008) that have investigated perception thresholds for hand-transmitted vibration. The detection of vibrotactile stimuli at the fingertip for frequencies below 10 Hz involves the NP I

(FA I) and NP III (SA I) tactile channels as it was found by Bolanowski et al. (1988) . As suggested by Kekoni et al. (1989), the mechanoreceptor mechanisms involved in the detection of 20-Hz vibration on the sole of the foot are similar to those on the palm of the hand, but there are no known studies at frequencies less than 20 Hz.

5.2 Objective

The objective of this study was to determine perception thresholds for vertical vibration at the hands and the feet at low frequencies (i.e., 2 to 12.5 Hz). It was hypothesised that the frequency-dependence of perception vibration thresholds would be similar at the hands and the feet, assuming that the same tactile channel mediates perception of vibration at the hands and the feet.

5.3 Method

5.3.1 Subjects

Twelve healthy male subjects with a mean age of 25.7 years old (standard deviation, SD=4.3), mean height of 179 cm (SD=8.2) and mean weight of 75.8 kg (SD=6.8), participated in the experiment. All subjects had not experienced any severe exposure to vibration. A series of anthropometric measurements (e.g., sitting height, hand length, foot length, etc.) were obtained to investigate any association with absolute thresholds for the perception of vibration.

5.3.2 Apparatus

The equipment set-up employed for the experiment is shown in Figure 5.1. The subjects sat on a contoured rigid wooden seat mounted on an electrodynamic vibrator (Derritron VP85) that did not vibrate. The subjects were exposed to vertical vibration at both hands via two rigid cylindrical handles or at both feet via two rigid wooden footrests, with each interface rigidly mounted to a vibration system (MB Dynamics). The two vibration systems (at both hands and both feet) produced in-phase sinusoidal vibration. Each of the four vibration systems comprised an electrodynamic vibrator, an external xure, an air spring and a cooling system. The background vibration due to electrical noise at 50 Hz was less than 0.006 ms^{-2} r.m.s and was not perceptible via the handles or the footrests. The direction of vibration presented to the hands and the feet was defined by basicentric co-ordinate systems (x-axis for vertical vibration at the hands, z-axis for vertical vibration at the feet). The vibration stimuli were created and acquired by HVLab Data Acquisition and Analysis Software (version 3.81) via a personal computer. The computer was fitted with anti-aliasing filters (TechFilter) and the signals were digitised by analogue-to-digital converter (PCL-818) at a fixed sample rate of 4000 Hz.

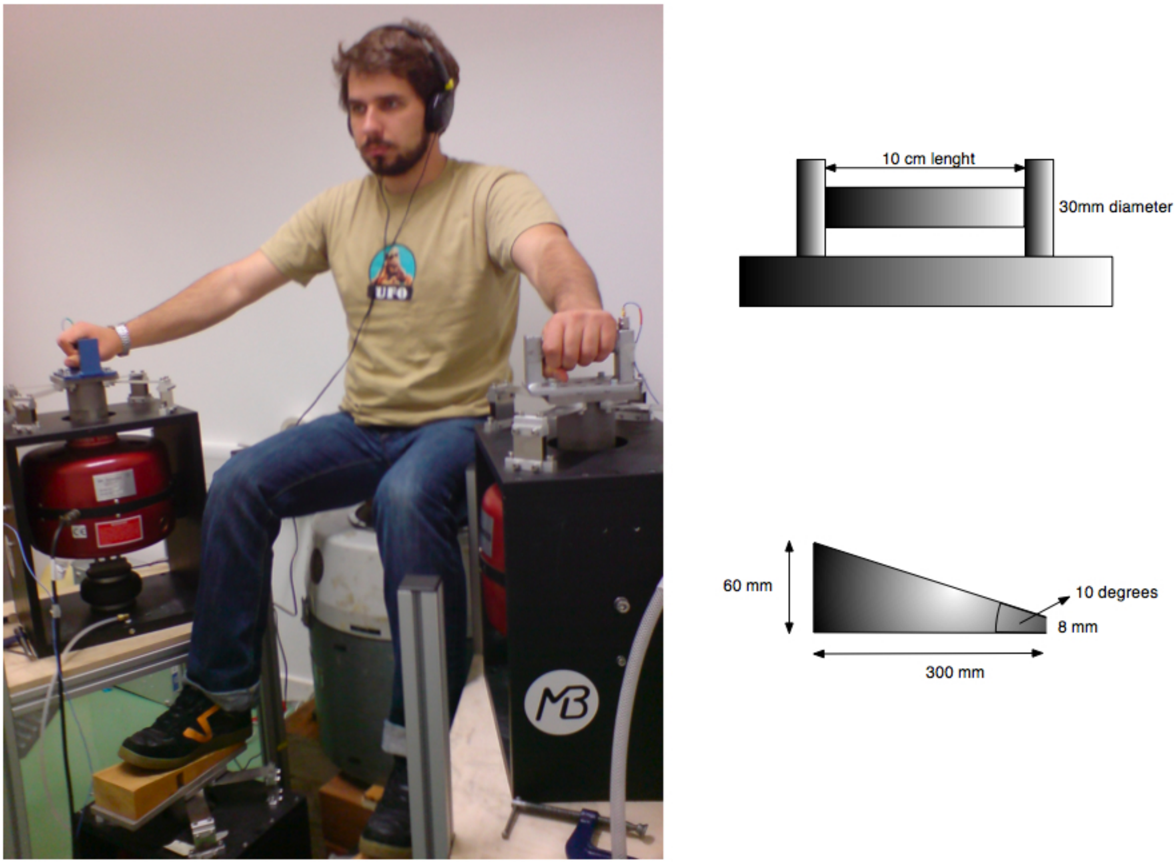

FIGURE 5.1: Set-up of the rig: independent vibration inputs to the hands and the feet

5.3.3 Procedure

Absolute thresholds for the perception of vertical vibration at the hands and at the feet were determined over the frequency range from 2 to 12.5 Hz using a staircase method with a two-alternative forced-choice (2AFC) procedure in conjunction with a three-down one-up rule; the test conditions are described in Table 5.1. A set of two periods (one of which contained a vibration stimulus) were presented either at the hands (Condition A) or at the feet (Condition B). Each period lasted two seconds (accompanied by an illuminating light) with the vibration having cosine-tapered ends over 250 ms.

The order of presenting the two periods was randomised (see Figure 5.2). After each pair of periods, the subjects were asked to indicate in which of the two periods they felt vibration by saying first or second. The magnitude of the stimulus was decreased by 2 dB after three consecutive correct responses. The magnitude of the stimulus was increased by 2 dB after every incorrect response. A threshold was calculated by taking the mean of the last four reversals (two peaks and two troughs) omitting the first two reversals. The threshold measurements only proceeded if the skin temperature of the hands and the feet was greater than 29^oC.

TABLE 5.1: Test conditions employed in the experiment

	Condition A	**Condition B**
Location	*Hands*	*Feet*
Frequency (Hz)	2, 2.5, 3.15, 4, 5, 6.3, 8, 10 and 12.5	
$Magnitude\ rangems^{-2}$	approx. 0.006-0.5 (in 2 dB step)	
Stimulus duration	2 seconds (250 ms cosine taper)	
Psychophysical method	Staircase method (2IFC procedure, 3-down 1-up rule	

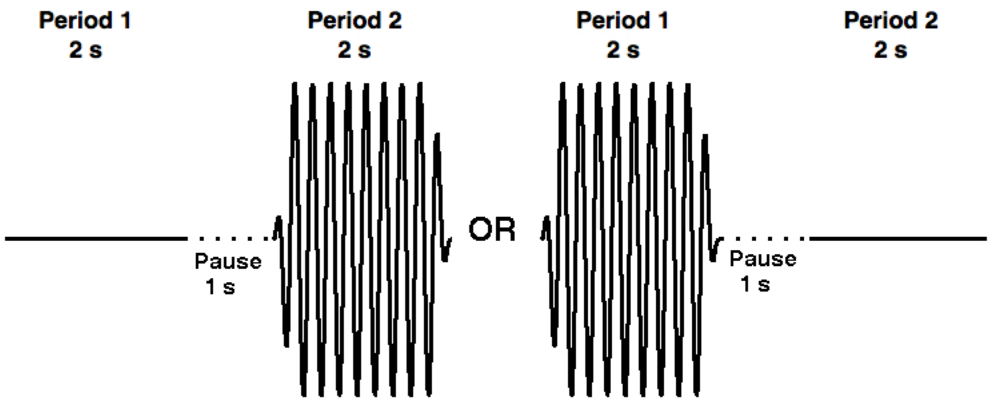

FIGURE 5.2: Stimuli presentation of each trial (left: Period 2 contains a vibration stimulus; right :Period 1 contains a vibration stimulus).

5.4 Results

The median absolute thresholds for perception of vertical vibration at the hands and the feet, and the inter-quartile range (25th-75th percentiles), for the 12 subjects are presented as a function of frequency in Figure 5.3. The acceleration thresholds at the hands and the feet were both dependent on vibration frequency (Friedman, $p<0.001$). With vibration at the hands, the perception thresholds increased significantly with increasing frequency from 2 to 4 Hz (Wilcoxon, $p<0.05$), except between 2.5 and 3.15 Hz. There was no significant difference in the thresholds for all combinations of paired frequencies between 4 and 6.3 Hz ($p>0.126$). From 6.3 to 12.5 Hz, the thresholds increased significantly with increasing vibration frequency (Wilcoxon, $p<0.05$), except between 8 and 10 Hz. With vibration at the feet, the thresholds increased significantly with increasing frequency from 2 to 5 Hz (Wilcoxon, $p<0.05$), except between 3.15 and 4 Hz and between 4 and 5 Hz. At frequencies greater than 5 Hz, there was no significant change in thresholds, except between 5 Hz and 8, 10 and 12 Hz, where the 5 Hz thresholds were significantly greater than the thresholds at 8, 10 and 12 Hz.

A comparison of the median absolute thresholds between the hands and the feet is shown in Figure 5.3. Thresholds at the feet were significantly lower than those at the hands for frequencies less than 5 Hz and at frequencies greater than 6.3 Hz (Wilcoxon, $p<0.05$). As it can be seen in Figure 5.3 (top), although the thresholds increased with increasing frequency when expressed in terms of their acceleration, the absolute thresholds had similar velocities at frequencies from 2 to 5 Hz. There were no systematic correlations between the absolute thresholds at the hands or at the feet and the characteristics of the subjects (i.e., age, height, shoe size, or weight).

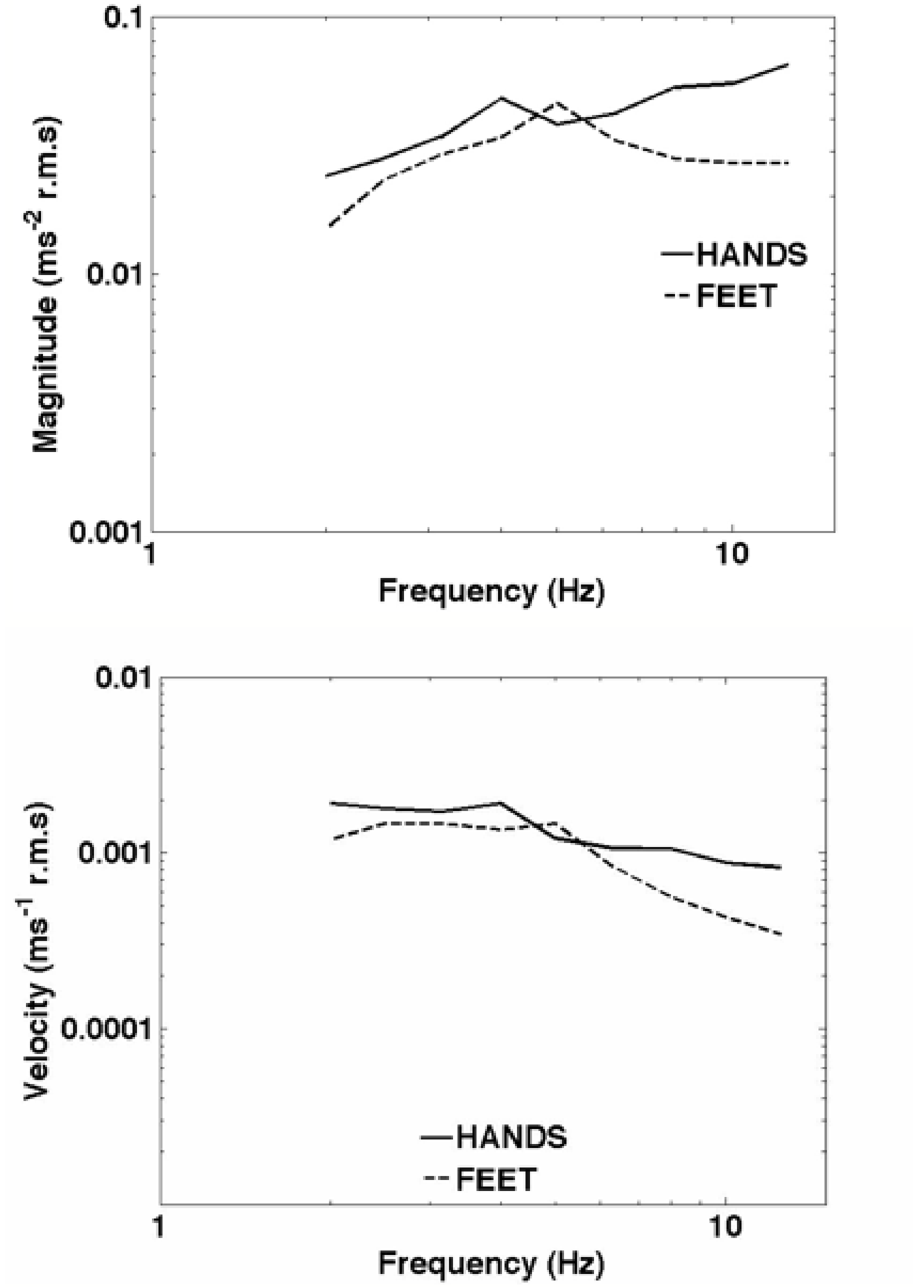

FIGURE 5.3: Comparison of median absolute thresholds between the hands and the feet expressed in terms of acceleration (top) and in terms of velocity (bottom).

5.5 Discussion

The absolute thresholds for the perception of low frequency (2 to 12.5 Hz) vertical acceleration at the hands and the feet were frequency-dependent. At frequencies between 2 and 4 Hz, the acceleration thresholds for both the hands and the feet increased significantly with increasing frequency, so that they had similar velocity over this frequency range (see Figure 5.4). This implies that the hands and the feet detect vibration velocity at frequencies less than about 5 Hz. At frequencies greater than 5 Hz (up to 12 Hz), the frequency-dependence of the perception thresholds differed between the hands and the feet, with the acceleration thresholds at the hands increasing significantly with increasing frequency while the thresholds of the feet did not significantly change over this frequency range.

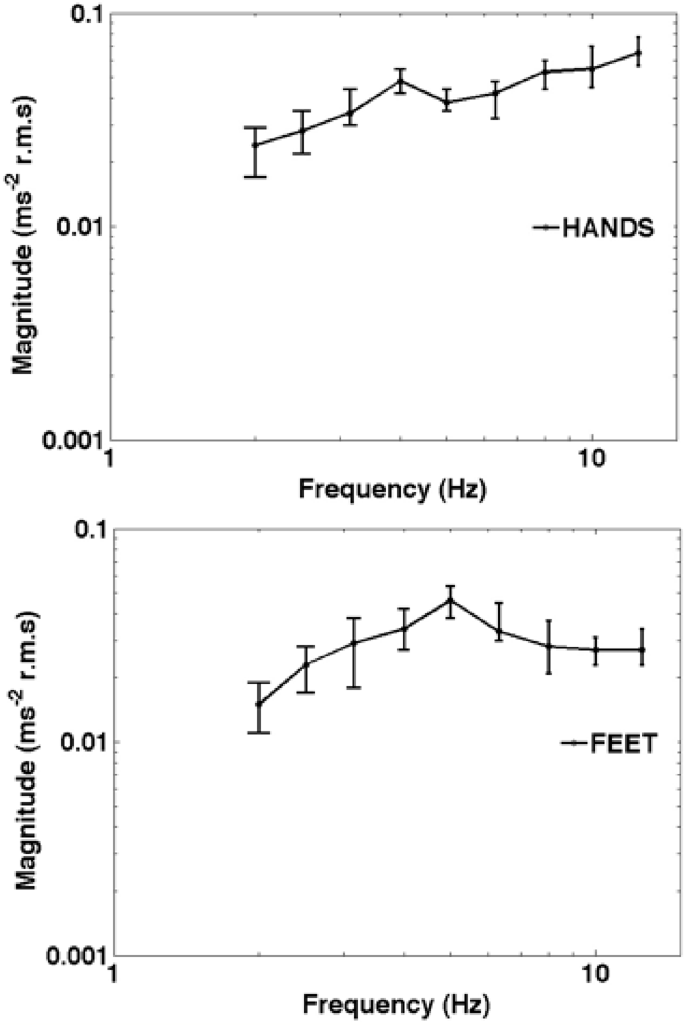

FIGURE 5.4: Median absolute thresholds for vertical vibration acceleration at the hands (top) and the feet (bottom).

This suggests that at frequencies between 6.3 and 12 Hz thresholds at the hands and the feet may be mediated by different tactile channels or different sensory mechanisms, although no related literature is available to support this speculation. It can be seen in Figure 5.5 that the perception thresholds at the hands and at the feet in this study were lower than those determined by Morioka and Griffin (2008). The differences in thresholds between the two studies may be due to the use of different psychophysical methods and experimental conditions. The present study employed a staircase method with a two-alternative forced-choice (2AFC) procedure while Morioka and Griffin (2008) employed a staircase method with a yes-no procedure. The effect of psychophysical method on vibrotactile thresholds at the fingertip was examined by Morioka and Griffin (2002) who found that the yes-no procedure elevated the thresholds by about 2.2 dB (29%) relative to the forced-choice procedure.

The results were explained by a criterion difference between the two procedures; with a yes-no procedure, subjects may not provide a positive response until detecting vibration with sufficient stimulus intensity, whereas with the forced-choice procedure, subjects may tend to give a correct answer after detecting a faint stimulus. In addition, the size of the increment in vibration magnitude differed between the two studies (2 dB step in the present study, 3 dB step by Morioka and Griffin (2008), but the use of a different increment is unlikely to influence the thresholds other than their variability, according to a study by Maeda and Griffin (1995).

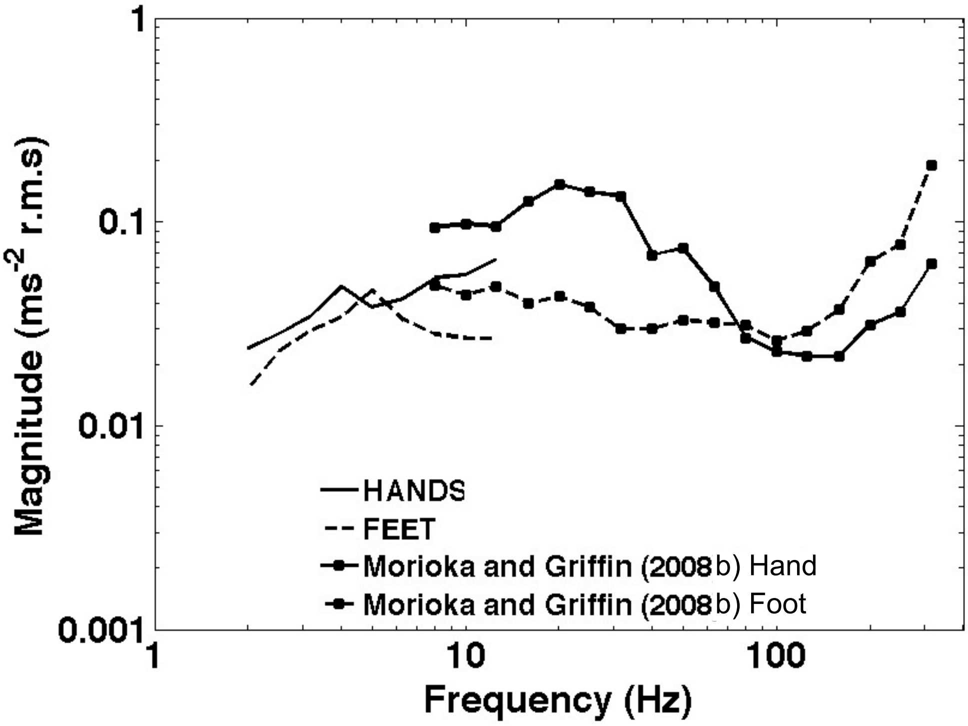

FIGURE 5.5: Median absolute thresholds at the hands and the feet for vertical vibration compared with the absolute thresholds obtained by Morioka and Griffin (2008b)

5.6 Conclusions

Absolute thresholds for the perception of vertical vibration at the hands and the feet at low frequencies (i.e., 2 to 12.5 Hz) are frequency-dependent when expressed in terms of acceleration. The thresholds for the hands and the feet at frequencies between 2 and 5 Hz are independent of frequency when expressed in terms of velocity. At frequencies greater than 5 Hz, the differences in the frequency-dependence of the thresholds at the hands and the feet suggest that different tactile channels may be involved in the detection of vibration at the hands and the feet. Differences between the absolute thresholds determined in the present study and previously determined by Morioka and Griffin (2008) may be explained by the use of different psychophysical methods (i.e., yes-no procedure and forced-choice procedure) and whether one hand (or one foot) or both hands (or both feet) are exposed to vibration.

Chapter 6

Magnitude-dependence of equivalent comfort contours for vertical vibration at the hands and the feet

6.1 Introduction

Absolute thresholds for the perception of vertical vibration of the hands and the feet at low frequencies (e.g. 2 to 12.5 Hz) tend to show increasing acceleration thresholds with increasing frequency, so that thresholds have approximately the same velocity over this range Pamouktsoglou (2008). It may be expected that sensitivity to supra-threshold vertical hands and feet transmitted vibration over the range 2 to 12.5 Hz may display a similar frequency-dependence. Increasing the magnitude of vibration increases the sensations caused by vibration, with the rate at which the strength of sensation increases with increasing frequency of vibration, leading to a magnitude-dependence in the equivalent comfort contours Morioka and Griffin (2006b) and Morioka and Griffin (2010) . However, the rate of growth of sensations caused by vibration transmitted at the hands and the feet has been little investigated at low frequencies (i.e. less than 12.5 Hz)

6.2 Objective

The objective of this experiment was to determine equivalent comfort contours for vertical vibration transmitted at the hands and the feet at low frequencies (2 to 12.5 Hz) and examine the effects of the frequency and the magnitude of vibration on the sensitivity of the hands and the feet. Also the localisation of sensation, on which part of the body the vibration is detected, was investigated.

6.3 Hypothesis

Taking into account the findings from previous studies on comfort contours at the hands by Miwa (1967a), Morioka and Griffin (2008), Morioka and Griffin (2009) and as well at the feet by Griffin and Whitham (1982) , Morioka and Griffin (2010) and Miwa (1987), it was hypothesised that comfort contours at the hands and the feet are frequency dependent (vibration sensitivity decrease as frequency increase) and magnitude dependent (the vibration discomfort increase as magnitude of vibration increase). It was also hypothesised, due to lower thresholds at the feet compared to the hands at high frequencies (i.e. 6.3 to 12.5 Hz) as found in Experiment 1, that the feet will present greater sensitivity (lower comfort contours) compared to the hands at higher frequencies and similar sensitivity at low frequencies (i.e. 2 to 5 Hz). The effect of vibration magnitude on the body location of discomfort was examined, expecting the vibration to be perceived at the body other than the body parts in contact with the vibration surface (i.e. hands, feet).

6.4 Method

6.4.1 Subjects

Twelve healthy male subjects with a mean age of 27.3 years old (standard deviation, SD=5.8), mean height 176 cm (SD=10.4), and mean weight 74 kg (SD=18.0) participated in the experiment. None of them had experienced any severe exposure to hands and feet transmitted vibration. A series of anthropometric measurements (sitting height, hand length, foot length, etc.) were obtained to investigate any association with the derived comfort contours.

6.4.2 Apparatus

The subjects sat on a contoured rigid wooden seat mounted on an electrodynamic vibrator (Derritron VP85) that did not vibrate. The subjects were exposed to vertical vibration at both hands via two rigid cylindrical handles or at both feet via two rigid wooden footrests, with each interface rigidly mounted to a vibration system (MB Dynamics). The two vibration systems (at both hands or both feet) produced in-phase sinusoidal vibration. Each of the four vibration systems comprised an electrodynamic vibrator, an external flexure, an air spring and a cooling system.

The background vibration due to electrical noise at 50 Hz was less than 0.006 ms^{-2} r.m.s and was not perceptible via the handles or the footrests. The direction of vibration presented to the hands and the feet was defined by basicentric co-ordinate systems (x-axis for vertical vibration at the hands, z-axis for vertical vibration at the feet). The vibration stimuli were created and acquired by HV Lab Data Acquisition and Analysis Software (version 3.81) via a personal computer. The computer was fitted with anti-aliasing filters (TechFilter) and the signals were digitised by analogue-to-digital converter (PCL-818) at a fixed sample rate of 4000 Hz.

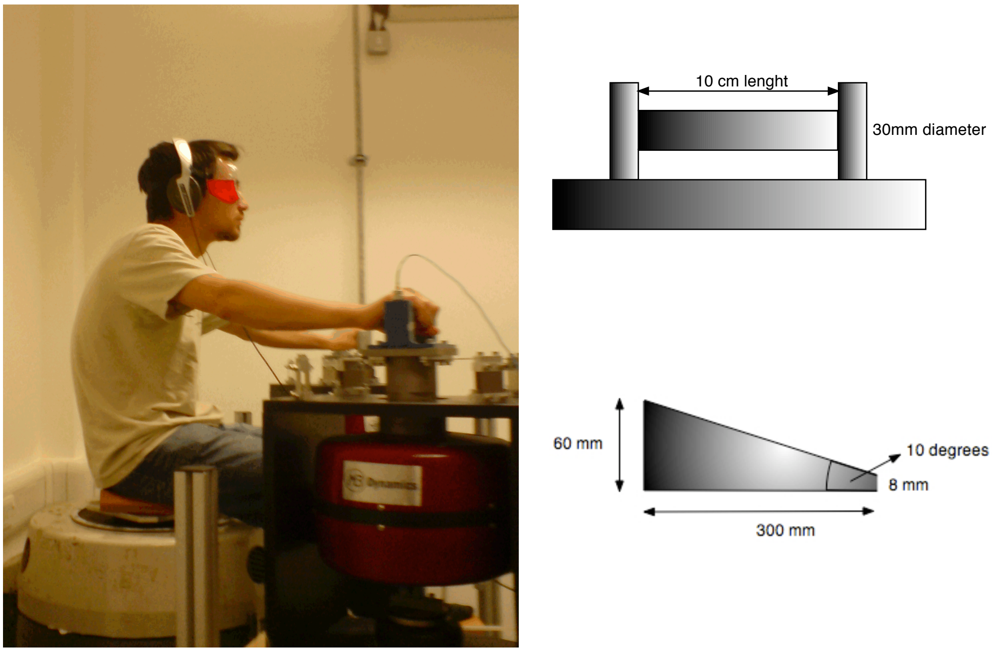

FIGURE 6.1: Arrangement of the rig: vibration stimuli were presented at the hands and the feet

6.5 Procedure

6.5.1 Study 1-Equivalent comfort contours

Equivalent comfort contours for vertical vibration at the hands and the feet were determined over the frequency from 2 to 12.5 Hz using the method of magnitude estimation; the test conditions are summarised in Table 6.1. During the experiment, subjects were presented with pairs of vibration stimuli, a reference vibration (always at the hands) and a test vibration (at the hands or at the feet), with 1-second pause between the two stimuli. Each stimulus lasted 2 seconds with the vibration having 250-ms cosine-tapered ends. The task of the subjects was to assign a number that represented the discomfort of the test vibration relative to the discomfort of the reference vibration, assuming the discomfort caused by the reference vibration corresponded to 100, as shown in Figure 6.2. The 5-Hz sinusoidal reference vibration had a fixed magnitude of 0.56 ms^{-2} r.m.s. The test stimuli were presented in random order from a range of frequencies (2 to 12.5 Hz) and magnitudes (approximately 0.04 to 3.16 ms^{-2} r.m.s) (see Table 6.1). The subjects could ask for a pair of stimuli to be repeated if they were unsure of their judgment. The subjects were instructed to indicate no sensation if the test vibration was not perceived.

TABLE 6.1: Test conditions employed in Study 1

$Location\ ofreference\ stimuli$	$Hands$
$Location\ of\ test\ stimuli$	$Hands\ (session\ 1)\ or\ Feet\ (session\ 2$
$Reference\ frequency$	$5\ Hz$
$Reference\ magnitude$	0.56 ms^{-2} r.m.s.
$Test\ frequency$	2 2.5 3.15 4 5 6.3 8 10 12.5 Hz
$Magnitude\ range$	*Approx* 0.04 *to* 3.16 ms^{-2} r.m.s. *in 3dB steps*
$Stimulus\ duration$	2 *seconds* (250 *ms cosine taper end*
$Psychophysical\ method$	$Magnitude\ estimation$

Prior to the tests, the subjects practiced in a magnitude estimation practice by judging the lengths of lines drawn on paper and then by judging a few selected vibration stimuli. This provided an opportunity for the subjects to familiarise themselves with the procedure and the vibration stimuli. During the tests, subjects were exposed to white noise at approximately 70 dB(A) via a pair of headphones to prevent them from hearing the vibration, although none of the stimuli presented audible noise. The subjects wore a pair of goggles (without glasses) with the frames covered with coloured vinyl tape to prevent them from seeing the motions of their hands. The subjects were instructed to look straight ahead during the tests. They were instructed to grasp the handles with a force they felt most comfortable.

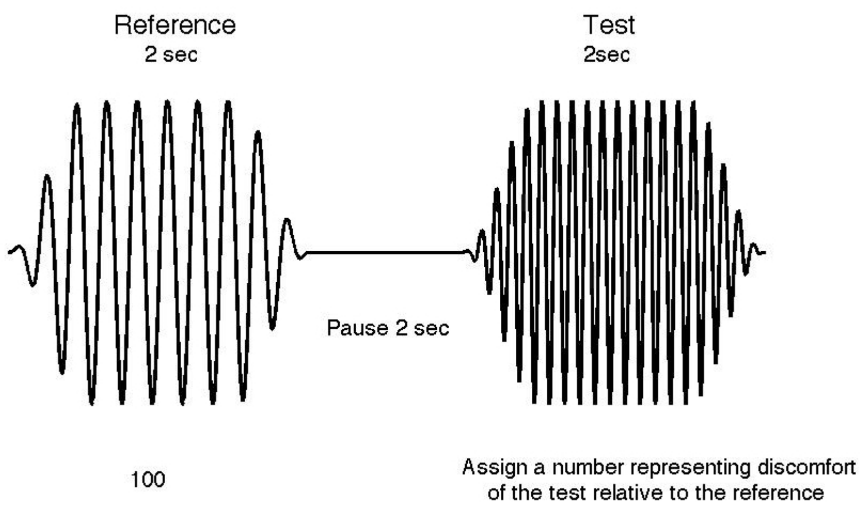

Figure 6.2: Schematic representation of stimuli for each trial. The reference stimulus was presented at the hands and the test stimuli were presented either at the hands or the feet.

6.5.2 Study 2-Localisation of sensation

The subjects were presented with a series of 2-second motions varying frequency and magnitude of vibration at the hands or the feet depending on the session. After each motion they were asked to indicate in which part of the body they detected the vibration by replying with a number referring to the bodymap (see Figure 6.3). They were instructed to indicate with only one number that reflected the body location that dominated vibration sensation. If they were unsure, they could have the stimuli to be repeated by saying "REPEAT". If they felt the vibration in more than one part of the body, they could indicate only one more additional number

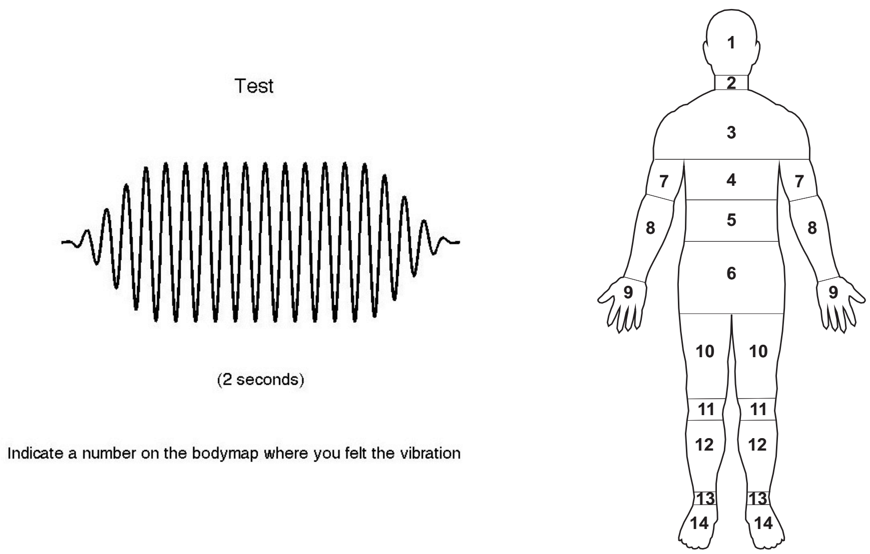

FIGURE 6.3: Schematic representation of stimuli fo Study 2 and bodymap presentation

TABLE 6.2: Test conditions employed in Study 2

Location of test stimuli	*Hands* (*session* 1) *or Feet* (*session* 2)
Test frequency	2 2.5 3.15 4 5 6.3 8 10 12.5 *Hz*
Test magnitude	*Low Medium High*
Stimulus duration	2 *seconds* (250 *ms cosine taper end*)
Method	*Assign a number on the provided bodymap*

6.6 Analysis

6.6.1 Study 1-Equivalent comfort contours

The relationship between sensation magnitude, ψ, and vibration magnitude, ϕ, for each frequency of the experiment was determined using Stevens Power law with an additive constant, as in Eq. (6.1):

$$\psi = k * (\phi - \phi_o)^n \tag{6.1}$$

where
ψ is the sensation magnitude of the stimulus
k is a constant depending on the units employed
ϕ is the vibration magnitude of the stimulus
ϕ_o is the absolute threshold magnitude at the frequency of the stimulus
n is a constant that determines the rate of growth in sensation at each stimulus frequency

The absolute threshold, ϕ_o, was taken from the median perception threshold for the appropriate frequency as determined by Pamouktsoglou (2008). The rate of growth of sensation was determined by linear regression at each frequency for each subject after transforming Eq. (6.1) to:

$$log_{10}\psi = n * log_{10}(\phi - \phi_o) + log_{10} * k \tag{6.2}$$

Equivalent comfort contours were determined by calculating the vibration acceleration, ϕ, corresponding to sensation magnitudes of 50, 100, 200, and 300 (where 100 is equivalent to 0.56 ms^{-2} r.m.s. at 5 Hz) for each subject and each vibration frequency. Statistical analysis was performed on the experimental data using non-parametric statistical tests. The Friedman two-way analysis of variance and the Wilcoxon matched-pairs signed ranks tests were applied to examine the effect of frequency on the rate of growth of sensation (i.e. the exponent n) and each of the four levels of equivalent comfort contours (i.e. 50, 100, 200 and 300%) expressed in terms of vibration acceleration and in terms of vibration velocity. Statistical results from the Wilcoxon tests were not adjusted for multiple-comparisons; the significance criterion for testing two samples was set at p=0.05.

6.6.2 Study 2-Localisation of sensation

The experimental data were obtained as nominal numbers (referring to the bodymap shown in Figure 6.3) corresponding to the body locations of vibration sensation. In order to test the hypotheses with an appropriate statistical test, the data were transformed into binary (dichotomous) numbers as shown in Table 6.3. The body locations were categorised into two groups (i.e. 1 an 0), the body location with direct contact (i.e. the hands or the feet, depending on the session) and the rest of the body locations with no direct contact with the vibration source. With the transformed data, two statistical tests, Cochran Q test and McNemar test, were applied in order to examine the effect of frequency and the effect of magnitude on localisation of vibration sensation for vibration transmitted at the hands and the feet.

Table 6.3: Binary transformation of the data from Study 2.

Location			
Hands		Feet	
Direct contact	Indirect contact	Direct contact	Indirect contact
9	1, 2, 3, 4, 5, 6, 7, 8 10, 11, 12, 13, 14	14	1, 2, 3, 4, 5, 6, 7, 8 9, 10, 11, 12, 13

6.7 Results

6.7.1 Rate of growth of discomfort

The median exponents, n, and the constants, k, over the 12 subjects for each of the nine frequencies (2 to 12.5 Hz) are shown in Table 6.4. The median exponents varied from 0.580 to 0.875, but there were no significant differences in the exponent values over the nine frequencies investigated (Friedman, p=0.387 for the hands, p=0.297 for the feet). There were no systematic correlations between the rate of growth of discomfort at the hands or the feet derived from the subjective magnitudes provided by the subjects and the subject characteristics (i.e., age, height, shoe size, or weight) (Spearman, p>0.05).

Table 6.4: Values of the median exponents, n and constant k determined from the sensation magnitude of the 12 subjects.

Frequency	Hands		Feet	
	n	k	n	k
2	0.644	272	0.519	315
2.5	0.844	257	0.510	232
3.15	0.763	219	0.680	217
4	0.875	155	0.827	159
5	0.840	132	0.706	148
6.3	0.756	112	0.639	153
8	0.791	119	0.456	157
10	0.580	130	0.604	185
12.5	0.787	108	0.816	190

6.7.2 Equivalent comfort contours for vertical vibration transmitted at the hands

Median equivalent comfort contours for vertical vibration of the hands over the range 2 to 12.5 Hz are presented in terms of acceleration in Figure 6.4. The derived equivalent comfort contours show that sensitivity to hand-transmitted vibration depends on the frequency of vibration, but that the frequency-dependence of the equivalent comfort contours is more or less independent of the magnitude of vibration (i.e. similarly shaped equivalent comfort contours at all sensation magnitudes). When expressed in terms of vibration acceleration, sensitivity differed significantly between the nine frequencies (from 2 to 12.5 Hz) at each of the four sensation magnitudes (i.e. 50, 100, 200, and 300) (p<0.001; Friedman). The acceleration comfort contours show a general trend of decreased sensitivity (i.e. increasing acceleration of comfort contours) with increasing frequency from 2 to 5 Hz, most of the pairs of adjacent frequencies presented significant differences in the acceleration contours for any of the four sensation magnitudes (Wilcoxon, p<0.05). For frequencies greater than 5 Hz, most of the pairs of adjacent frequencies presented no significant differences in the acceleration contours for any of the four sensation magnitudes (Wilcoxon, p>0.05).

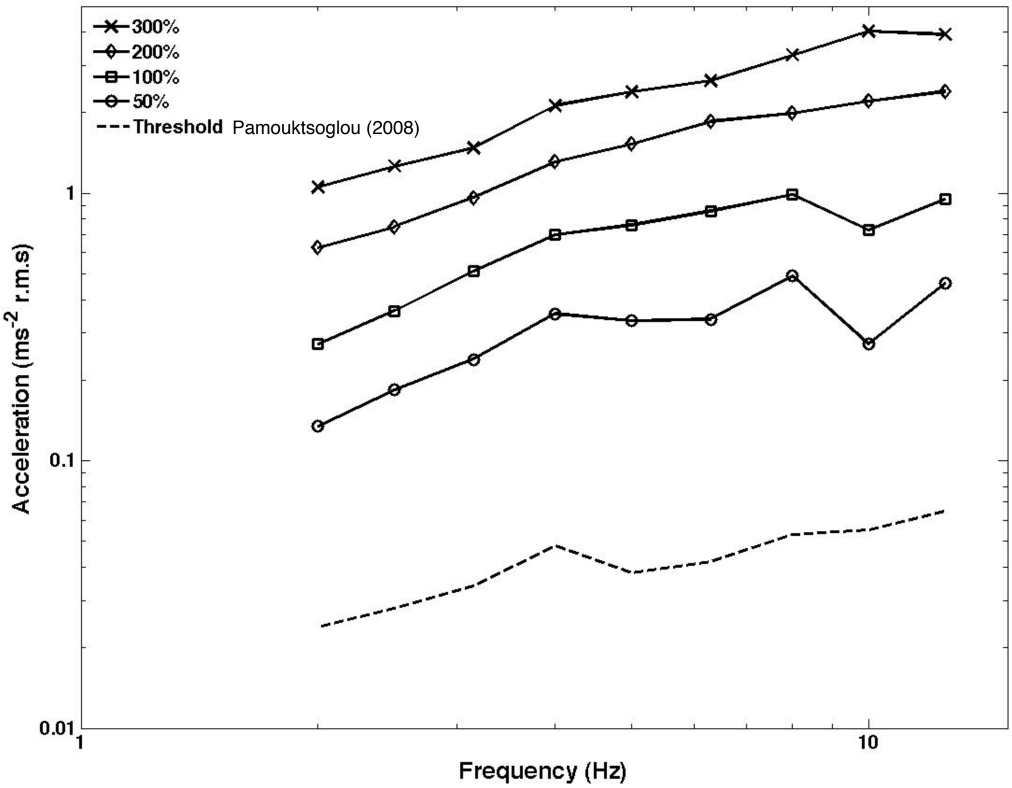

FIGURE 6.4: Equivalent comfort contours for vertical vibration of the hands at sensation magnitudes from 50 to 300 (relative to 100 for 5-Hz vertical vibration at 0.56 ms^{-2} r.m.s. at the hands), expressed in acceleration. Median absolute perception thresholds for vertical vibration of the hands from Pamouktsoglou (2008) are also shown.

6.7.3 Equivalent comfort contours for vertical vibration transmitted at the feet

Median equivalent comfort contours for vertical vibration of the feet over the range 2 to 12.5 Hz are presented in terms of acceleration and in Figure 6.5. For frequencies between 2 and 6.3 Hz, the derived equivalent comfort contours show that sensitivity to feet-transmitted vibration depends on the frequency of vibration, but that the frequency-dependence of the equivalent comfort contours is more or less independent of the magnitude of vibration (i.e. similarly shaped equivalent comfort contours at all sensation magnitudes). For higher frequencies from 6.3 to 12.5 Hz, the magnitude dependence on the equivalent comfort contours is evident (i.e. different shape of equivalent comfort contours between the sensation magnitudes).

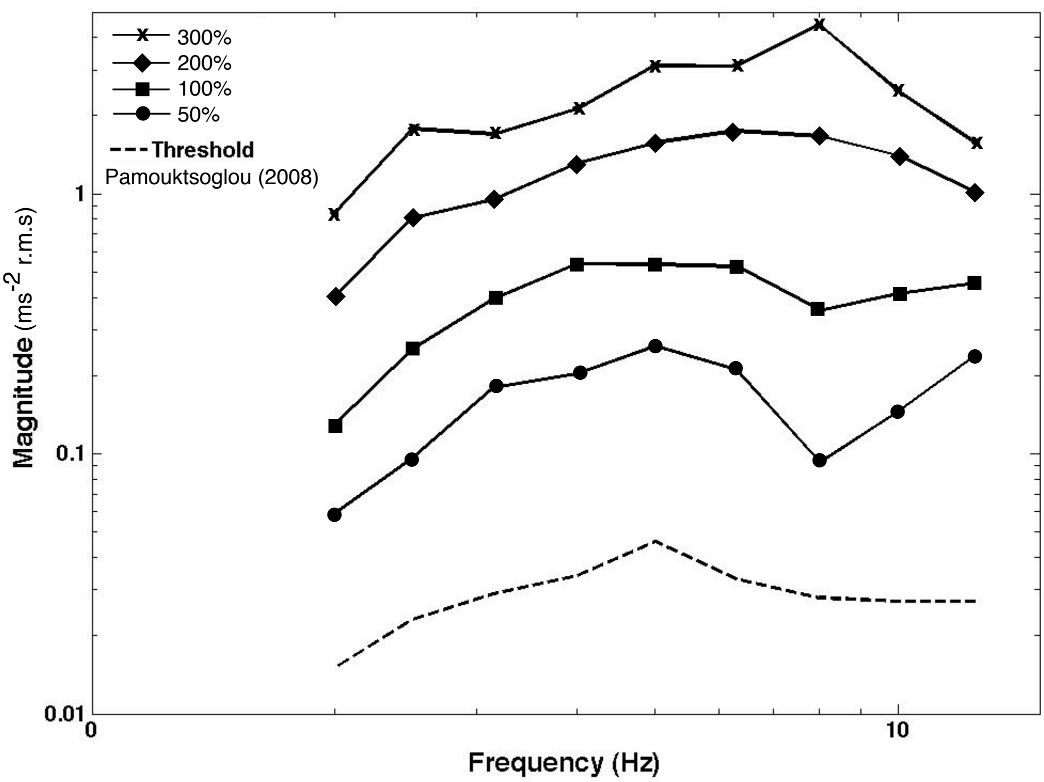

Figure 6.5: Equivalent comfort contours for vertical vibration of the feet at sensation magnitudes from 50 to 300 (relative to 100 for 5-Hz vertical vibration at 0.56 ms^{-2} r.m.s. at the hands), expressed in acceleration. Median absolute perception thresholds for vertical vibration of the feet from Pamouktsoglou (2008) are also shown

The sensitivity to vibration acceleration differed significantly between the nine frequencies (from 2 to 12.5 Hz) at each of the four sensation magnitudes (i.e. 50, 100, 200, and 300) ($p<0.001$, Friedman). The acceleration comfort contours show a general trend of decreased sensitivity (i.e. increasing acceleration of comfort contours) with increasing frequency from 2 to 6.3 Hz, although only the pair of adjacent frequencies for sensation magnitude at 200% presented significant differences in the acceleration contours (Wilcoxon, $p<0.05$). For frequencies greater than 6.3 Hz most of the pair of adjacent frequencies showed no significant differences (Wilcoxon, $p>0.05$).

6.7.4 Localisation of sensation

The localisation of the vibration sensation was obtained through Session 2, where the subjects were asked to indicate on which part of the body they felt the vibration. The location data were transformed into binary data (1 = body location in direct contact with vibrating surface, 0 = other body locations) and Figure 6.6 shows a percentage of subjects perceived the greatest vibration at the body location in contact with vibrating surface at each condition (i.e. Hands, Feet) for each of 9 frequencies at each of three magnitudes.

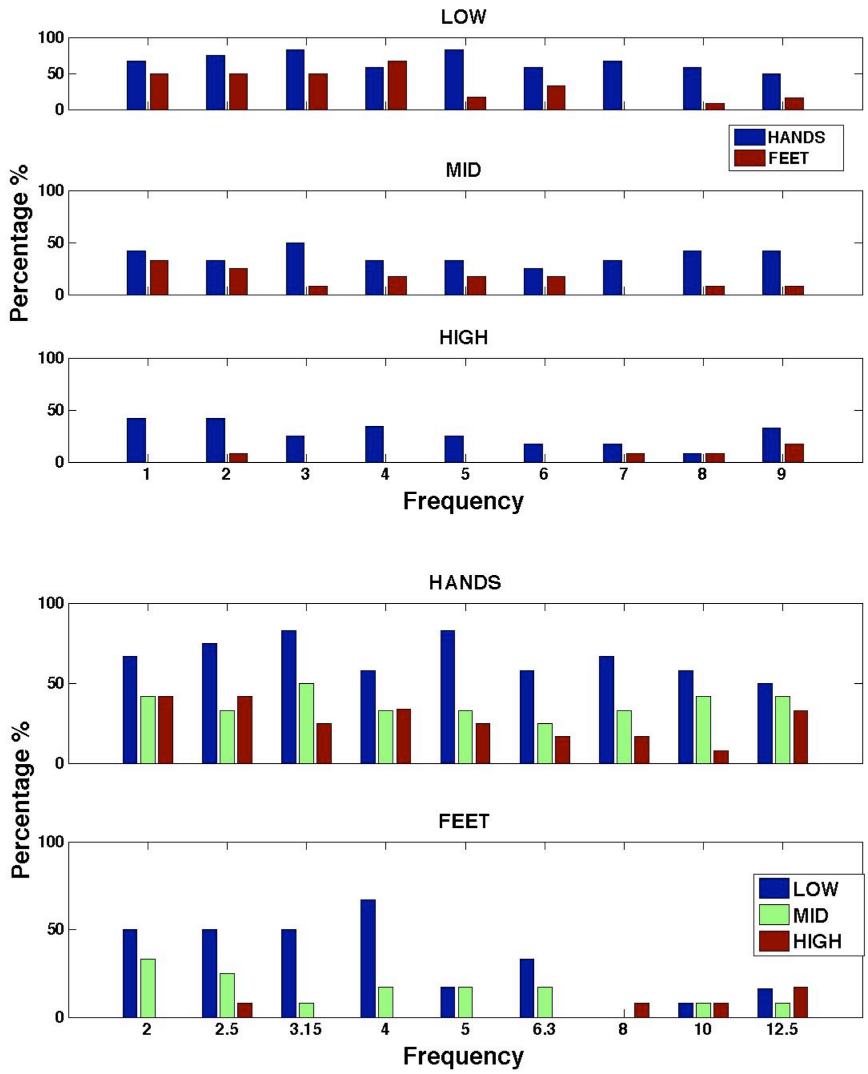

Figure 6.6: Percentage of subjects who perceived greatest vibration at the body location in contact with vibrating surface (hands or feet) for each of 9 frequencies at three magnitudes.

6.7.5 Effect of frequency

The Cochran Q test was performed with the transformed (binary) data, and the results are presented in Table 6.5. The percentage of subjects perceived the greatest vibration at the contact location at the hands (number 9) for hand transmitted vibration and at the feet (number 14) for feet transmitted vibration was independent of frequency at each of the three magnitudes investigated (i.e. low, mid high) (Cochran Q, $p>0.05$) except at low magnitude for the feet transmitted vibration with a trend that as frequency increased less subjects perceived the greatest vibration at the contact location (Cochran Q, $p=0.002$) (see Figure 6.6).

TABLE 6.5: Cochran Q test for the frequency effect on localisation of sensation

Location	*Low*	*Mid*	*High*
Hands	0.416	0.815	0.937
Feet	0.002	0.371	0.433

Further test, McNemar, was carried out for the Low magnitude of vibration at the feet (Table 6.6), and there was a significant change in the perceived body location between low frequencies (2-4 Hz) and 8 Hz; none of the subjects perceived the 8 Hz vibration at the contact area (i.e feet).

TABLE 6.6: McNemar test p values for the frequency effect on localisation of sensation at the feet with Low magnitude.

Hz	2	2.5	3.15	4	5	6.3	8	10	12.5
2	1	0.617	0.617	0.724	0.221	0.480	0.041	0.074	0.221
2.5	*	1	0.617	0.724	0.221	0.480	0.041	0.074	0.22
3.15	*	*	1	0.683	0.289	0.617	0.041	0.074	0.289
4	*	*	*	1	0.077	0.289	0.013	0.023	0.077
5	*	*	*	*	1	0.617	0.480	1	0.480
6.3	*	*	*	*	*	1	0.134	0.250	0.617
8	*	*	*	*	*	*	1	1	0.480
10	*	*	*	*	*	*	*	1	1
12.5	*	*	*	*	*	*	*	*	1

6.7.6 Magnitude effect

The magnitude effect on localisation of sensation was investigated with the Cochran Q test as shown in Table 6.7. For vibration transmitted at the hands, the percentage of the subjects that perceived the greatest vibration at the hands was reduced significantly with increasing vibration magnitude at 3.15, 5 and 8 Hz (Cochran, $p<0.05$). For vibration transmitted at the feet, the percentage of the subjects indicated the greatest vibration at the feet was reduced significantly with increasing the vibration magnitude at 2, 3.15, 4 Hz (Cochran, $p<0.05$).

TABLE 6.7: .Cochran Q test for the magnitude effect on localisation of sensation

Location	2	2.5	3.15	4	5	6.3	8	10	12.5
Hands	0.529	0.072	0.005	0.367	0.008	0.426	0.030	0.449	0.367
Feet	0.018	0.066	0.005	0.003	0.367	0.050	0.367	1	0.778

Additional tests (McNemar) were applied to individual frequencies with significant effect of magnitude on the transformed (binary) data. . For hand transmitted vibration at 3.15 and 8 Hz the reduction was significant between low and high vibration magnitudes at 3.15 Hz (McNemar, $p=0.023$) and 8 Hz (McNemar, $p=0.041$), whereas at 5 Hz the reduction was significant for both pairs of vibration magnitudes at low and medium magnitudes (McNemar, $p=0.041$) and low and high magnitudes (McNemar, $p=0.023$). For vibration transmitted at the feet at 2, 3.15 and 4 Hz the reduction was significant between low and high vibration magnitudes at 2, 3.15 and 4 Hz (McNemar, $p<0.05$).

6.7.7 Comparison of vibration sensation between the hands and the feet.

The difference in comfort contours (as shown in Figure 6.7) between the two body locations (i.e. hands and feet) was examined statistically using the Wilcoxon Matched Pairs Test for each of the nine frequencies at each of four sensation magnitudes (i.e. 50, 100, 200, 300). For lower level of sensation magnitudes (i.e., 50% and 100 %) the sensitivity of the feet was significantly higher (lower comfort contours) than that of the hands at 2, 2.5, 3.15 and 8 Hz for the rating of 50% and at 2, 5, 8 and 12.5 Hz for the rating of 100% (Wilcoxon, $p<0.05$). For higher levels of discomfort (i.e. 200% and 300%) there were no significant differences in comfort contours between the two locations in most of the frequencies except at 10 and 12.5 Hz for the rating of 200% (Wilcoxon, $p<0.05$) and at 12.5 Hz for the rating of 300% (Wilcoxon, $p<0.012$).

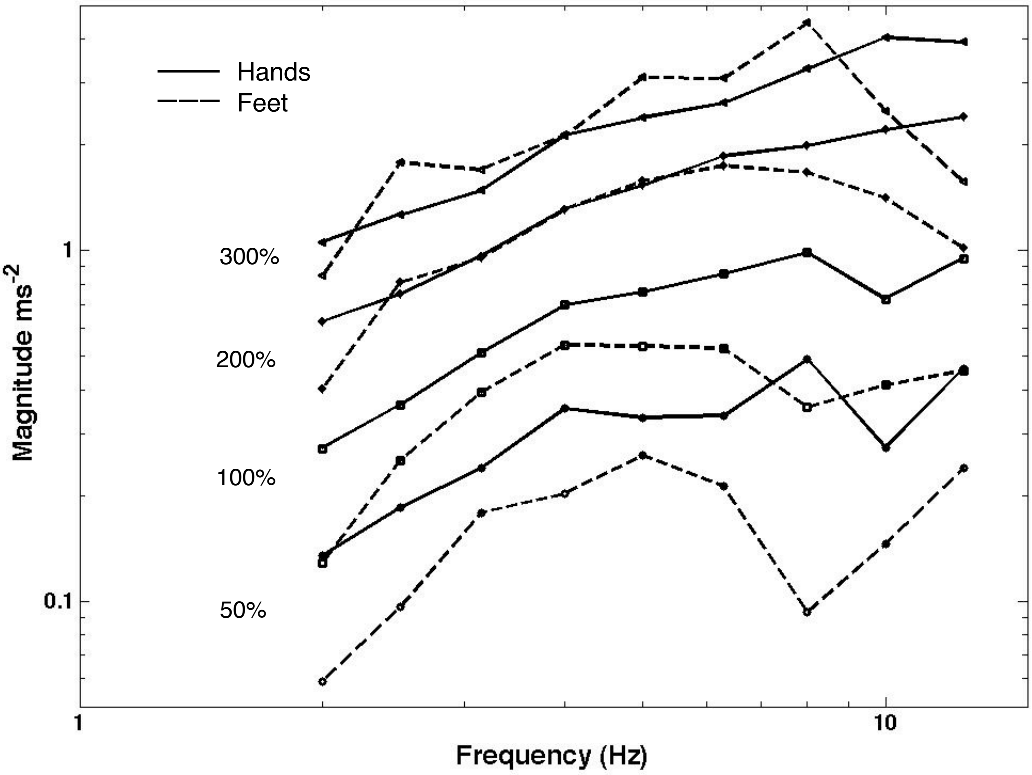

Figure 6.7: Equivalent comfort contours for vertical vibration of the hands and the feet (solid lines: Hands, dash lines: Feet) at sensation magnitudes of 50, 100, 200 and 300 (100 = discomfort caused by 5 Hz vertical vibration at 0.56 ms^{-2} r.m.s.at the hands).

6.8 Discussion

6.8.1 Rate of growth of discomfort

The rates of growth in discomfort with increasing magnitude of hands-transmitted vibration (i.e. the exponent n) did not show a dependence on vibration frequency over the nine frequencies (from 2 to 12.5 Hz) . With a similar posture to the current experiment but with vibration of only one hand, Morioka and Griffin (2006b) determined rates of growth of sensation for hands-transmitted vibration over the frequency range 8 to 400 Hz and found no significant difference in the exponent within the frequency range 8 to 12.5 Hz. Morioka and Griffin (2009) employed a posture in which the hand grasped a steering wheel and also found no significant change in the exponent within the frequency range 4 to 16 Hz. The median rates of growth in the two studies varied from 0.573 to 0.786 at frequencies less than 16 Hz, similar to the range from 0.580 to 0.875 obtained in the present study. The exponent n for the feet vibration presented similar values, for the common frequencies, with the study of Morioka and Griffin (2010).

6.8.2 Comfort contours at the hands

The derived median equivalent comfort contours expressed in terms of vibration acceleration imply a gradual decrease in sensitivity (i.e. increasing acceleration) as the frequency increases from 2 to 5 Hz, consistent with contours for vertical vibration of the hand (a whole hand pressing on a flat plate) determined by Miwa (1967a) . However, the present results seem to conflict with the findings of Giacomin et al. (2004) who suggested constant acceleration comfort contours between 3 and 5 Hz from a study with rotational vibration of two hands grasping a steering wheel. The difference in posture and the different axis of vibration excitation may explain the discrepancy with the present results.

The equivalent comfort contours derived in the present study are compared in Figure 6.8 with contours obtained by Morioka and Griffin (2006b). The comfort contours between 8 and 12.5 Hz are similar in both studies. The combination of the two studies shows the trend in the contours over the frequency range 2 to 300 Hz. The combined contours suggest a progressive decrease in sensitivity to vibration acceleration as the frequency increases from 2 Hz to about 40 Hz, particularly at higher sensation magnitudes. Different reference vibration stimuli were employed in the two studies: 0.56 ms^{-2} r.m.s at 5 Hz in the present study and 5.0 ms^{-2} r.m.s. at 50 Hz in the study of Morioka and Griffin (2006b). So the magnitude estimates associated with the two sets of contours from the two studies in Figure 6.8 do not have the same meaning (for example, the contour labelled 100 in the present study is not associated with the same severity of sensations as the contour labelled 100 in the study of Morioka and Griffin (2006b)). Another difference between the studies is that the present study examined the discomfort caused by vibration presented to both hands, whereas Morioka and Griffin (2006b) presented vibration to only one hand.

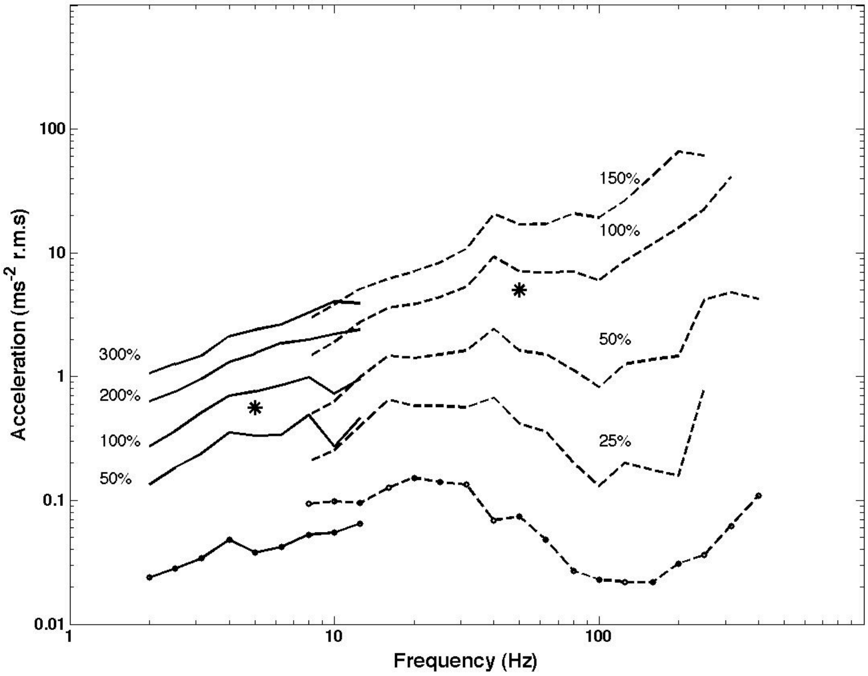

FIGURE 6.8: Comparisons of equivalent comfort contours at the hands derived from the present study (solid lines; relative to 0.56 ms^{-2} r.m.s at 5 Hz) and from Morioka and Griffin (2006) (broken lines: relative to 5.0 ms^{-2} r.m.s. at 50 Hz). The lowest curves indicated the threshold values. The two asterisks refer to the reference stimulus in each study

The equivalent comfort contours determined for low frequencies (2 to 12.5 Hz) in the present study show less-pronounced magnitude-dependence than found with higher frequencies (12.5 to 400 Hz) by Morioka and Griffin (2006b). The low-frequency vibration equivalent comfort contours found here have similar shapes to the absolute thresholds determined previously for the same conditions Pamouktsoglou (2008) (see Figure 6.5). The similarity in the frequency-dependence at threshold and at supra-threshold levels suggests the same tactile channel (or other sensory mechanism) may be involved in both detecting vibration and perceiving the strength of sensation of hand-transmitted vibration over the range 2 to 12.5 Hz. The candidate tactile channels responsible for perception of supra-threshold vibration at frequencies less than about 40 Hz are

NP I (associated with Meissner corpuscles) and NP III (associated with Merkel discs), based on studies of vibrotactile perception at small areas of the hand by Bolanowski et al. (1988) .

6.8.3 Comfort contours at the feet

The equivalent comfort contours at the feet derived in the present study are compared with comfort contours obtained by Morioka and Griffin (2010), which is shown in Figure 6.9. The combination of the two studies shows the trend in contours over the frequency range from 2 to 315 Hz.. At the overlapping frequencies from 8 to 12.5 Hz, the pairs of comfort contours by the present study and the study by Morioka and Griffin (2010) present some inconsistency, which may be explained by the use of different magnitude of the reference stimuli 0.56 ms^{-2} r.m.s at 5 Hz at the hands for the present study and 5.0 ms^{-2} r.m.s at 50 Hz at the foot in the study of Morioka and Griffin (2010). It can be suggested that magnitude dependency of the feet contours for frequencies greater than 6.3 Hz is due to the non-linear biodynamic response of the foot as found by Kitazaki and Griffin (1997) and Nawayseh and Griffin (2004).

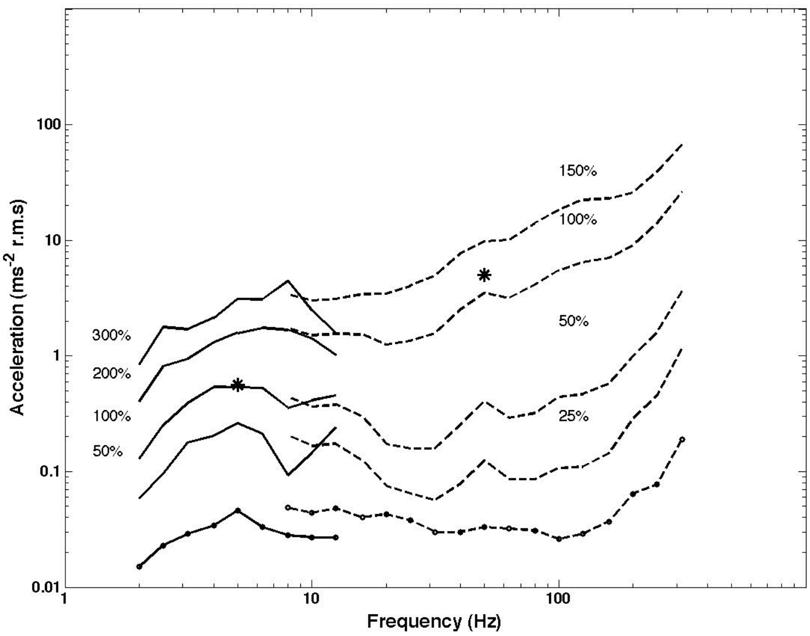

FIGURE 6.9: Comparisons of equivalent comfort contours at the feet derived from the present study (solid lines; relative to 0.56 ms^{-2} r.m.s at 5 Hz at the hands) and from Morioka and Griffin (2010) (broken lines: relative to 5.0 ms^{-2} r.m.s. at 50 Hz at the feet). The lowest curves indicated the threshold values. The two asterisks refer to the reference stimulus in each study

6.8.4 Effect of contact location on comfort contours

The comfort contours at the feet were lower than that of the hands at lower sensation magnitudes (50 and 100% of discomfort caused by 0.56 ms^{-2} r.m.s. at 5 Hz at the hands), whereas the difference in sensitivity between the hands and the feet diminished at the higher sensation magnitudes (200 and 300%). The greater sensitivity at the feet relative to the hands at low sensation magnitudes was consistent with the lower perception thresholds at the feet compared to the hands found in Experiment 1. With increasing vibration magnitude, the vibration discomfort tended to locate at body parts other than the location with direct contact (i.e. hands, feet), with the 8-12 Hz vibration at the feet causing discomfort at the location with non-direct contact at all magnitudes. This implies that the judgement of discomfort for sensation magnitudes is determined not only from the body location in contact with the vibration inputs. The other parts of the body contributing to the discomfort judgements, as seen in Figure 6.6, could partly explain the change in the comfort contours trends.

6.9 Conclusions

Comfort contours at the hands for vertical vibration presented a decrease in sensitivity to acceleration with increasing vibration frequency from 2 to 5 Hz. The shapes of equivalent comfort contours over the frequency range 2 to 12.5 Hz did not show a dependence in vibration magnitude, with similar shape to the absolute thresholds for the perception of hand-transmitted vertical vibration determined by Pamouktsoglou (2008)), suggesting the same tactile channels (or the same sensory mechanism) may be involved in the perception of vibration at threshold and supra-threshold levels within this frequency range. Comfort contours at the feet for vertical transmitted vibration also presented a decrease in sensitivity to acceleration with increasing frequency from 2 to 6.3 Hz. However, for frequencies greater than 6 Hz, the increased vibration sensitivity at the feet with increasing frequencies from 2 to 6.3 Hz may be explained by the non-linear biodynamic response, and the localisation of vibration sensation at the body part other than the direct contact with the vibration input (feet).

Chapter 7

Equivalence of sensation caused by vertical vibration of the hands, the feet and the seat

7.1 Introduction

Multiple-input vibration (vibration simultaneously transmitted to different locations on the body) can occur in many transport environments and affect the overall sensation of vibration discomfort. For example, vehicle drivers may experience vibration discomfort via the steering wheel, via the floor as well as via the seat. Standardised methods of predicting the discomfort caused by multiple-input vibration allow the inclusion of vibration at the back, the seat, and the feet, but not vibration of the hands, International Organisation for Standardisation (1997) ; British Standards Institution (1987). Understanding of differences in sensitivity to hand-transmitted vibration and whole-body vibration should assist the identification of the causes of discomfort as well as the extent of discomfort.

The frequency-dependence of human sensitivity to vibration is often expressed by equivalent comfort contours (showing the vibration magnitudes that produce similar degrees of discomfort across a range of frequencies) and has previously been determined at the hand by Miwa (1967a); Reynolds et al. (1977); Giacomin et al. (2004); Morioka and Griffin (2006b, 2009) , at the foot by Morioka and Griffin (2010) and at the seat by Miwa (1967b); Corbridge and Griffin (1986); Griffin and Whitham (1977a); Parsons et al. (1982); Morioka and Griffin (2006a). The equivalence of sensations at the hands, the seat, and the feet for three frequencies (12.5, 50, and 100 Hz) suggests greatest sensitivity to vertical vibration at the seat and least sensitivity at the hands Morioka (2007). The relative discomfort between the three locations varies with vibration frequency and vibration magnitude, reflecting the frequency-dependence and magnitude-dependence of equivalent comfort contours at the hand (8-400 Hz), at the feet (8-400 Hz), and at the seat (2-315 Hz) as reported by Morioka and Griffin (2006b,a), Morioka and Griffin (2010). However it was found from the previous experiment (see chapter 6) that equivalent comfort contours for vertical vibration at the hands and the feet were not greatly dependent on vibration magnitude over the frequency range 2 to 12.5 Hz. If the rate of growth of sensation with increasing vibration magnitude differs between the two locations, the relative sensitivity to vibration between the locations will depend on vibration magnitude.

7.2 Objective

The objective of this study was to determine magnitudes of vertical vibration that produce similar degrees of vibration discomfort at the hands and the feet for frequencies from 2 to 12.5 Hz, at the hands and the seat, and at the feet and the seat for frequencies from 4 to 12.5 Hz. The effects of vibration frequency and vibration magnitude on the relative sensitivity between the hands and the feet, the hands and the seat, and the feet and the seat were also examined.

7.3 Hypothesis

It was hypothesised that the equivalence of sensations at the hands the feet and the seat would be frequency-dependent due to the different shapes of equivalent comfort contours at the hands and the feet and with the ratio of acceleration at the seat to acceleration at the hands decreasing with increasing frequency of vibration, especially from 4 to 6.3 Hz. It was also hypothesised that relative sensitivity at the hands and the feet would not be magnitude-dependent, since equivalent comfort contours at the hands and the feet are not magnitude-dependent over the frequency range 2 to 12.5 Hz but the relative sensitivity at the hands and the seat would be magnitude-dependent, assuming the rate of growth of discomfort differs between the hands and the seat.

7.4 Method

7.4.1 Subjects

Twelve healthy male subjects aged between 23 and 41 years old with a mean age of 29.4 years old (standard deviation, SD=5.51), mean stature 171 cm (SD=4.83), and mean weight 70.8 kg (SD=12.7) participated in the experiment. None of the subjects had experienced severe exposure to vibration. A series of anthropometric measurements (sitting height, hand length, etc.) were obtained to investigate any association with their judgements of vibration discomfort.

7.4.2 Apparatus

Vertical vibration at the hands, at the feet and at the seat was delivered using a multiple-input vibration simulator via rigid cylindrical handles (100 mm in length, 30 mm in diameter), rigid footrests (30.5 mm x 10.5 mm with 10-degree inclination) and a rigid contoured seat (250 mm x 150 mm) mounted on electrodynamic vibrators (MB Dynamics for the hands and the feet, Derritron VP85 for the seat) (see Figure 7.1).

The vertical vibration was in the z-axis at the hands at the feet and the seat, using a conventional basicentric co-ordinate system. Piezoelectric accelerometers (DJ Birchall model A/20/T at the handles and the footrests and BK model 4371 at the seat) were mounted on the vibrating surfaces so as to measure the acceleration during the experiment. The vibration stimuli were created and acquired using HVLab Data Acquisition and Analysis software (version 3.81) via a personal computer. The computer was fitted with anti-aliasing filters (TechFilter) and the signals were digitised by an analogue-to-digital converter (PCL-818) at a fixed sample rate of 2000 samples per second. The background vibration due to electrical noise at 50 Hz was less than 0.006 ms^{-2} r.m.s. in the vertical direction.

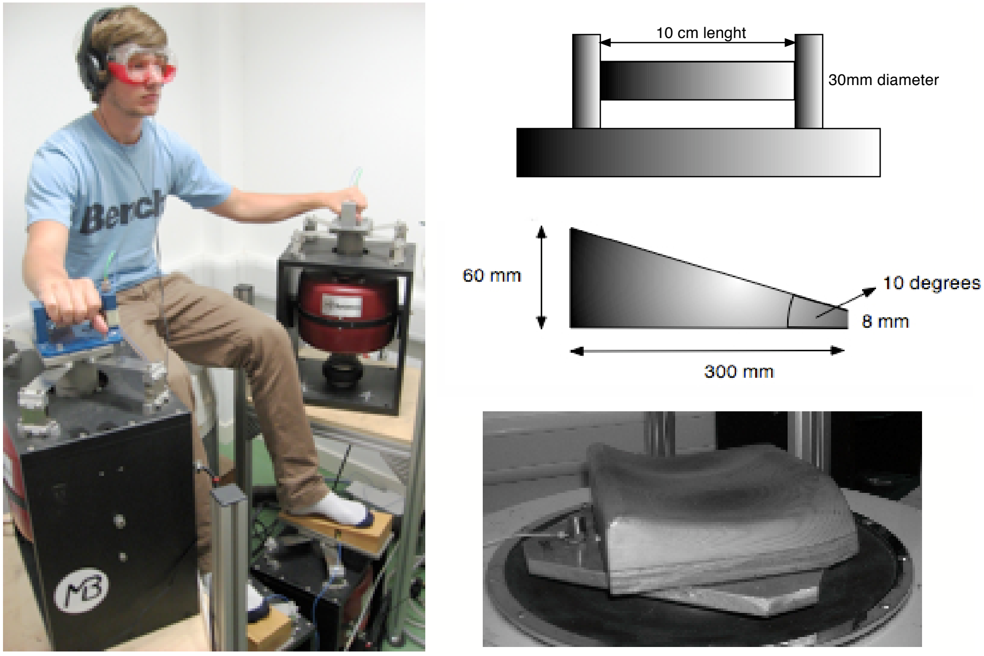

FIGURE 7.1: Set-up of the rig: Independent vibration inputs to the hands, the feet and the seat. The subjects wore socks but no shoes.

7.4.3 Stimuli

Sinusoidal vibration of 4 seconds duration including 500 ms cosine-tapered ends were created for the nine preferred one-third octave centre frequencies in the range 2 to 12.5 Hz. Reference stimuli (presented to the hands) were created with three magnitudes in 6 dB steps, with the same velocity at all frequencies because equivalent comfort contours for the hands over the frequency range 2 to 12.5 Hz correspond approximately to constant velocity according to the findings of the previous experiment (see chapter 6). Table 7.1 shows the frequencies and magnitudes of the reference stimuli presented at the hands. Test stimuli (presented to the feet or at the seat) were created with magnitudes ranging from 0.05 to 0.8 ms^{-2} r.m.s. in 1.0 dB steps at each frequency.

TABLE 7.1: Reference stimuli (presented to the hands) used in the study.

Frequency	Acceleration ($ms^{-2} r.m.s$)		
	LOW	MEDIUM	HIGH
2	0.48		
2.5	0.60		
3.15	0.75		
4	0.64	0.96	1.28
5	1.20		
6.3	1.50		
8	1.28	1.92	2.56
10	2.4		
12.5	3.00		
Velocity $ms^{-1} r.m.s$	0.025	0.038	0.050

7.4.4 Procedure

The acceleration magnitudes of the vertical vibration that produced similar degrees of discomfort at the hands, the feet and the seat were determined using the method of constant stimuli. A 4.0-second reference stimulus was followed by a 1.0-second pause, then a 4.0-second test stimulus, then a 1.0-second pause, then a repeat of the 4.0-second reference stimulus, the 1.0-second pause and the 4.0-second test stimulus (see Figure 7.2). The reference and test stimuli were always presented with the same frequency. The reference stimulus was presented at the hands with a fixed magnitude. The test stimulus was presented at the feet or at the seat with a range of nine magnitudes (in 1 dB steps) in random order. The task of the subjects was, to indicate which of the two motions they would most like to be reduced if they were to be presented with them again for the same period in the laboratory, adopting an exact sentence used by Corbridge and Griffin (1986). The subjects were asked to reply by saying First (i.e. the reference motion) or Second (i.e. the test motion).

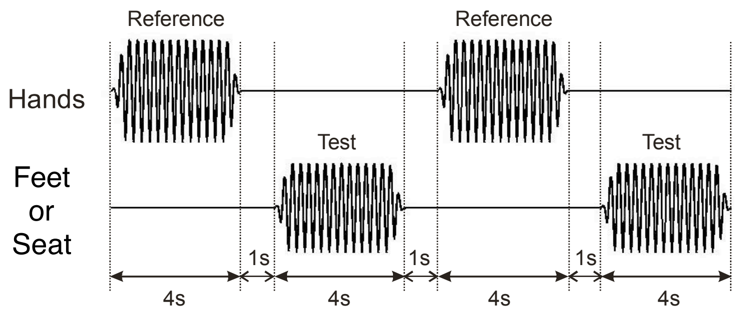

Figure 7.2: Stimuli presentation

The experiment consisted from two sessions, as shown in Table 7.2 and during the experiment the subjects wore a blindfold to prevent them from seeing the vibration. They were exposed to white noise at 70 dB(A) via a pair of headphones to prevent them from hearing the vibration (although it was inaudible without the white noise) and to mask any environmental sound to help them concentrate on the vibration stimuli.

Table 7.2: Experimental sessions that the subjects attended.

Session 1	Equivalence of vibration sensation between the hands and the seat from 4 to 12.5 Hz
Session 2	Equivalence of vibration sensation between the hands and the feet from 2 to 12.5 Hz

7.4.5 Analysis

The equivalent subjective magnitude of the test stimulus was determined from the geometric mean of the highest magnitude (T_h) of the test stimulus at the feet or at the seat considered less uncomfortable than the reference stimulus at the hands and the lowest magnitude (Tl) of the test stimulus at feet or the seat considered more uncomfortable than the reference stimulus at the hands:

$$Equivalent\ magnitude = (T_h * T_l)^{1/2} \tag{7.1}$$

7.5 Results

For the MEDIUM vibration magnitude at each of the range of frequencies investigated, and for each of the three vibration magnitudes at 4 Hz and 8 Hz (see Table 7.1), the median r.m.s. acceleration of the test vibration at the feet and at the seat that produced sensations equivalent to the same frequency of reference vibration at the hands were calculated using Equation (7.1) and the median values are shown in Figure 7.3 and Figure 7.4. The figure also shows the reference vibration at the hands for each frequency and each magnitude, so it indicates the r.m.s. accelerations at the hands, at the feet and at the seat were considered equivalent. For example, at 12.5 Hz, 0.31 ms^{-2} r.m.s. at the seat was judged equivalent to the 3.0 ms^{-2} r.m.s. reference vibration at the hands. The measured acceleration median data are also shown in Tables 7.3 and Tables 7.4.

TABLE 7.3: Median acceleration (ms^{-2} r.m.s.) at the hands and the feet producing equivalent sensations. Also showing the ratios of the magnitude of feet acceleration and the magnitude of hands acceleration when they produce equivalent sensations. At each of the three magnitudes investigated at 4 and 8 Hz, the reference vibration stimuli at the hands have the same velocity (ms^{-1} r.m.s.). Figure 7.3 shows a graphical representation.

Frequency (Hz)	Magnitude	Hands	Feet	Ratio (Feet/Hands)
2	MEDIUM	0.49	0.29	0.60
2.5	MEDIUM	0.67	0.44	0.66
3.15	MEDIUM	0.76	0.53	0.69
4	LOW	0.64	0.47	0.73
4	MEDIUM	0.97	0.75	0.77
4	HIGH	1.29	1.00	0.77
5	MEDIUM	1.25	1.06	0.84
6.3	MEDIUM	1.60	1.36	0.85
8	LOW	1.29	1.05	0.81
8	MEDIUM	1.97	1.26	0.63
8	HIGH	2.58	1.68	0.65
10	MEDIUM	2.40	1.14	0.47
12.5	MEDIUM	3.00	0.89	0.29

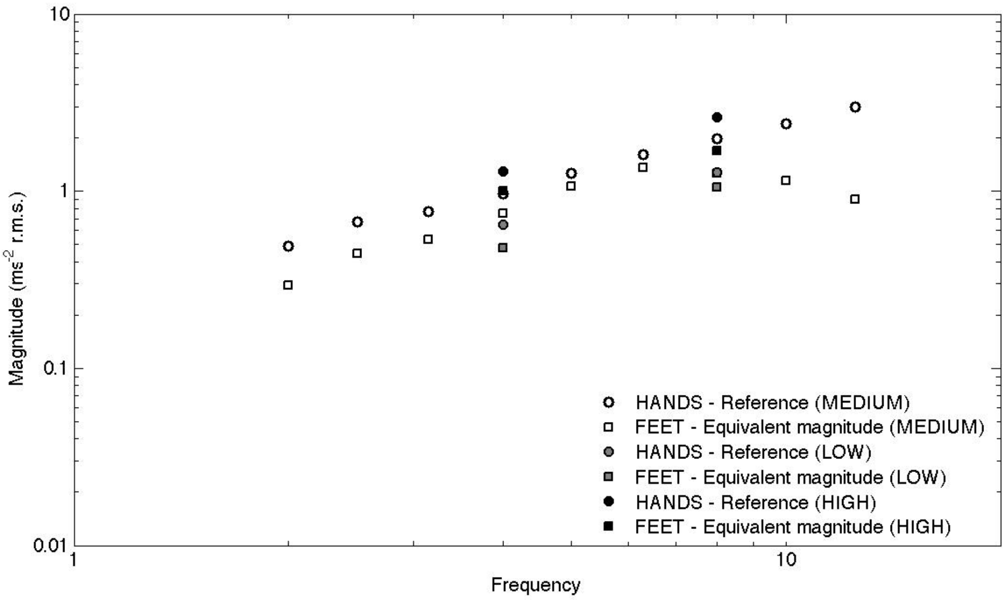

FIGURE 7.3: Acceleration magnitudes at the hands (reference) and at the feet (test) judged equivalent at each of the nine frequencies from 2.5 to 12.5 Hz. Three magnitudes shown at 4 Hz and 8 Hz. Median values for 12 subjects.

TABLE 7.4: Median acceleration (ms^{-2} r.m.s.) at the hands and the seat producing equivalent sensations. Also showing the ratios of the magnitude of seat acceleration and the magnitude of hands acceleration when they produce equivalent sensations. At each of the three magnitudes, the reference vibration stimuli at the hands have the same velocity (ms^{-1} r.m.s.). Figure 7.4 shows a graphical representation.

Frequency (Hz)	Magnitude	Hands	Seat	Ratio (Seat/Hands)
4	LOW	0.65	0.18	0.27
4	MEDIUM	0.98	0.20	0.20
4	HIGH	1.30	0.24	0.18
5	MEDIUM	1.29	0.20	0.16
6.3	MEDIUM	1.58	0.18	0.11
8	LOW	1.29	0.15	0.11
8	MEDIUM	1.93	0.24	0.12
8	HIGH	2.60	0.31	0.12
10	MEDIUM	2.40	0.27	0.11
12.5	MEDIUM	3.00	0.31	0.10

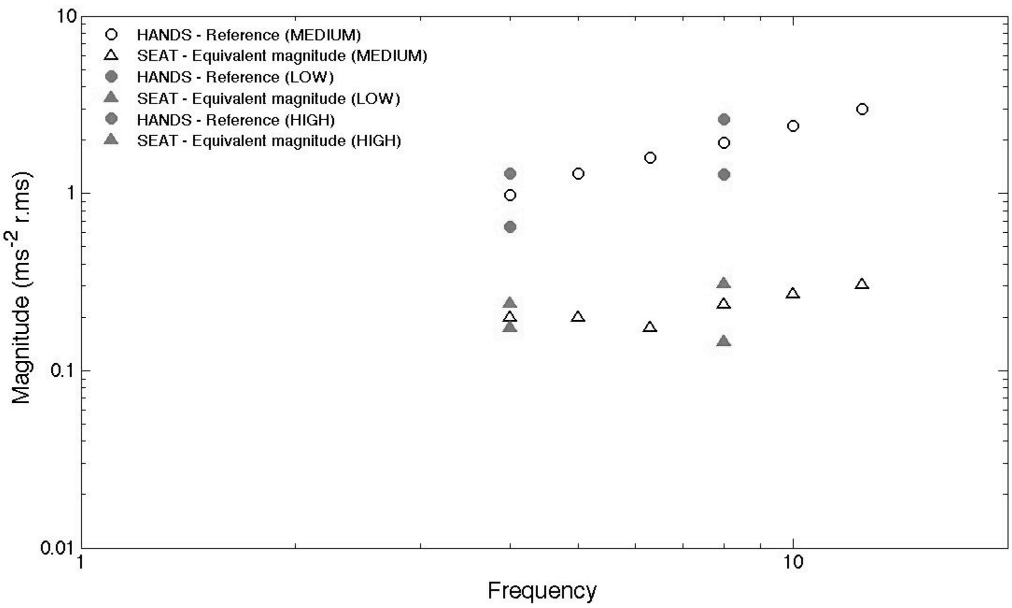

FIGURE 7.4: Median r.m.s. acceleration of the reference vibration at the hands and the median r.m.s. accelerations of the test vibration at the seat judged equivalent for the six frequencies (from 4 to 12.5 Hz) and the three magnitudes (at 4 and 8 Hz).

For equivalence of vibration sensation between the hands and the feet shown in Figure 7.3, similar accelerations were required at the feet for equivalence with a reference vibration having the same frequency at the hands. This indicates similar sensitivity between vertical vibration at the feet and vertical vibration at the hands for frequencies below 8 Hz.

As seen in Figure 7.4 on relative sensitivity to vibration between the hands and the seat, lower accelerations were required at the seat for equivalence with a reference vibration having the same frequency at the hands. This indicates greater sensitivity to vertical vibration at the seat than vertical vibration at the hands. There were no systematic correlations between the measured data (i.e. ratio of the feet acceleration to hands acceleration when they gave similar discomfort) and the characteristics of the subjects (i.e. age, height, and weight).

7.5.1 Effect of vibration frequency

7.5.1.1 Equivalence of sensation between the hands and the feet

The equivalence of sensations between the hands and the feet was expressed in terms of the ratio of the magnitude of acceleration at the feet to the magnitude of acceleration at the hands required for equivalence, and is shown as a function of frequency in Figure 7.5 for the MEDIUM vibration magnitude. The relative sensitivity of the hands and the feet depended on frequency (Friedman, $p=0.001$). There were no significant differences in the relative sensitivity ratios for any combination of frequencies between 2.5 and 6.3 Hz, except that the ratios for 5 and 6.3 Hz were significantly greater than the ratio for 2.5 Hz (Wilcoxon, $p<0.05$) and the ratio at 5 Hz and 6.3 Hz were significantly greater than the ratio for 3.15 Hz (Wilcoxon, $p<0.05$) (see Table 7.5). The ratio decreased with increasing frequency from 6.3 to 12.5 Hz, with significant decreases in the ratio between each pair of frequencies from 6.3 to 12.5 Hz (Wilcoxon, $p<0.05$), except between 8 Hz and 10 Hz (Wilcoxon, $p=0.071$).

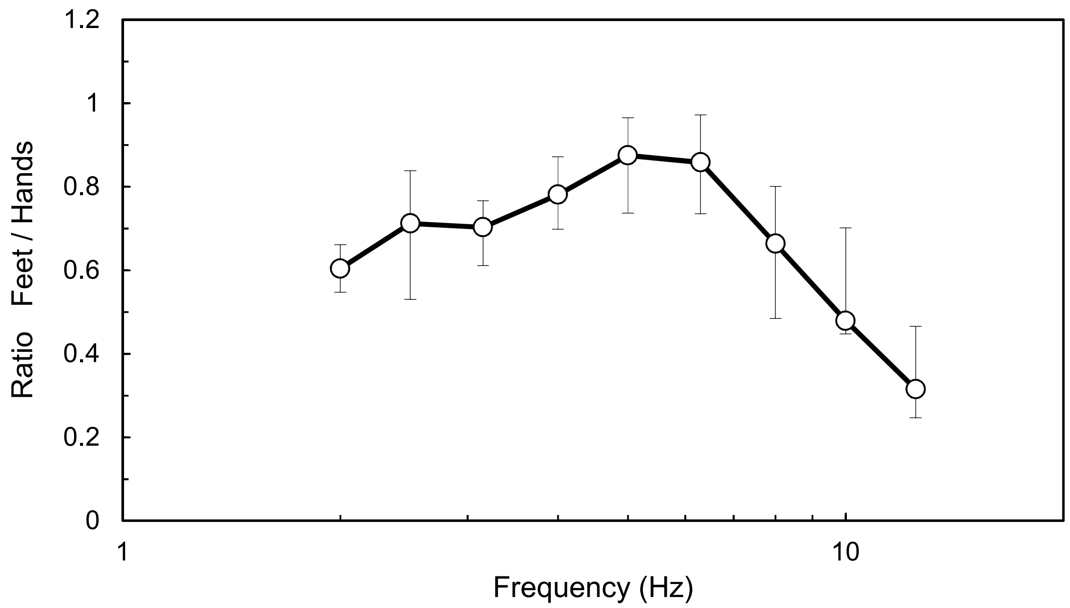

FIGURE 7.5: Effect of frequency on the equivalence of sensation between the hands and the feet, expressed as the ratio of the magnitude of acceleration at the feet to the magnitude of acceleration at the hands required for equivalence at frequencies from 2 to 12.5 Hz (with the MEDIUM magnitude, 0.038 ms^{-2} r.m.s.). Medians and inter-quartile ranges for 12 subjects

TABLE 7.5: Statistical significance (p-values from the Wilcoxon matched-pairs signed ranks test) for differences in the ratios of the magnitude of acceleration at the feet to the magnitude of acceleration at the hand required for equivalence at frequencies from 2 to 12.5 Hz (with the MEDIUM magnitude, 0.038 ms^{-2} r.m.s.).

Frequency (Hz)	2	2.5	3.15	4	5	6.3	8	10	12.5
2	1	0.209	0.388	0.023	0.004	0.006	0.814	0.158	0.002
2.5	*	1	0.969	0.099	0.012	0.008	0.638	0.060	0.002
3.15	*	*	1	0.170	0.010	0.023	0.388	0.075	0.002
4	*	*	*	1	0.084	0.071	0.033	0.004	0.002
5	*	*	*	*	1	0.875	0.015	0.015	0.002
6.3	*	*	*	*	*	1	0.002	0.003	0.002
8	*	*	*	*	*	*	1	0.071	0.002
10	*	*	*	*	*	*	*	1	0.002
12.5	*	*	*	*	*	*	*	*	1

7.5.1.2 Equivalence of sensation between the hands and the seat

The equivalence of sensation between the hands and the seat was expressed in terms of the ratio of seat acceleration to hands acceleration and is shown as a function of frequency in Figure 7.6 for the MEDIUM vibration magnitude. The relative sensitivity of the hands and the seat depended on frequency (Friedman, p=0.001), with ratios varying from 0.1 to 0.2. The ratios were significantly higher at 4 and 5 Hz than at 6.3, 8.0, 10 and 12.5 Hz (Wilcoxon, p<0.05) with a trend to decreased ratios with increasing frequency of vibration from 4 to 6.3 Hz (Wilcoxon, p<0.01) (see Table 7.6), indicating that sensitivity to vibration of the seat relative to vibration of the hands increased with increasing frequency from 4 to 6.3 Hz. There were no significant differences in the ratios at frequencies between 6.3 and 12.5 Hz (Wilcoxon, p>0.25), except for the single comparison between 8 and 12.5 Hz (Wilcoxon, p=0.04).

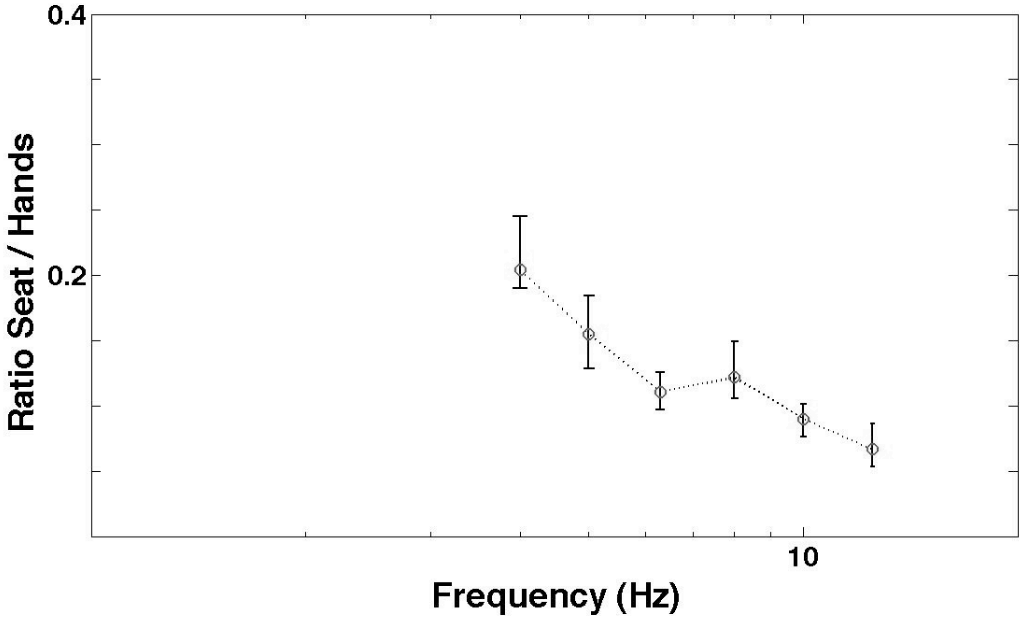

FIGURE 7.6: Effect of frequency on the equivalence of sensation between the hands and the seat expressed as a ratio of seat acceleration to hand acceleration at frequencies from 4 to 12.5 Hz (at MEDIUM magnitude, 0.038 ms^{-2} r.m.s.). The median ratios with inter-quartile range are shown.

TABLE 7.6: p-values from the Wilcoxon signed rank test on the ratios of seat acceleration to hands acceleration between pairs of frequencies.

Frequency (Hz)	4	5	6.3	8	10	12.5
4	1	0.002	0.001	0.001	0.001	0.001
5	*	1	0.004	0.030	0.002	0.001
6.3	*	*	1	0.340	0.970	0.370
8	*	*	*	1	0.071	0.040
10	*	*	*	*	1	0.310
12.5	*	*	*	*	*	1

7.5.2 Effect of vibration magnitude

7.5.2.1 Equivalence of sensation between the hands and the feet

The relative discomfort between the hands and the feet (expressed as a ratio of acceleration at the feet to the acceleration at the hands when they were judged to be equivalent) is presented as a function of vibration magnitude at the hands for 4-Hz and 8-Hz vibration in Figure 7.7. There were no significant differences in the ratios between the three magnitudes of 4-Hz vibration (Friedman, p=0.826). With 8-Hz vibration the ratios differed between the three magnitudes (Friedman, p=0.031), with a significantly higher ratio at LOW magnitude than at MEDIUM magnitude (Wilcoxon, p=0.005). With increasing magnitude of vibration, the median ratios varied from 0.73 to 0.77 with 4 Hz vibration and from 0.81 to 0.63 with 8 Hz vibration.

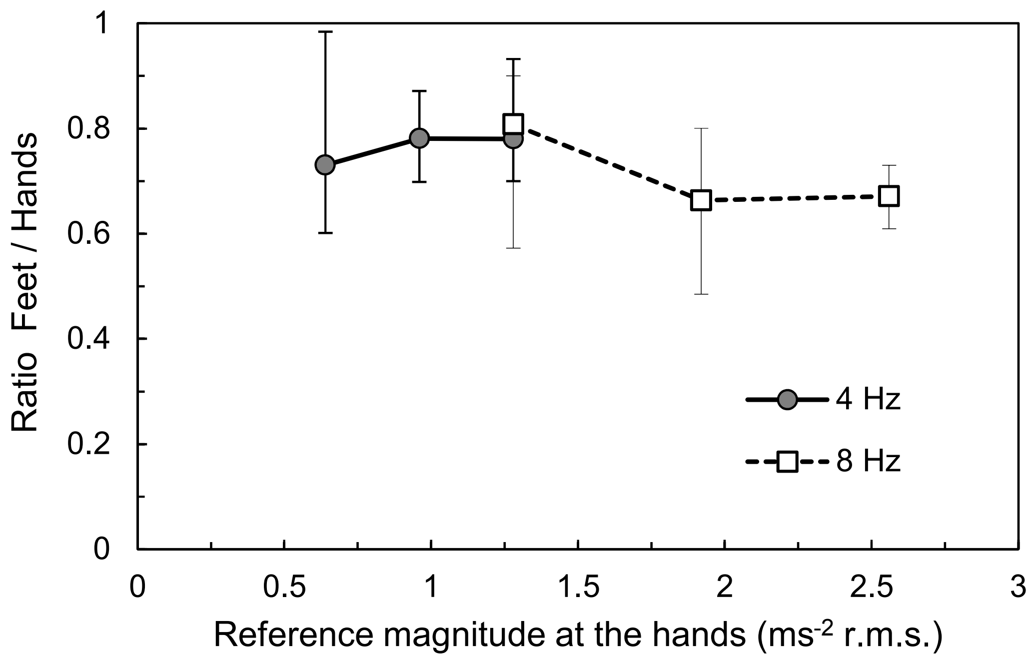

FIGURE 7.7: Equivalence of sensation expressed as a ratio of acceleration at the feet to acceleration at the hands for three magnitudes of 4 Hz and 8 Hz vibration. Medians and inter-quartile ranges for 12 subjects.

7.5.2.2 Equivalence of sensation between the hands and the seat

The relative discomfort between the hands and the seat (expressed as a ratio of acceleration at the seat to the acceleration at the hands when they were judged to be equivalent) is presented as a function of vibration magnitude for 4-Hz and 8-Hz vibration in Figure 7.8. With 4-Hz vibration, the ratios differed significantly between the three magnitudes (Friedman, $p=0.001$) with the ratio decreasing with increasing vibration magnitude (Wilcoxon, $p<0.05$). There was no significant effect of vibration magnitude on the ratio with 8-Hz vibration (Friedman, $p=0.92$).

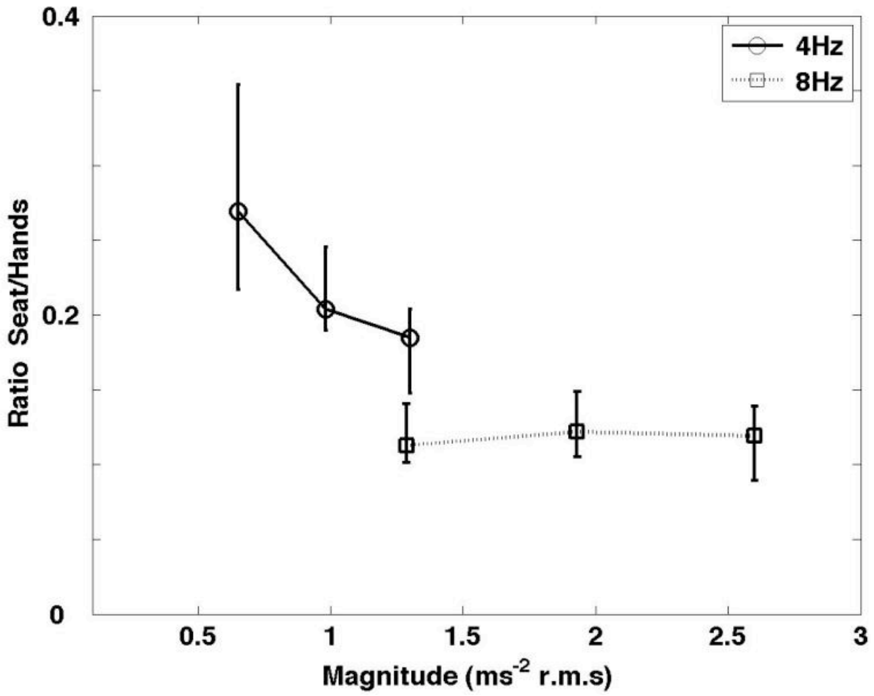

FIGURE 7.8: Equivalence of sensation expressed as a ratio of seat acceleration to hands acceleration for three vibration magnitudes at 4 and 8 Hz. Medians and inter-quartile ranges for 12 subjects.

7.6 Discussion

As may be expected, if there is the same vibration at the hands, the feet and the seat, vibration of the seat is likely to be the principal cause of vibration discomfort. The relative sensitivity to vertical vibration at the hands and the seat (the median ratio of acceleration at the seat relative to acceleration at the hands when they are equivalent) was in the range 0.1 to 0.27 (as shown in Table 7.3), indicating greater sensitivity at the seat than at the hands. The relative sensitivity to vertical vibration at the hands and at the feet (i.e., the median ratio of acceleration at the feet relative to acceleration at the hands when they are subjectively equivalent) was in the range 0.29 to 0.84, indicating greater sensitivity at the feet than at the hands over the frequency range investigated

The results are consistent with the finding of Morioka (2007) who determined sensitivity to vertical vibration at the seat and at the feet relative to vertical vibration at the hands for three frequencies (12.5, 50 and 100 Hz at vibration magnitudes of 2.5, 5.0 and 10.0 ms^{-2} r.m.s., respectively) using the same psychophysical method and body posture as the present study. At 12.5 Hz, Morioka (2007) found that the median ratio of the seat acceleration relative to the hands vibration at 2.5 ms^{-2}r.m.s. was 0.12 (0.10 at the present study). The median ratio of the feet acceleration relative to the hands vibration at 2.5 ms^{-2} r.m.s. was 0.31 (0.29 at the present study).

7.6.1 Effect of vibration frequency

The frequency-dependence of the relative discomfort between the hands and the feet at frequencies from 6.3 to 12.5 Hz may be explained by the different shapes of the equivalent comfort contours at the different body locations. The present results of equivalence of sensations presented in Table 7.3 (with the MEDIUM magnitude) are overlaid with equivalent comfort contours for vertical vibration at the hands and at the feet determined previously in Chapter 6 and by Morioka and Griffin (2006b) in Figure 7.9.

The equivalent comfort contours have been adjusted by applying the ratio of accelerations that equate sensations at the hand and the foot at 12.5 Hz, as determined by Morioka (2007). As seen in Figure 7.9, all the reference stimuli presented at the hands over the frequency range from 2 to 12.5 Hz in the present study had the same velocity, and followed the shape of the equivalent comfort contours for the hands determined in the previous experiment, consistent with sensitivity to hand-transmitted vibration depending on vibration velocity (i.e., a doubling of acceleration required for a doubling of frequency to maintain similar discomfort).

The present results for the equivalence of acceleration at the feet and at the hands at each frequency also follow the shape of the equivalent comfort contours for the feet determined in the previous experiment (see Figure 7.9). The decreased ratio of feet acceleration to hands acceleration from 8 to 12.5 Hz reflects increased sensitivity to vertical acceleration at the feet with increasing frequency from 8 to 12.5 Hz, whereas sensitivity to vertical acceleration at the hands progressively decreases with increasing frequency.

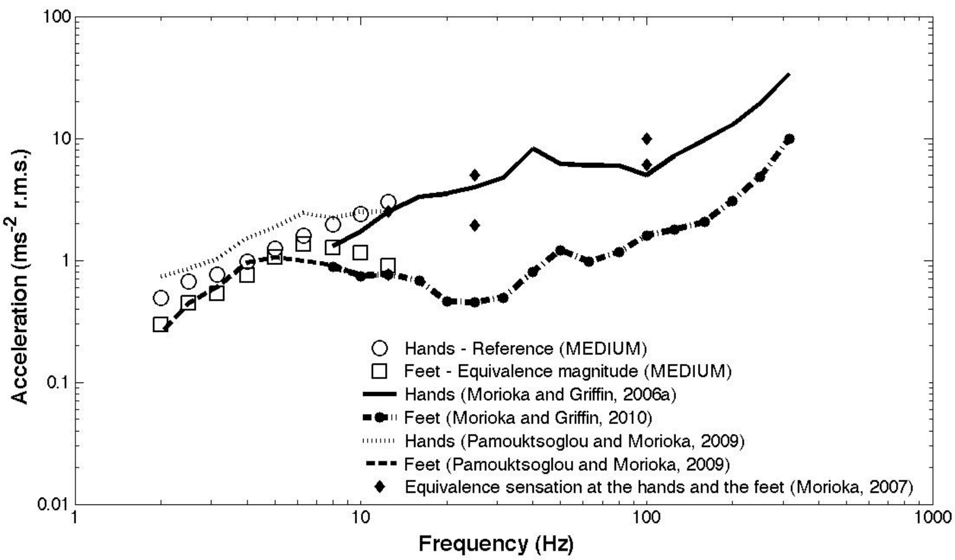

FIGURE 7.9: Equivalence of sensation between the hands and the feet expressed in acceleration with the MEDIUM magnitude overlaid with equivalent comfort contours from previous studies. The contours were adjusted to produce equivalent discomfort according to the relative sensitivity between the hands and feet at 12.5 Hz as determined by Morioka (2007).

In the same manner, the frequency-dependence in the relative discomfort between the hands and the seat at frequencies from 4 to 6.3 Hz may be explained by the different shapes of the equivalent comfort contours at the different body locations. In Figure 7.10, the present results (with the MEDIUM magnitude) are overlaid with equivalent comfort contours for vertical vibration at the hands and seat determined in previous research by Morioka and Griffin (2006b) and Morioka and Griffin (2006a). The contours have been adjusted to produce equivalent discomfort according to the relative sensitivity between the hands and seat at 12.5 Hz as determined by Morioka (2007). As expected, the reference stimuli presented at the hands follow the shape of the equivalent comfort contours determined from the previous experiment (see Chapter 6), consistent with sensitivity to hand-transmitted vibration being approximately dependent on the vibration velocity. The present results for seat acceleration equivalent to hand acceleration at each frequency also follow the shape of the equivalent comfort contours for the seat determined by Morioka and Griffin (2006a). The decreased ratio of seat acceleration to hands acceleration from 4 to 6.3 Hz reflects the finding that sensitivity to vertical acceleration at the seat increases, or remains constant, with increasing frequency from 4 to 6.3 Hz whereas sensitivity at the hands progressively decreases with increasing frequency.

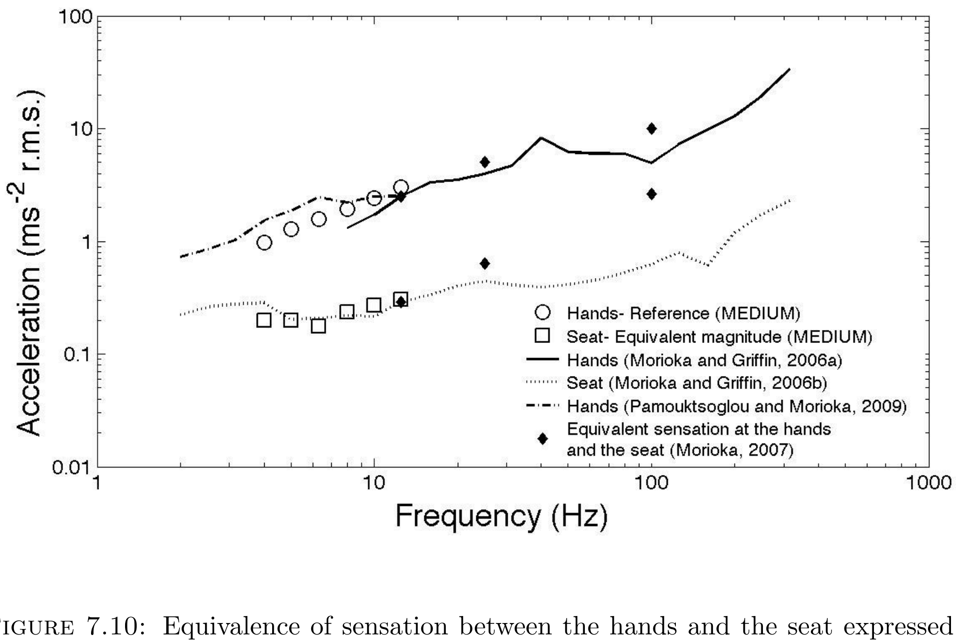

FIGURE 7.10: Equivalence of sensation between the hands and the seat expressed in acceleration with the MEDIUM magnitude overlaid with equivalent comfort contours from previous studies. The contours were adjusted to produce equivalent discomfort according to the relative sensitivity between the hands and seat at 12.5 Hz as determined by Morioka (2007).

7.6.2 Effect of vibration magnitude

The relative discomfort caused by vertical vibration of the hands, the feet and the seat varied with the magnitude of 4 Hz vibration between the hands and the seat, but not with the magnitude of 8 Hz vibration. The magnitude dependence of the relative sensitivity to vibration at the two locations indicates the two locations have different rates of growth of discomfort with increasing magnitude of vibration. Figure 7.11 shows the median accelerations at the hands, the feet and the seat that produced equivalent discomfort at 4 Hz and 8 Hz for three magnitudes of vibration. The diagonal line drawn in the figure indicates an equal rate of growth of sensation between the hands and the feet or between the hands and the seat. Although the results for 8 Hz are parallel to the diagonal line, the results for 4 Hz between the hands and the seat are not parallel to the line, but indicate discomfort grows faster (a greater rate of growth of sensation) at the seat than at the hands when exposed to vertical vibration at 4 Hz.

The finding is partly consistent with previous research that determined the rate of growth of sensation: the rates of growth of sensation determined by the present author in Experiment 2 (see Chapter 6) and determined by previous studies are compared in Table 7.7. The median rate of growth of sensation for 4 Hz vibration at the seat was 0.897 as determined by Morioka and Griffin (2006a) but at the hands it was 0.710 as determined by Morioka and Griffin (2009) or 0.875 (Experiment 2), supporting the present finding by the greater rate of growth at the seat than at the hands, although not very different. For 8 Hz vibration, the median rate of growth of sensation at the hands, the feet and the seat are expected to be similar (in order to support the present finding), but varied from 0.456 to 0.791. this might be attributed to the use of a different reference frequency and a different range of vibration magnitudes. The magnitude-dependence in the present results implies that the frequency-dependence in the relative sensitivity between the hands and the seat will depend on vibration magnitude.

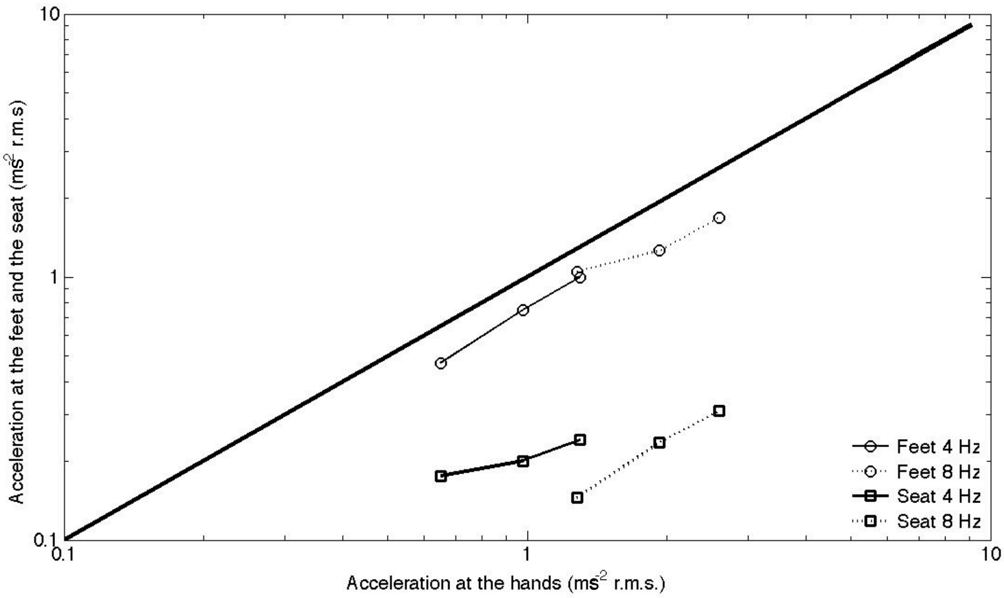

Figure 7.11: Effect of vibration magnitude on the equivalence of sensation between the hands and the feet and between the hands and the seat for 4-Hz and 8-Hz.

Table 7.7: Rate of growth of sensation (n) for 4 and 8 Hz vibration at the hands, at the feet and at the seat determined in Experiment 2 and in previous studies.

	Rate of growth (n)				
Frequency	Hands		Feet		Seat
	Morioka & Griffin (2008)	Experiment 2 Chapter 6	Morioka & Griffin (2010)	Experiment 2 (Chapter 6)	Morioka & Griffin (2006b)
4 Hz	0.710	0.875		0.827	0.897
8 Hz	0.558	0.791	0.75	0.456	0.702

7.7 Conclusions

The magnitudes of vertical vibration required producing equivalent sensations between the hands and the feet and between the hands and the seat indicating a greater sensitivity to vertical vibration at the seat than at the feet and the hands over the frequency range 4 Hz to 12.5 Hz. With increasing frequency there is a decrease in the ratio, from 6.3 Hz to 12.5 Hz between the equivalent feet acceleration and the equivalent hands acceleration and from 4 Hz to 6.3 Hz between the equivalent seat acceleration and the equivalent hands acceleration.

The frequency-dependence in the equivalence of sensation between the three inputs is consistent with the previous finding that the frequency-dependence of equivalent comfort contours at the hands, the feet and the seat are different. The absence of a strong magnitude-dependence in the relative sensitivity at the hands and the feet with 4-Hz vibration indicates that at these two frequencies the hands and the feet have similar rates of growth of discomfort with increasing magnitude of vibration. On the other hand a magnitude-dependence in the relative sensitivity found between the hands and the seat at 4-Hz vibration indicates that the hands and the seat have different rates of growth of discomfort with increasing vibration magnitude.

Chapter 8

Difference thresholds and discomfort caused by phase between multiple-input vertical vibration

8.1 Introduction

Discomfort due to multiple vibration input is dependent from the input locations involved, difference on vibration sensitivity (this was examined in the previous Chapter 7). Another factor that may influence the discomfort is when phase is introduced between the vibration inputs, in order to examine how the introduction of phase on a multiple-input motion can alter the overall discomfort compared to an in-phase multiple-input motion its is necessary to determine the difference thresholds for the detection of phase between vertical motions at pairs of inputs. Since phase thresholds are calculated then the next step is to examine the effects of the detectable phase motions on discomfort.

8.2 Objective

The objective of this experiment was to determine the difference thresholds (just noticeable difference, JND) for the detection of phase between vertical motions at pairs of inputs (i.e. the hands and the feet, the hands and the seat, the seat and the feet) at frequencies from 2 to 12.5 Hz and to examine the effects of the phase motions on discomfort. The localisation (i.e. body location) at which phase differences are detected was also investigated.

8.3 Hypothesis

According to the findings (see Chapter 2) from previous studies by Jang and Griffin (1999), Jang and Griffin (2000) and Dupuis et al. (1972) on the effect on discomfort from phase of differential vertical vibration at the seat and the feet, and also a study by Pamouktsoglou (2008) on determination of phase thresholds for phase motion between the hands and the feet, it was hypothesized that phase thresholds at low frequencies (2 to 5Hz) are expected to be lower than high frequencies (5 to 12.5 Hz due to the biodynamic response (for frequencies greater than 6 Hz the body presents spring and damping properties where below 6 Hz it is more a mass like system as proposed by Dupuis et al. (1972).

Since the phase caused by multiple input vibration involves different contact areas and body locations between the vibration inputs (i.e. seat vibration is perceived at a greater area of the body compared to the hands and the feet), it is hypothesized that phase motions involving the seat are expected to present lower phase thresholds (greater sensitivity to detect the phase difference). Although not many studies investigated vibration discomfort caused by out of phase motions between two inputs, the findings by Jang and Griffin (1999) suggest that vibration discomfort can be influenced by the phase between the seat and the feet, particularly at low vibration magnitude and low frequencies.

8.4 Method

8.4.1 Subjects

Twelve healthy male subjects aged between 23 and 41 years old with a mean age of 29.2 years old (standard deviation, SD=5.6), mean stature 173.6 cm (SD=7.5), and mean weight 74.5 kg (SD=16.6) participated in the experiment. Eleven out of twelve subjects participated in the previous experiment (see Chapter 7) were invited to participate in this experiment. An additional subject (12th) recruited for this experiment had to participate in the previous experiment (see Chapter 7) before being able to participate in this experiment. The reason why all subjects needed to participate in the previous experiment is that it was necessary to acquire individual vibration magnitudes producing equivalence of sensation between the hands, the seat and the feet for each subject, in order to conduct this study. None of the subjects had experienced severe exposure to vibration. A series of anthropometric measurements (sitting height, hand length, etc.) were obtained to investigate any association with their judgements of vibration detection and vibration discomfort.

8.4.2 Apparatus

Vertical vibration at the hands, at the feet, and at the seat was delivered using a multiple-input vibration simulator via rigid cylindrical handles (100 mm in length, 30 mm in diameter), rigid footrests (30.5 mm x 10.5 mm with 10-degree inclination) and a rigid contoured seat (250 mm x 150 mm) mounted on electrodynamic vibrators (MB Dynamics for the hands the feet, Derritron VP85 for the seat) (see Figure 8.1). The vertical vibration was defined as the x-axis at the hands and the feet and in the z-axis at the seat, using a conventional basicentric co-ordinate system. Piezoelectric accelerometers (DJ Birchall model A/20/T at the handles and the footrests and BK model 4371 at the seat) were mounted on the vibrating surfaces of the seat so as to measure the acceleration during the experiment. The vibration stimuli were created and acquired using HVLab Data Acquisition and Analysis software (version 3.81) via a personal computer. The computer was fitted with anti-aliasing filters (TechFilter) and the signals were digitised by an analogue-to-digital converter (PCL-818) at a fixed sample rate of 2000 samples per second. The background vibration due to electrical noise at 50 Hz was less than 0.006 ms^{-2} r.m.s in the vertical direction.

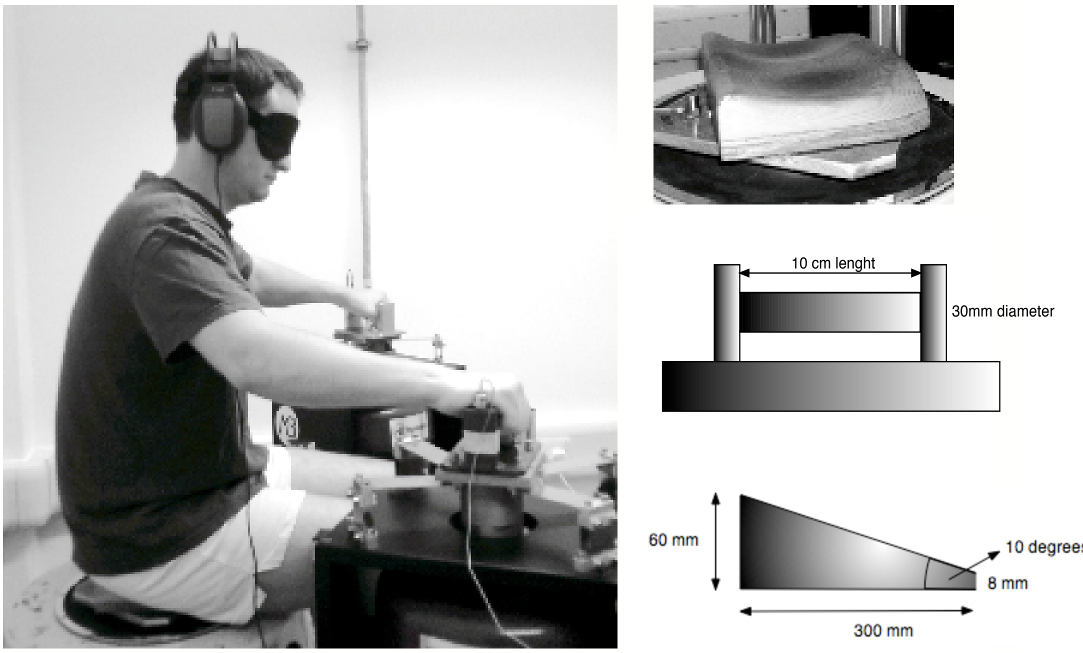

Figure 8.1: Set-up of the rig: independent vibration inputs to the hands, the feet and the seat. The subjects wore socks but no shoes.

8.4.3 Stimuli

Sinusoidal vibration of 4 seconds duration including 500 ms cosine-tapered ends was created in the range of 2 to 12.5 Hz for sessions involving vibration between the hands and the feet and between 4 to 12.5 Hz for the sessions involving vibration between the hands and the seat and between the feet and the seat.

The vibration stimuli at hands and feet had frequency range 2 to 12.5 Hz, whereas the vibration stimuli at the seat had frequency between 4 to 12.5 Hz. For vibration stimuli at the hands, all the subjects were presented with the same pre-fixed magnitudes (see Table 8.1), giving the same velocity at all frequencies, This was because it was found in the previous experiment (see Chapter 7) that equivalent comfort contours for the hands over the frequency range 2 to 12.5 Hz showed approximately constant velocity (see Chapter 6). The vibration magnitudes at the feet and the seat were individually adjusted (according to the results of the previous experiment, Chapter 7), so as to ensure that the vibration at the three body locations produced similar sensation for each subject. For each frequency, vibration stimuli at the seat and the feet were prepared with various phases from 0^o to 180^o in 15^o step. Table 8.1 shows the fixed magnitudes presented at the hands and the median magnitudes at the feet and the seat from the twelve subjects of this experiment, producing equivalence of sensation between the hands, the seat and the feet.

TABLE 8.1: Stimuli used for the study, with the accelerations of the seat and feet shown here are median acceleration from the 12 subjects producing equivalence of sensation between the hand, seat and feet.

Hands		Seat		Feet	
Frequency (Hz)	Magnitude ms^{-2} r.m.s	Frequency (Hz)	Median magnitude ms^{-2} r.m.s	Frequency (Hz)	Median magnitude ms^{-2}r.m.s
2	0.49			2	0.29
2.5	0.67			2.5	0.44
3.15	0.76			3.15	0.53
4	0.64	4	0.17	4	0.47
4	0.97	4	0.20	4	0.75
4	1.29	4	0.24	4	1.00
5	1.25	5	0.20	5	1.06
6.3	1.60	6.3	0.17	6.3	1.36
8	1.29	8	0.14	8	1.05
8	1.97	8	0.23	8	1.26
8	2.58	8	0.31	8	1.68
10	2.40	10	0.27	10	1.14
12.5	3.00	12.5	0.30	12.5	0.89

8.4.4 Procedure

The subjects attended three different conditions with each condition consisting two tests (i.e. a and b), as described in Table 8.2. The test a involved determination of difference thresholds of phase motions and test b looked at the effect of phase motions on discomfort. The three conditions (i.e. A, B and C) were tested on a separate day and were randomly presented in order to minimise possible order effects. During the experiment, the subjects were barefoot, but with socks on, and they were also wearing a pair of headphones presenting white noise at approximately 75 dB(A) in order to minimise any audible clues.

TABLE 8.2: Three conditions and six tests designed for this experiment

Condition	Test	Description
A: HANDS & FEET	Aa	Difference thresholds of phase between motions at the hands and the seat
	Ab	Effect of phase between hands and seat on discomfort
B: HANDS & SEAT	Ba	Difference thresholds of phase between motions at the feet and the seat
	Bb	Effect of phase between feet and seat on discomfort
C: SEAT & FEET	Ca	Difference thresholds of phase between motions at the hands and the feet
	Cb	Effect of phase between hands and feet on discomfort

8.4.4.1 Difference thresholds of phase between motions (Tests Aa, Ba, and Ca)

Difference thresholds for vibration phase caused by multiple-input vertical vibration (between the hands and eat, the seat and feet, or the hands and feet) were determined using the staircase method in conjunction with 3-down 1-up rule. In order to ensure the subjects perceived the similar degree of vibration sensation between the two inputs (i.e. hands, seat, feet), the magnitude of the stimuli was adjusted individually according to the results obtained from the previous experiment (see chapter 7). The magnitudes of the hands, the seat and the feet produced approximately similar sensation level for each subject. The median vibration magnitudes at the seat and the feet from the twelve subjects of this experiment and the fixed magnitudes of vibration at the hands are shown in Table 8.1.

The subjects were exposed to a series of trials; each trial consisted of three 4.0-second stimuli (divided by 1.0-second pause) of the same frequency. One of the three stimuli was out-of-phase and the other two stimuli were in-phase of vertical vibration between the two inputs (i.e. hands-seat, seat-feet, or hands-feet). The order of presenting the three stimuli was randomised (see Figure 8.2 for an example presentation of the three stimuli). After each exposure of the trial, the subjects were asked to judge which of the three stimuli they perceived different from the other stimuli by answering first, second or third. After each incorrect answer the phase of the out-of-phase stimuli was increased by 15 degrees (until reaching the first reversal, a phase step was set at 30 degrees). After the three consecutive correct answers, the phase of the out-of-phase stimuli was decreased by 15 degrees. When six reversal points (the point where changing the direction of stimuli) were collected, the test was complete. In the case which the subjects were unable to detect any difference between the three presented motions (incorrect answers) and reached the maximum value (i.e. 180 degrees), the test was stopped and the phase threshold from the test was assigned as 180 degrees.

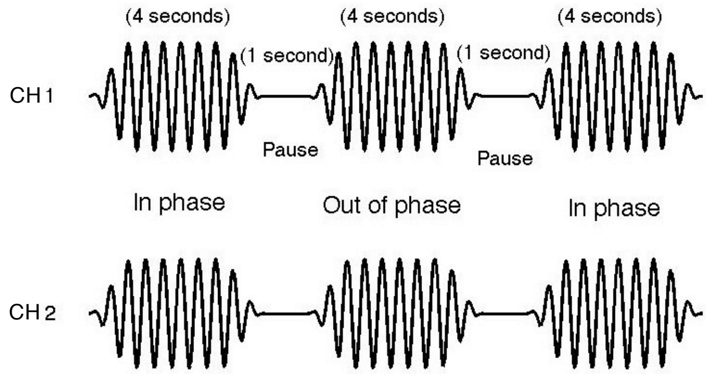

FIGURE 8.2: An example of a single trial consisting of three motions employed for Test Aa, Ba, Ca (The second stimulus being out of phase).

After each threshold test, the subjects were asked to indicate which part of the body they detected the difference among the three motions (i.e. first, second or third) by referring to a number provided on the bodymap shown in Figure 8.3. They were instructed to give a number of zero), if they could not detect the difference at anywhere in the body.

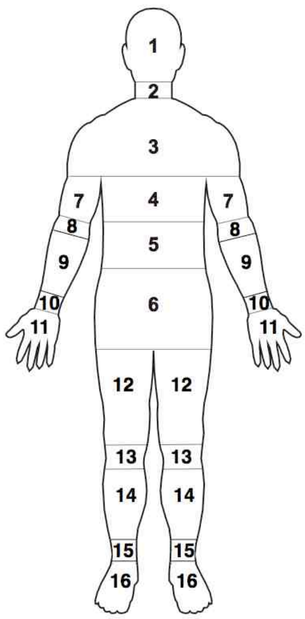

FIGURE 8.3: Bodymap presentation. The subjects were asked to indicate which part of the body they detected the difference by assigning a number shown on the bodymap

8.4.4.2 Effect of phase between the hands and seat on discomfort (Tests Ab, Bb, and Cb)

Discomfort due to out of phase motions was investigated through Tests Ab, Bb and Cb for each combination (a pair of inputs), as described in Table 8.2. The method of magnitude estimation was used; a 4.0 sec in-phase (zero degree) reference stimulus was followed by a 1.0-second pause and then a 4.0-second out-of phase test stimulus with the same pair of the reference and the test stimuli being repeated twice, as shown in Figure 8.4. The magnitude of the reference and the test stimuli were identical. The discomfort caused by phase between two input locations was investigated with a total of 9 frequencies (for Test Ab, Bb) and 12 frequencies (for Test Cb), with a total of 7 test stimuli (in phase step of 30 degrees) at each frequency, as summarised in Table 8.3. The reference (in-phase motion) and the test (out-of phase motion) were presented at the same location for each test. The test stimuli were randomly presented in order to minimise any possible order effects. After each exposure, the subjects were asked to judge the discomfort caused by the test motion relative to the discomfort of the reference motion (zero degree phase). The discomfort of the reference motion was fixed with a nominal value of 100.

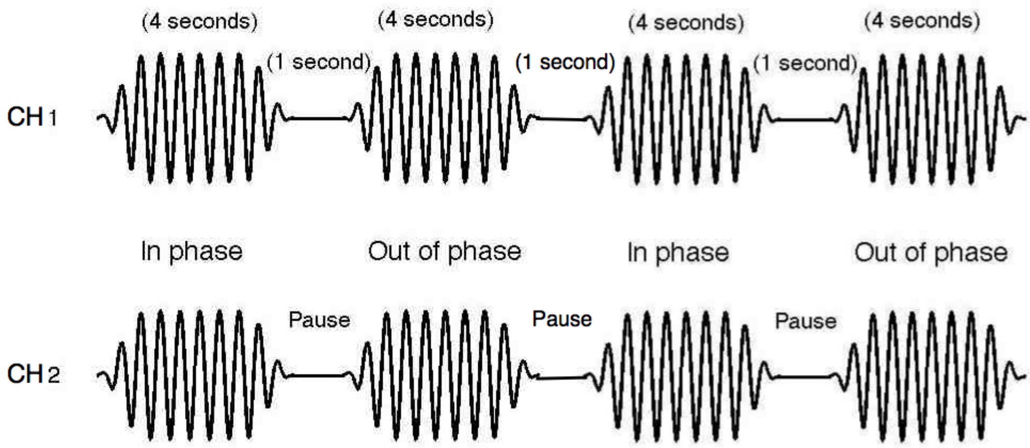

FIGURE 8.4: An example of stimuli presentation for Tests Ab, Bb, Cb. The reference stimulus was evaluated with 100% discomfort.

Table 8.3: Organisation of the stimuli employed for the study. The vibration magnitude of the reference and the test stimuli was identical

	Frequency (Hz)	Phase degree						
		0	30	60	90	120	150	180
HANDS & FEET	2, 2.5, 3.15 4(1), 4(2), 4(3) 5, 6.3 8(1), 8(2), 8(3) 10, 12.5	Reference	Test1	Test2	Test3	Test4	Test5	Test6
HANDS & SEAT	4(1), 4(2), 4(3) 5, 6.3, 8(1) 8(2), 8(3), 10, 12.5							
FEET &SEAT								

After each phase discomfort trial, the subjects were asked to indicate on which part of the body they judged the discomfort of the out-of-phase stimuli by referring to a number provided on the bodymap shown in Figure 8.3.

8.5 Analysis

Phase thresholds were calculated by averaging the last four reversal points (out of six reversals). In the case of subjects being unable to distinguish the difference between the in-phase and out-of phase motions before reaching six reversals, the threshold value was assigned as 180 degrees, which corresponds to no sensation of phase motions. Discomfort due to phase motions presented as a function of phase for each frequency (see Section 8.6.2). The localisation of sensation was determined immediately after each of the phase thresholds test and the vibration discomfort test. The location data were analysed by calculating percentage of subjects who assigned specific body locations (e.g. lower body, upper body) for each stimulus, as presented in Section 8.6.3.

8.6 Results

8.6.1 Thresholds for the detection of phase between vibration at pairs of inputs

8.6.1.1 Effect of frequency

The median difference thresholds of phase between vertical vibration at the pairs of inputs determined with the three conditions (HANDS FEET, HANDS SEAT, and SEAT FEET) from the twelve subjects are shown in Figures 8.5, 8.6 and 8.7) With vertical vibration between the hands and the feet, the ability to detect the phase difference of vertical vibration between the two inputs significantly depended on the frequency (Friedman, $p<0.001$); with the 2 Hz causing significantly lower difference thresholds (in terms of phase degrees) than any greater frequencies (2.5 to 12.5 Hz) investigated (Friedman, $p< 0.03$) (see Figure 8.5). At frequencies greater than 5 Hz, more than 90% of the subjects were unable to detect any phase differences (threshold values of 180 degrees). Between the hands and the seat or between the feet and the seat (see Figure 8.6 and 8.7), the detection thresholds for vibration phase between the two input locations did not show any significant effect of the vibration frequency (Friedman, $p>0.3$) for the range of frequencies investigated (4-12.5 Hz).

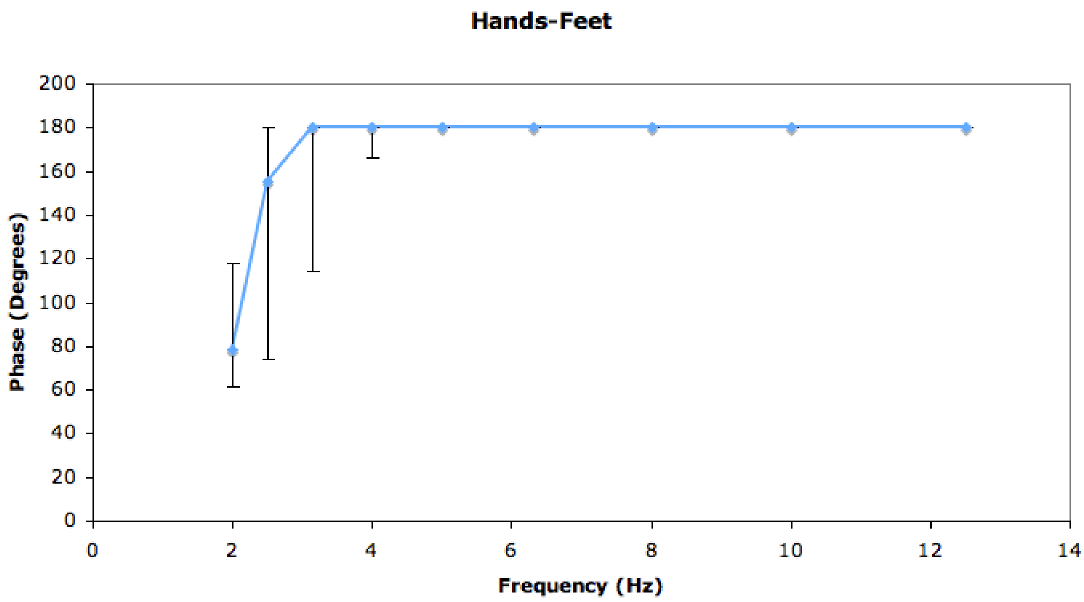

FIGURE 8.5: Median phase thresholds between hands and feet and inter-quartile range (25-75 percentiles) from the twelve subjects at 2 to 12.5 Hz.

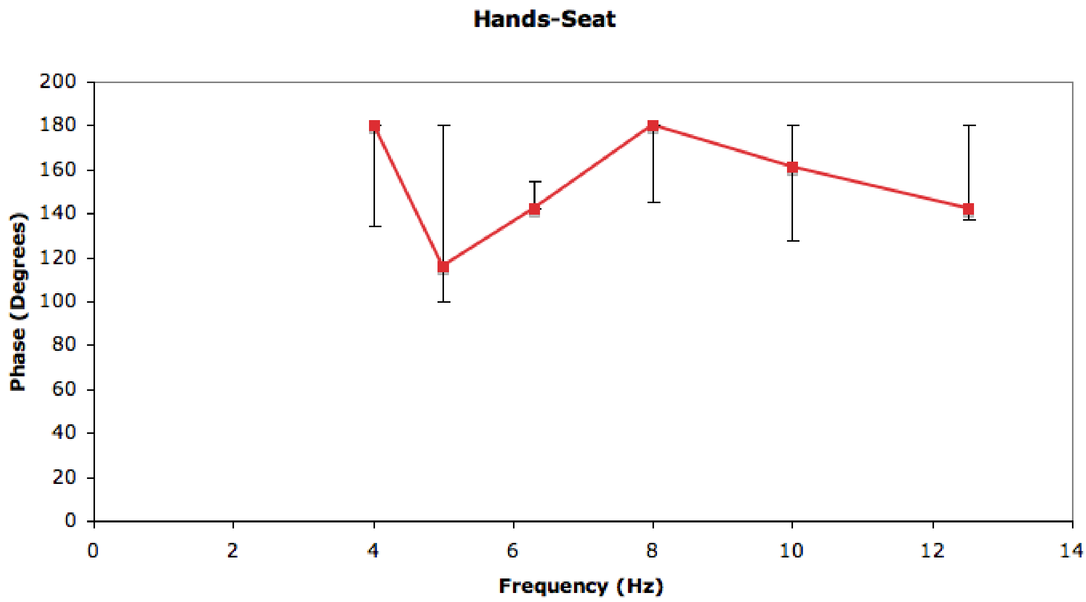

FIGURE 8.6: Median phase thresholds between the hands and seat and inter-quartile range (25-75 percentiles) from the 12 subjects at 4 to 12.5 Hz.

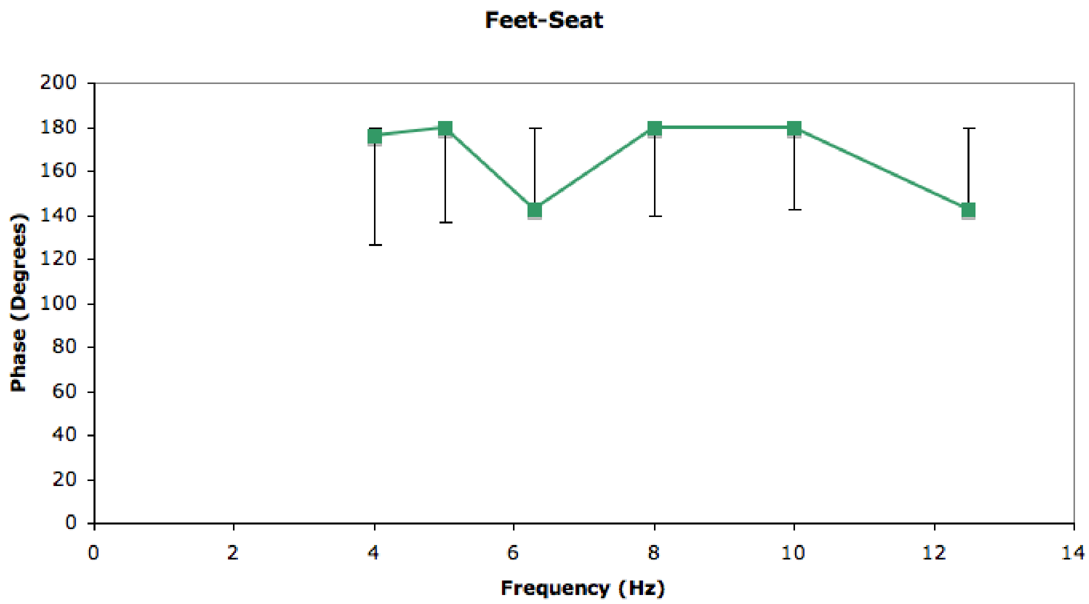

FIGURE 8.7: Median phase thresholds between the feet and seat and inter-quartile range (25-75 percentiles) from the 12 subjects at 4 to 12.5 Hz.

8.6.1.2 Effect of magnitude

The difference thresholds of phase between vertical vibration at the hands and the feet, between the hands and the seat, and between the feet and the seat were determined with three magnitudes at 4 Hz and 8 Hz. The median and inter-quartile range of the thresholds from the twelve subjects were expressed as a function of vibration magnitude in Figures 8.8, 8.9 and 8.10, respectively. With all combinations of the pairs of input locations, there were no significant effects of magnitude on the thresholds for detection of phase motions at both 4 Hz and 8 Hz (Friedman, $p>0.09$).

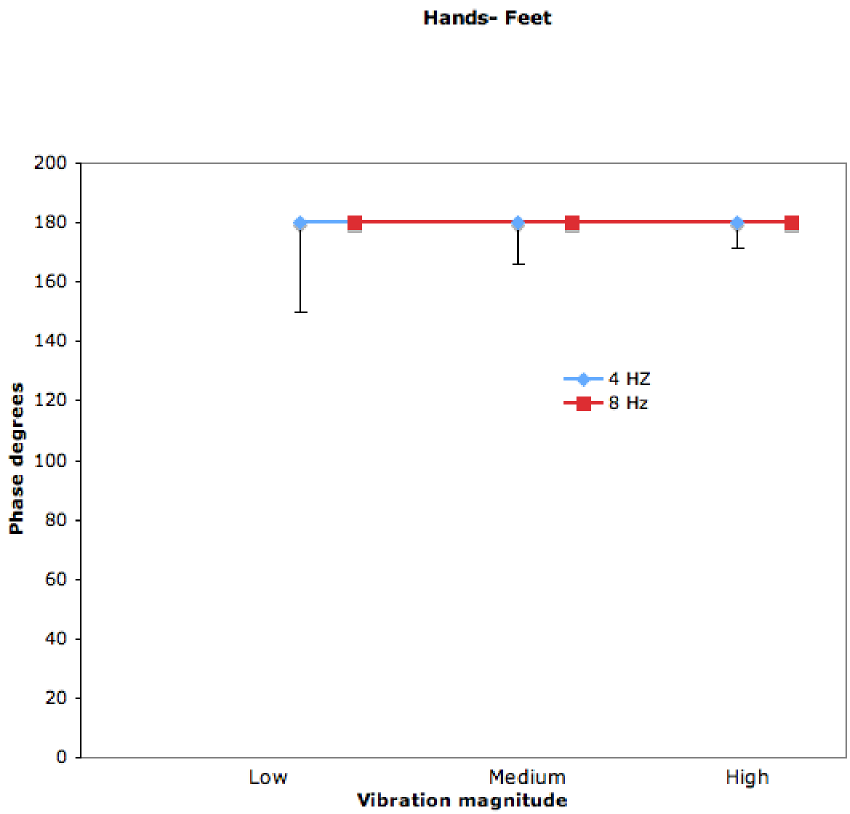

FIGURE 8.8: Median phase thresholds between the hands and feet and the inter-quartile range (25-75) for 12 subjects at three different vibration magnitudes at 4 and 8 Hz

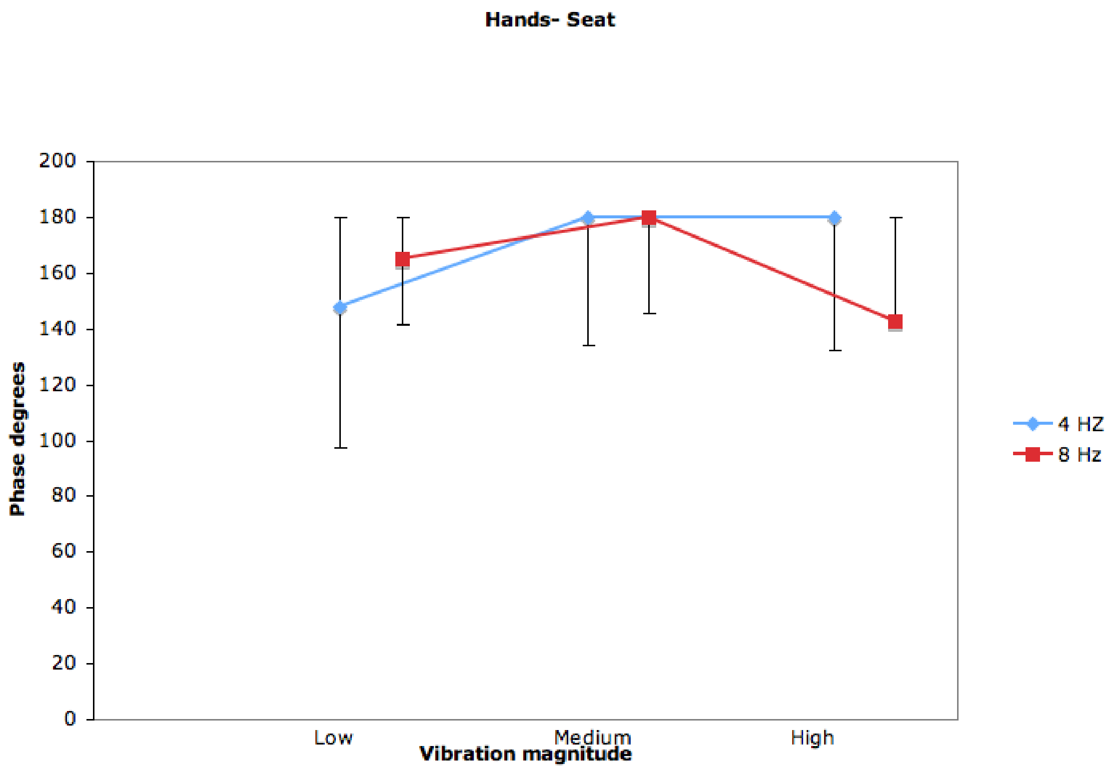

FIGURE 8.9: Median phase thresholds between the hands and seat and the inter-quartile range (25-75) for 12 subjects at three different vibration magnitudes at 4 and 8 Hz.

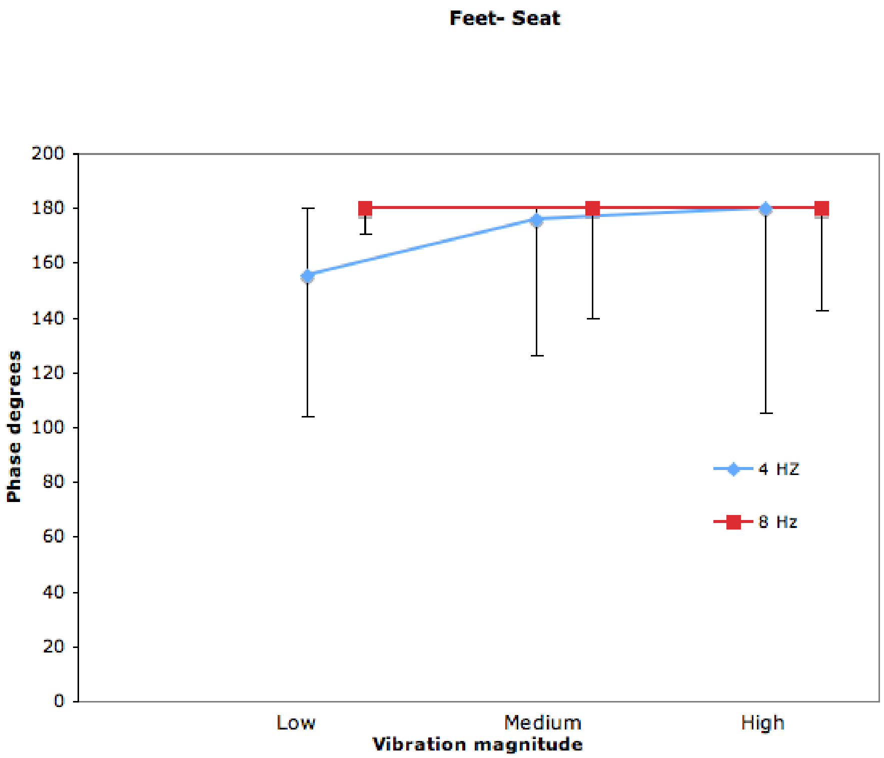

Figure 8.10: Median phase thresholds between feet and seat and inter-quartile range (25-75) for 12 subjects at three different vibration magnitudes at 4 and 8 Hz.

8.6.1.3 Effect of input location

A comparison of the thresholds for detection of differential phase of vertical vibration between the three combinations of the pairs of inputs (i.e. HANDS FEET, HANDS SEAT, and SEAT FEET) is presented in Figure 8.11. The phase thresholds significantly differed between the three combinations of the pairs of inputs at 5, 6.3, 10 and 12.5 Hz (Friedman, $p<0.05$). At 5 and 6.3 Hz, the phase thresholds were significantly lower with the pairs of inputs involving vibration at the seat (i.e. HANDS SEAT and FEET SEAT) than the pair of inputs not involving vibration at the seat (i.e. HANDS FEET) (Wilcoxon, $p<0.05$). At 10 and 12.5 Hz, the thresholds for detection of phase between motions of the hands and seat were significantly lower than that of the hands and the feet (Wilcoxon, $p<0.05$).

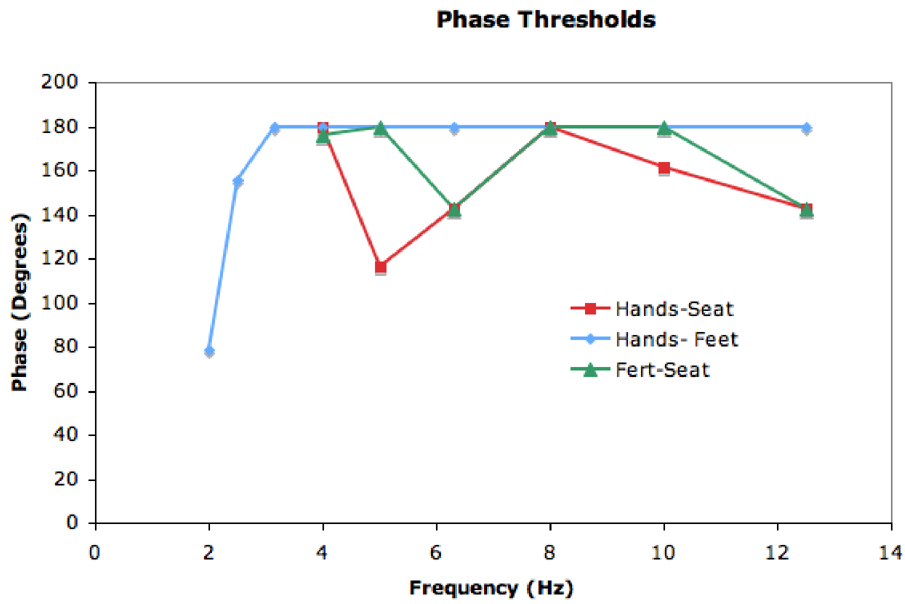

FIGURE 8.11: Comparison of the median phase thresholds between pairs of the three examined paired inputs (i.e. hands-feet, hands-seat, feet-seat).

8.6.2 Discomfort due to phase between vibration at pairs of inputs

Median discomfort ratings due to phase between vibration at the pairs of inputs for each frequency are overlaid with the median phase thresholds of the same frequency, which are shown in Figures 8.12, 8.13 and 8.14. With vibration at the hands and the feet, the phase differences did not alter the discomfort ratings at any of the frequencies investigated (2.0-12.5 Hz), except at 8 Hz (Friedman, $p=0.014$) where the discomfort ratings at 60 degrees were significantly higher than that of 120 and 180 degrees (Wilcoxon, $p<0.03$), the ratings at 150 degrees were significantly higher at 150 degrees than that of 120 and 180 degrees (Wilcoxon, $p<0.03$) (see Figure 8.12).

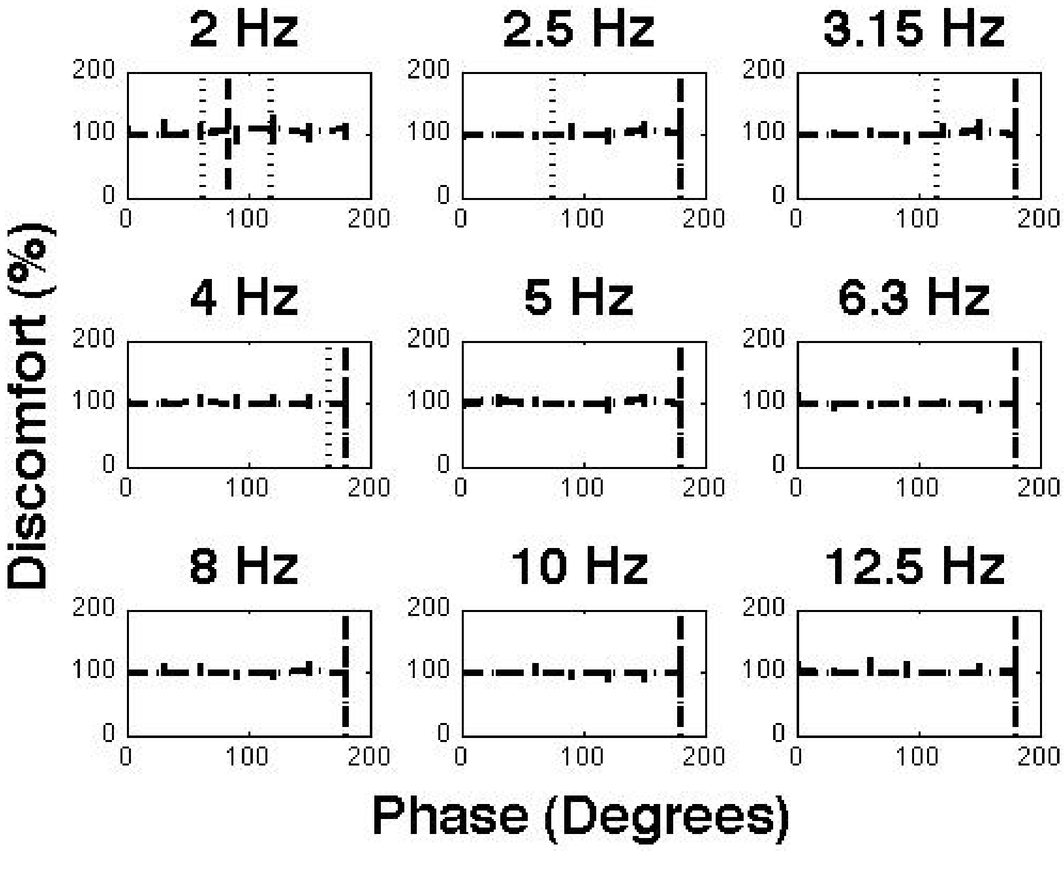

FIGURE 8.12: Median values of discomfort rating due to phase motion between the hands and feet (The vertical lines indicate the median and the inter-quartile range phase thresholds).

With vibration at the hands and the seat, there was a significant effect of the phase difference on discomfort for all six frequencies investigated (Friedman, $p<0.05$). Additional statistical tests showed that the discomfort significantly increased (except at 4 Hz) when the phase difference between vibration at the hands and the seat was at 150 degrees (compared to discomfort at any other phase degrees) at 6.3, 8, 10 and 12.5 Hz (Wilcoxon, $p<0.01$) and at 180 degrees (compared to discomfort at lower phase degrees) at 5 and 10 Hz (Wilcoxon, $p<0.05$). At 4 Hz, the discomfort caused by the phase difference at 150 degrees were significantly less than those by any other phase degrees (Wilcoxon, $p<0.05$).

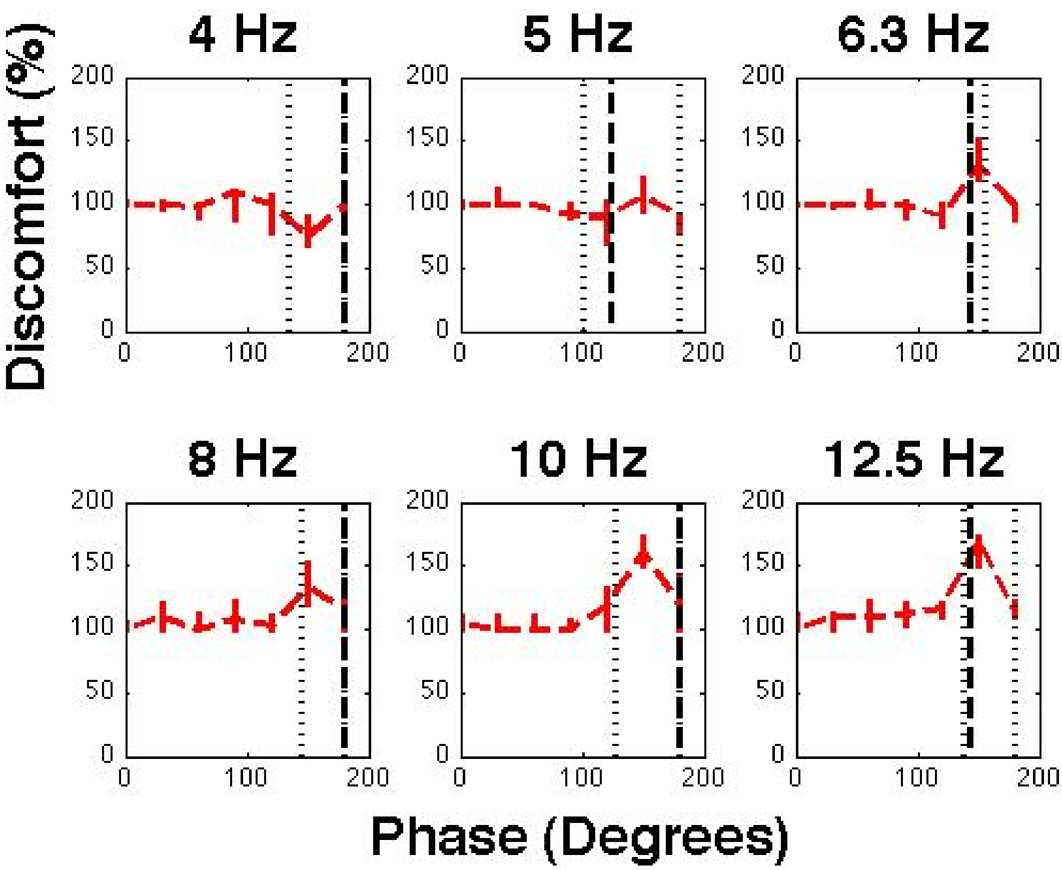

FIGURE 8.13: Median values of discomfort rating due to phase motion between the hands and seat (The vertical lines indicate the median and the inter-quartile range phase thresholds).

Similarly, the discomfort ratings are significantly influenced by phase differences between vibration at the feet and the seat for all frequencies (Friedman, $p<0.05$) except at 4 Hz (Friedman, $p=0.191$). Additional statistical tests showed significantly increased discomfort with the phase differences of vibration at 150 degrees (compared to discomfort at any other phase degrees) at 6.3, 8, 10, 12.5 Hz (Wilcoxon, $p<0.05$). The discomfort caused by phase difference at 180 degrees tended to be greater than lower phase degrees less than 90 degrees (Wilcoxon, $p<0.05$).

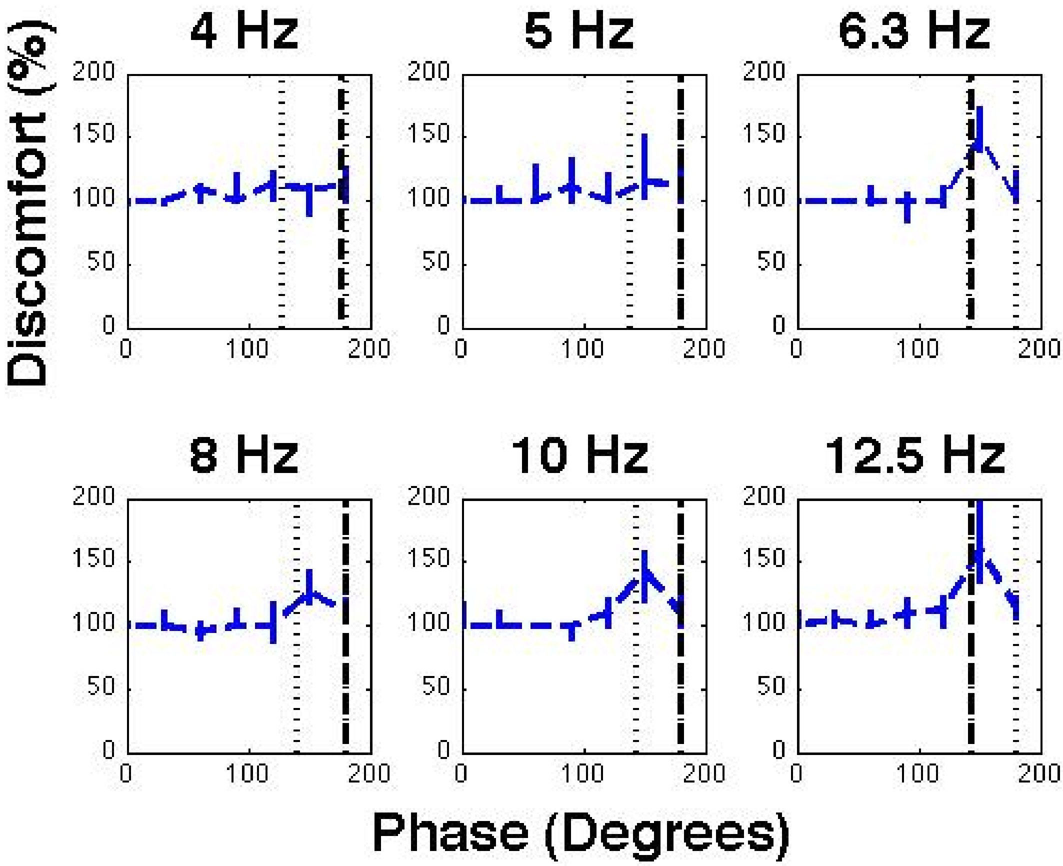

Figure 8.14: Median values of discomfort rating due to phase motion between the feet and seat. (The vertical lines indicate the median and the inter-quartile range phase thresholds).

8.6.3 Localisation of sensation caused by vibration phase

The collected data at each frequency were transformed into percentage values, describing a percentage of the subjects who detected the vibration phase at each of the body locations shown in the bodymap). The body locations in the bodymap were then re-categorised into three categories (i.e. upper body, lower body and no sensation) and presented in Tables 8.5, 8.7 and 8.9.

8.6.3.1 Hands and feet

TABLE 8.4: Categorisation of bodymap locations

Upper body	1, 2, 3, 7, 8, 9, 10, 11
Lower body	4, 5, 6, 12, 13, 15, 16
No sensation	0

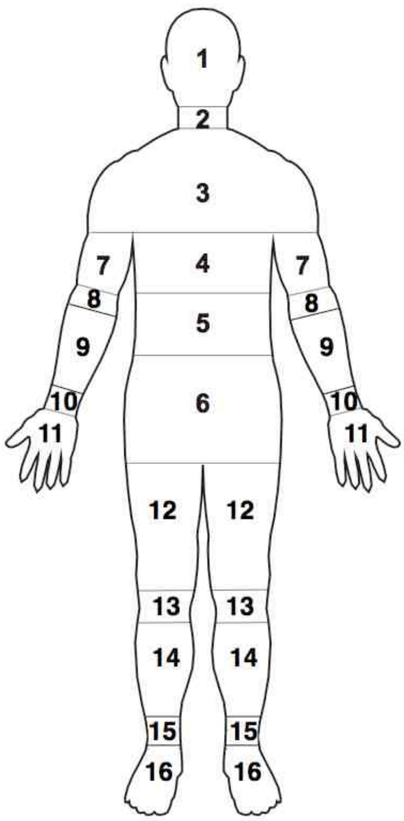

FIGURE 8.15: Bodymap

As it can seen on Table 8.5, vibration phase was perceived at both parts of the body (i.e. upper body and lower body). For frequencies between 2 to 5 Hz the sensation was approximately divided equally between the upper and lower body, except at 3.15 where the detection was major at the lower body and at 4(H) Hz where one third of the subjects did not felt any phase motions. As frequency increased from 6.3 to 12.5 Hz it is evident that almost half of the subjects were not able to distinguish the difference between an in-phase and out-of phase motion, except at 8(H) Hz where the majority of the subjects felt the out-of phase motions at the lower body.

With respect of vibration discomfort due to phase motions it can be seen at Table 8.5 that although at low frequencies from 2 to 5 Hz there was sensation of phase motions as mentioned before, there were subjects, ranging from 17 up to 34 % who did not feel any change on discomfort compared to an in-phase motion, except at 2 Hz that all the subjects felt either at the upper body or the lower body. For higher frequencies from 6.3 to 12.5 Hz there was not much divergence compared to the phase sensation data, since there was a logical consistency in terms of no sensation of phase motions had as result of no change of discomfort.

Table 8.5: Percentage of subjects who perceived the vibration phase between the hands and the feet for the phase thresholds and phase discomfort at two main locations recategorised from the bodymap.

Frequency Hz	2	2.5	3.15	4(L)	4(M)	4(H)	5	6.3	8(L)	8(M)	8(H)	10	12.5
Location	Percentage (%) - Body location of detecting vibration phase												
Upper body	42	58	8	34	50	25	58	25	34	25	25	16	25
Lower body	58	34	84	58	42	42	34	33	8	17	58	42	33
No sensation	0	8	8	8	8	33	8	42	58	58	17	42	42
Location	Percentage (%) - Body location of detecting vibration discomfort												
Upper body	50	33	33	33	34	8	33	25	25	33	33	25	42
Lower body	50	42	50	42	58	58	50	33	58	33	50	42	33
No sensation	0	25	17	25	8	34	17	42	17	34	17	33	25

8.6.3.2 Hands and seat

Table 8.6: Categorisation of bodymap locations

Center body	1, 2, 3, 4, 5, 6, 12
Hands and arms	7, 8, 9, 10, 11
No sensation	0

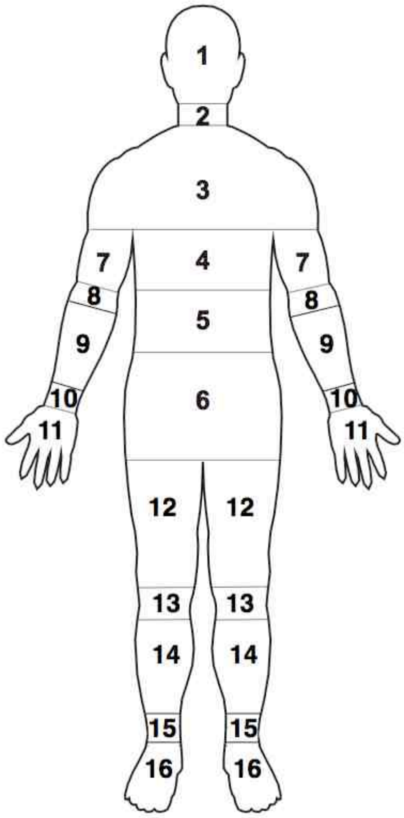

Figure 8.16: Bodymap

As it can seen on Table 8.7, vibration phase was detected at both parts of the body (i.e. upper center body and hands and arms). Almost for all frequencies between 4 to 12.5 Hz the sensation was approximately divided between the upper center body and the hands and the arms, except for a small percentage (i.e. 8%) at 4(H), 6.3, 8(L), 8(H) and 10 Hz did not feel any sensation of phase motions.

With respect of vibration discomfort due to phase motions it can be seen in Table 8.7 that discomfort due to phase motions was perceived from the subjects except at 12.5 Hz where 25% of the subjects did not feel any discomfort although phase motions were detectable. This shows that phase motions between the hands and the seat were detectable in terms of threshold and discomfort.

Table 8.7: Percentage of subjects who perceived the vibration phase between the hands and the seat for the two studies at two main locations recategorised from the bodymap.

Frequency Hz	4(L)	4(M)	4(H)	5	6.3	8(L)	8(M)	8(H)	10	12.5
Location	Percentage (%) - Body location of detecting vibration phase									
Upper center body	42	33	25	50	8	8	25	34	42	25
Hands and arms	58	67	67	50	84	84	67	58	50	75
No sensation	0	0	8	0	8	8	8	8	8	0
Location	Percentage (%) - Body location of detecting vibration discomfort									
Upper center body	17	75	58	67	58	50	83	42	50	58
Hands and arms	75	25	25	33	34	33	17	50	50	42
No sensation	8	0	17	0	8	17	0	8	0	25

8.6.3.3 Feet and seat

Table 8.8: Categorisation of bodymap locations

Upper body	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
Lower body	12, 13, 14, 15, 16
No sensation	0

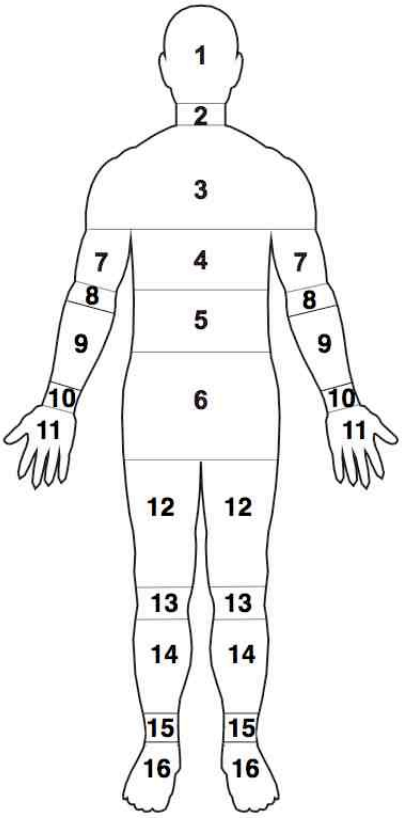

Figure 8.17: Bodymap

As it can seen on Table 8.9, vibration phase was detected at both parts of the body (i.e. upper body and lower body). For almost all frequencies between 4 to 12.5 Hz there was a small percentage from 8 that reached maximum at 25% for 5 Hz that subjects did not detect phase motions, except 4(L) Hz that all subjects were able to detect phase motions. There was no dominant location (i.e. upper or lower body) since the percentages follow a random trend except at 10 Hz where 92% of the subjects felt the phase at the upper body.

With respect to vibration discomfort due to phase motions it can be seen at Table 8.9 that discomfort due to phase motions was detected from the subjects mostly at the lower body for frequencies between 4(L) to 8(L) Hz and as frequency increased from 8(M) to 12.5 Hz the sensation of discomfort was transferred to the upper body. The percentage of the subjects that did not feel any change of discomfort due to phase motions was generally low from 8 to 17% except at 5 Hz where almost one third of the subjects did not feel any change of discomfort compared to an in-phase motion. This exception though can follow the trend of vibration phase detection at 5 Hz where 25% of the subjects were unable to detect phase motions at all, as mentioned previously.

Table 8.9: Percentage of subjects who perceived the vibration phase between the feet and the seat for the two studies at two main locations recategorised from the bodymap.

Frequency Hz	4(L)	4(M)	4(H)	5	6.3	8(L)	8(M)	8(H)	10	12.5
Location	Percentage (%) - Body location of detecting vibration phase									
Upper body	25	17	50	25	75	84	58	42	92	75
Lower body	75	67	33	50	17	8	25	50	0	17
No sensation	0	16	17	25	8	8	17	8	8	8
Location	Percentage (%) - Body location of detecting vibration discomfort									
Upper body	25	17	25	17	50	42	58	58	58	57
Lower body	67	83	67	50	50	42	25	34	25	33
No sensation	8	0	8	33	0	16	17	8	17	0

8.6.4 Minimum and maximum phase detection

The method for determining vibration phase thresholds was the staircase procedure (3-down, 1- up rule). The analysis of the data from phase detection thresholds and discomfort ratings caused by phase motions presents a contradiction for some conditions. There were occasions where some subjects gave significant change in discomfort ratings at specific out-of-phase motions (compared to in-phase = 0 degree phase motions), although these out-of-phase motions were less than median value of phase detection thresholds. This may indicate that majority of the subjects were able to judge changes in discomfort at phase motions which were undetectable by most of the subjects.

This observation may suggest that a threshold of phase motions may be better described in terms of a window (range) value rather than in terms of average (absolute) value. There is a possibility that some subjects were able to detect phase motions for some trials (within a range of the phase degrees), but their ability to detect phase motions fluctuated from time to time and reached 180 degrees, resulting in terminating the test. Figures 8.18, 8.19 and 8.20 overlay the median minimum and maximum phase degree motions at each frequency that subjects were able to detect, these minimum and maximum values derive from the individual values of all 12 subjects, over the individual discomfort ratings caused by phase motions.

The individual data were transformed (see Appendix C, Table C.19, Table C.20, Table C.21) to percentages, as seen in Table 8.13, 8.14 and 8.15, showing how many subjects felt out of phase motions between two inputs (i.e. hands-feet, hands-seat, feet-seat) according to the phase threshold data (threshold was determined when the answer was below 180 degrees) and how many subjects were in the min-max phase detection range (see Appendix C, Table C.55, C.56 and C57). The min-max detection values derive from the threshold test of each subject, according to the staircase procedure (3-down, 1-up rule) and the collection of their reversal points. According to their answers there were three categories of subjects, an example of subjects answers of each category is shown in Tables 8.10, 8.11 and 8.12

a) subjects that produced a spreadsheet with six reversal points

b) subjects had produced none reversal points (incline progress to 180 degrees)

c) subjects had less than six reversal points.

TABLE 8.10: Example of subject answers that produced six reversal points (category a)

PHASE STEP																						
180																						
165																						
150																						
135																						
120																			*	max	*	
105																		*				*
90																	*					
75										*	*	*				*						
60									*				*		*							
45				*	*	*		*						*								
30			*				min															
15		*																				
0	*																					

TABLE 8.11: Example of subject answers that produced none reversal points (category b)

PHASE STEP																								
180													min-max											
165												*												
150											*													
135										*														
120									*															
105								*																
90							*																	
75						*																		
60					*																			
45				*																				
30			*																					
15		*																						
0	*																							

TABLE 8.12: Example of subject answers that produced less than six reversal points (category c)

PHASE STEP																						
180																					*	
165																				*		
150																			*			
135																		*				
120													*	max	*		*					
105												*				*						
90											*											
75										*												
60									*													
45				*	*	*		*														
30			*				min															
15		*																				
0	*																					

The minimum and maximum phase motion, in terms of degrees, from each subject were recorded (noted with min and max in the example Tables 8.10, 8.11, 8.12) and all the data were gathered to create the min-max detection tables. It must be noted that it was not compulsory to produce six reversal points (i.e category c) this is why the data were not labelled as phase threshold but as min-max detection. So according to Table 8.10 the minimum phase value that could be detected was 30 degrees and the maximum value was 120 degrees. For table 8.11 both minimum and maximum phase values are 180 degrees since there was no sensation of phase motions. For Table 8.12 the minimum phase value is 30 degrees and the maximum phase value is 120.

8.6.4.1 Hands and feet

Most of the subjects felt phase motions at low frequencies (i.e. 2 to 4 mid Hz) whereas at frequencies greater than 4 Hz a minority of subjects detected phase motions.

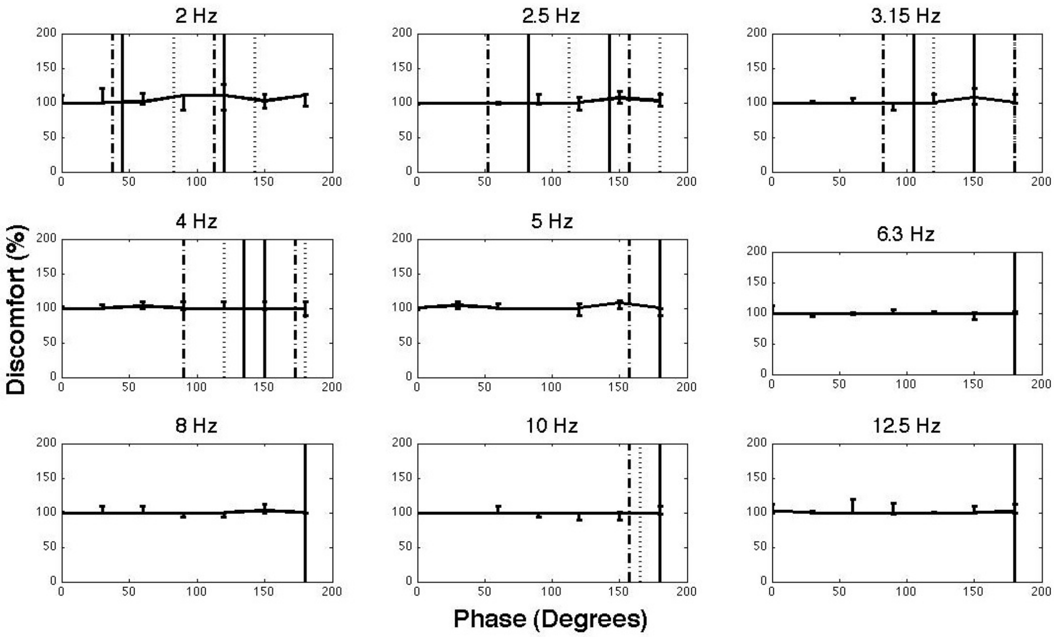

FIGURE 8.18: Median values of discomfort rating due to phase motion between hands and feet with interquartile range (horizontal error marks) and minimum and maximum phase threshold window (vertical solid lines) with interquartile range (dashed-doted vertical lines represent the minimum range and dotted vertical lines represent the maximum range)

Table 8.13: Percentage of subjects that felt the vibration phase between the hands and the feet according to the phase threshold data and the min-max phase detection.

Frequency	**Subjects percentage**	
Hz	Threshold	Min-max
2	75	92
2.5	50	75
3.15	33	67
4 low	42	58
4 mid	25	75
4 high	25	42
5	8	25
6.3	0	0
8 low	8	17
8 mid	8	8
8 high	8	25
10	8	25
12.5	8	17

8.6.4.2 Hands and seat

Most of the subjects felt phase motions at all frequencies when referring to the min-max data, whereas when the phase threshold percentage are used a minority of subjects felt phase motion at 4mid, 4high, 8mid Hz.

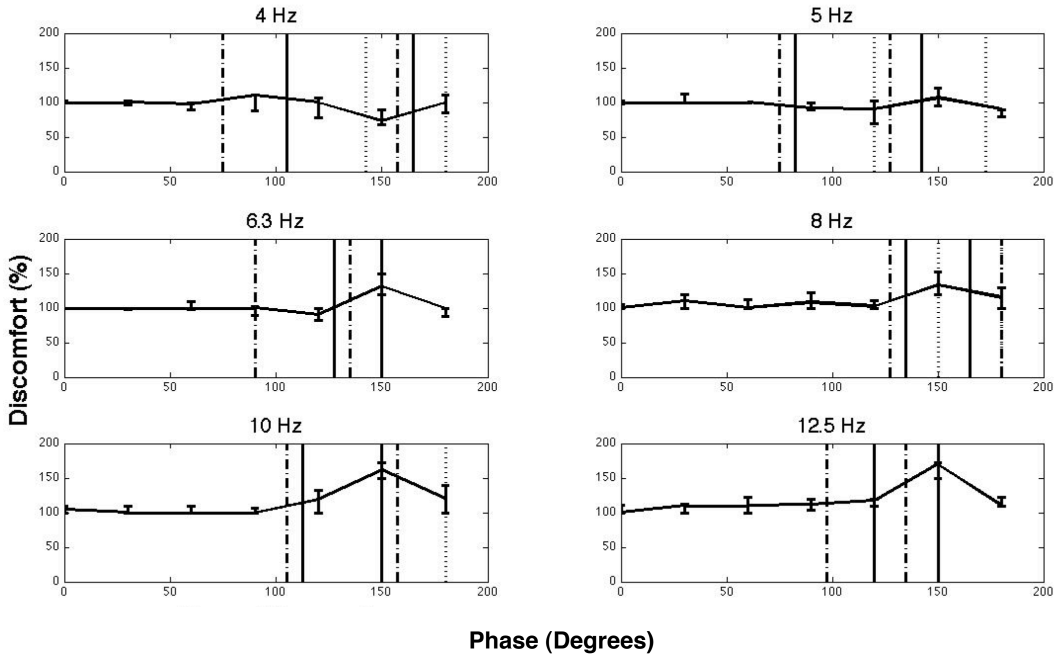

FIGURE 8.19: Median values of discomfort rating due to phase motion between hands and seat with interquartile range (horizontal error marks) and minimum and maximum phase threshold window (vertical solid lines) with interquartile range (dashed-doted vertical lines represent the minimum range and dotted vertical lines represent the maximum range)

Table 8.14: Percentage of subjects that felt the vibration phase between the hands and the seat according to the phase threshold data and the min-max phase detection.

Frequency	**Subject percentage**	
Hz	Threshold	Min-max
4 low	67	83
4 mid	42	75
4 high	42	83
5	58	83
6.3	75	92
8 low	50	58
8 mid	42	67
8 high	58	75
10	50	75
12.5	67	92

8.6.4.3 Feet and seat

Most of the subjects felt phase motions at all frequencies when referring to the min-max data except at 8mid Hz, whereas when the phase threshold percentage are used only a minority of subjects felt phase motions at 4high, 8low, 8mid, 8high and 10 Hz.

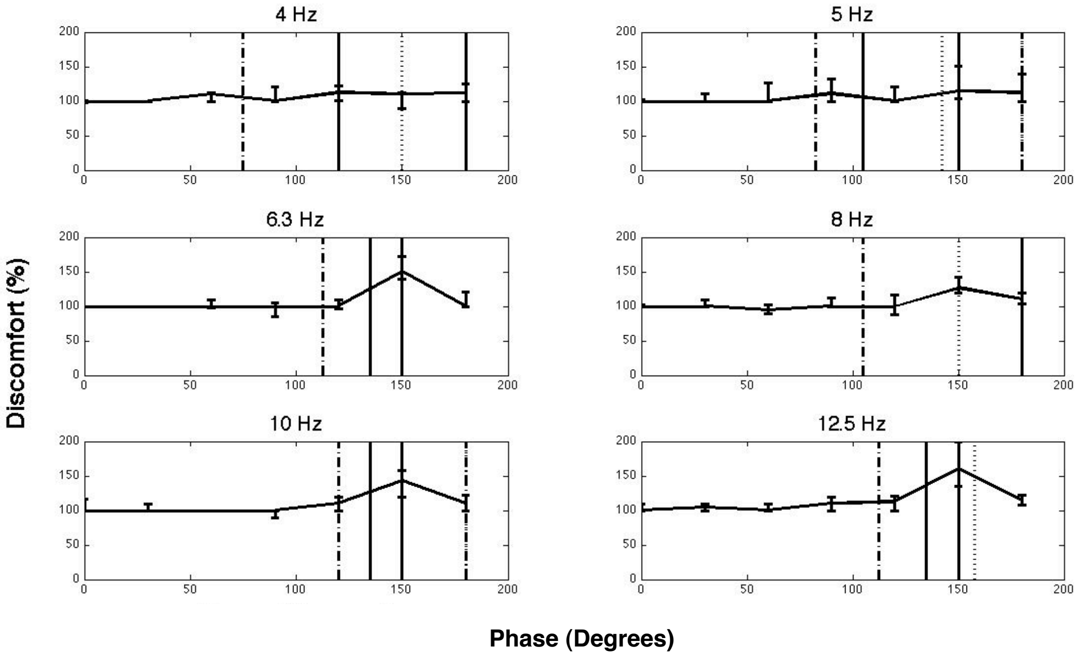

FIGURE 8.20: Median values of discomfort rating due to phase motion between feet and seat with interquartile range (horizontal error marks) and minimum and maximum phase threshold window (vertical solid lines) with interquartile range (dashed-doted vertical lines represent the minimum range and dotted vertical lines represent the maximum range)

TABLE 8.15: Percentage of subjects that felt the vibration phase between the feet and the seat according to the phase threshold data and the min-max phase detection.

Frequency	**Subject percentage**	
Hz	Threshold	Min-max
4 low	50	67
4 mid	50	58
4 high	42	58
5	42	67
6.3	67	83
8 low	25	67
8 mid	42	42
8 high	33	75
10	33	67
12.5	58	83

8.6.5 Phase thresholds relation to discomfort sensation

A series of figures, see Appendix C.4.1 (Figures C.1 to C.33) are produced in order to compare the body locations where subjects felt the phase motions during the threshold and the discomfort tests as noted in Table 8.2. The overlay of the bodymap percentages for the two tests (threshold-discomfort) can demonstrate in which frequencies the two tests produced similar percentages at the same body location. It would be expected, as a logical conclusion, that when subjects can detect phase motions, i.e. phase thresholds exists, then when they are introduced with a phase motion, in order to judge their levels of comfort, they will be able to detect. Although there are frequencies where percentages of the bodymap locations are matching between the two tests, it cannot be suggested that all frequencies match exactly the same. This leads to the conclusion that the introduction of the min-max analysis may provide a better way to relate phase detection and phase discomfort.

8.6.6 Ability of phase detection

In order to provide a better understanding of how phase thresholds are related with the sensation of discomfort when phase motions are introduced and to compare the findings with the proposed idea of the min-max phase detection all the percentages from each finding are overlaid. So the percentage of subjects who provided phase thresholds after the experiment (i.e. completed the test, Aa, Ba and Ca as in Table 8.2, producing six reversals), the percentage of subjects that indicate a bodymap position when they replied that they felt discomfort when phase motion was introduced (test, Ab, Bb and Cb as in Table 8.2) and the percentages of subjects that detect phase motions according to the min-max detection. The percentages of phase thresholds and min-max detection are already known from Tables 8.13, 8.14, 8.15 for the hands-feet test, hands-seat and feet-seat test. As seen in Figure 8.21, 8.22 and 8.23 the percentages between discomfort and min-max are similar, compared to the thresholds percentages, and in some occasions they are even matching (Figure 8.21 at 2.5 Hz, Figure 8.22 at 4(High) Hz, Figure 8.23 at 5 Hz).

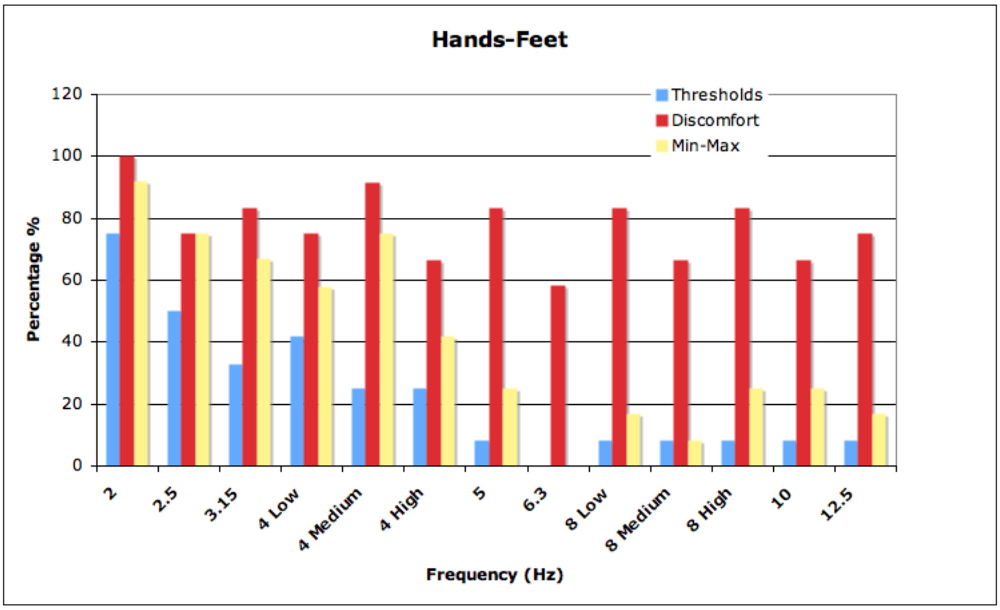

FIGURE 8.21: Percentages of subjects that produced phase thresholds, percentages of subjects that felt discomfort due to phase motions, and percentages of subjects that detect phase motions with the min-max analysis

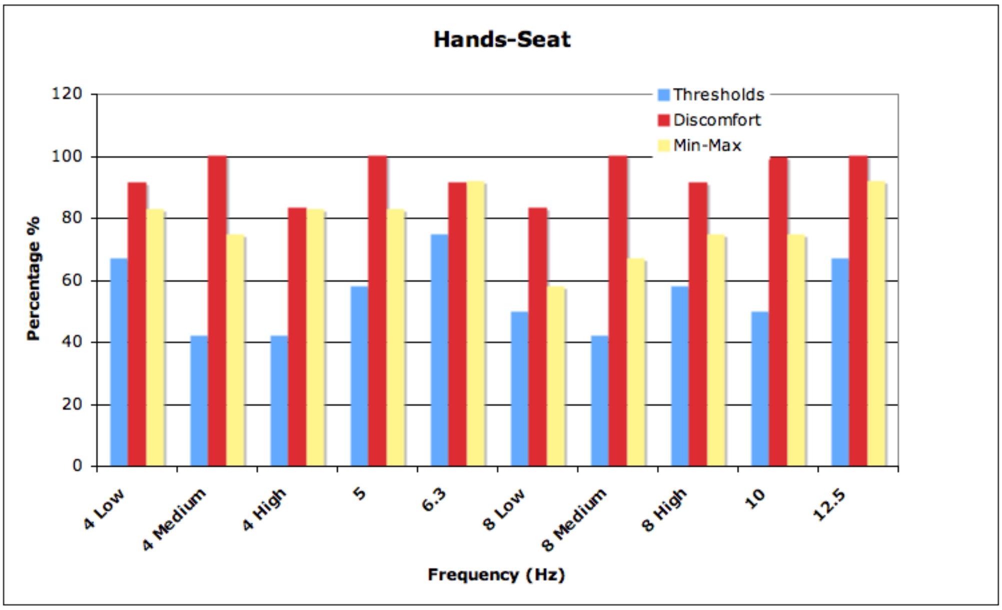

FIGURE 8.22: Percentages of subjects that produced phase thresholds, percentages of subjects that felt discomfort due to phase motions, and percentages of subjects that detect phase motions with the min-max analysis

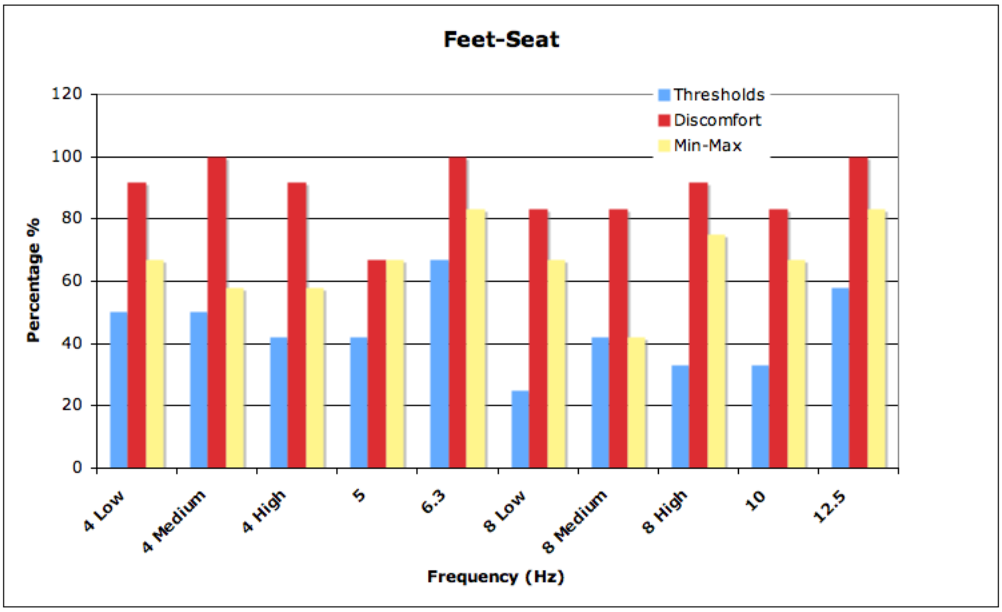

FIGURE 8.23: Percentages of subjects that produced phase thresholds, percentages of subjects that felt discomfort due to phase motions, and percentages of subjects that detect phase motions with the min-max analysis

This analysis allows a better understanding of when phase motions can be perceived and how phase detection is related to discomfort. The criteria used for this analysis assume that:

1. When phase motions cause an alteration of discomfort (i.e. increase or decrease of discomfort sensation compared to an in-phase motion that is rated with 100%) then phase motions are detectable (min and max phase degree values)

2. If phase motions are detectable (min and max phase degree values) it is not necessary that will alter the discomfort compared to an in-phase motion.

8.7 Discussion

8.7.1 Effect of frequency

8.7.1.1 Hands and feet

Subjects were able to detect phase motions according to the min-max phase detection data for lower frequencies (i.e. 2 to 4 Hz) between the hands and the feet. For frequencies greater than 5 Hz there was no sensation of phase motions (i.e. as explained in the analysis section 180 degrees correspond to no sensation) from most of the subjects. Although there are not many studies examined phase motion between hands and feet, it was found by Pamouktsoglou (2008), as shown in Figure 8.8, that at lower frequencies (i.e. 2.5 Hz) phase motions were also detected whereas as frequency increased (i.e. 5 and 10 Hz) there was no sensation (i.e. 180 degrees phase between hands and feet). It can be supported from the localisation of sensation data (see Table 8.5 for the phase thresholds study) that as frequency increased the percentage of subjects who didn't detect phase motions between the hands and the feet increased.

In terms of discomfort due to phase motions between the hands and the feet, as shown in Figure 8.12, there were no significant changes in discomfort rating as the phase increased (i.e. from 0 degrees to 180 degrees) at all frequencies investigated (except at 8 Hz). This shows that although subjects were able to perceive the difference between an in-phase and out-of-phase motion at low frequencies, there was no alteration on discomfort sensation. As frequency increased to 12.5 Hz the discomfort ratings maintained approximately constant (i.e.100%) at any phase degrees investigated, possibly because the subjects were already unable to detect any difference between and in phase and out of-phase motion. The findings seem consistent with the second assumption that out-of phase motions between the hands and the feet can be detected at low frequencies (below 5 Hz) but the discomfort of the out-of-phase motions relative to the in-phase motion will not be altered.

8.7.1.2 Hands and seat

Phase motions between the hands and the seat were found to be detectable at all frequencies according to the min-max phase detection data. Although there are not any studies that investigated phase motion between the hands and the seat to support the findings of this study, it can be suggested that the similarities between the detection of phase motions between the hands and the seat and the feet and seat can be closely related due to the fact that they share a common input (i.e. the seat).

The detection of out-of-phase differences of vertical vibration between the hands and the seat were associated with sensation at the hands and the arms, supported from the obtained data of Table 8.7. In terms of discomfort due to phase motions as shown in section 8.6.2 the change of discomfort is associated with the minimum and maximum degree values where the subjects detected the phase motion, as shown in Figure 8.13. This means that discomfort due to phase motions is more likely to be altered within a window of detectable phase motions (i.e. min and max). This suggests the results are consistent with the first assumption; detectable out-of phase motions caused by the hands and the seat are likely to alter the discomfort (relative to in-phase motions).

8.7.1.3 Feet and seat

Phase motions between the feet and the seat were detected by majority of the subjects at almost all frequencies, except at 8 Hz at medium acceleration magnitude where a minority of subjects were able to detect a minimum and maximum value of phase within the range of 0 to 180 degrees. A previous study by Jang and Griffin (1999) examined the effect of phase of differential vertical vibration at the seat and the feet on discomfort for five different magnitudes at 4 Hz at two different postures: with thigh contact and with no thigh contact. It was suggested that at low vibration magnitudes discomfort can be influenced by out of phase motion and also the posture has a significant role since thigh contact can increase the sensation of discomfort. From the data obtained from the localisation of sensation (see Table 8.9, for the phase threshold study). It can be suggested that the sensation of phase motions between the feet and seat tends to occur at the body location in contact with the seat for frequencies between 4 and 5 Hz and in contact with the feet for frequencies between 6.3 and 12.5 Hz.

A study by Suggs et al. (1976) concluded that phase motions could be detected at frequencies up to 4 Hz, although this study examined the effect of phase motions between the feet and seat at a greater frequency range (i.e. 1 to 32 Hz) compared to this study (i.e. 4 to 12.5 Hz) and the phase steps that employed were only 0, 90 and

180 degrees. Taking into account the findings by Suggs et al. (1976) about the apparent mass of the seat and the feet, maximum at 6 Hz for the seat and 8 Hz for the feet, it can be suggested that the sensation of phase motions between the feet and the seat were detected between 4 to 12.5 Hz due to greater transmissibility at both inputs.

The fact that there was no sensation of phase motions between the feet and the seat at 5 Hz may lead to the speculation of masking effect because of the seat due to body resonance. In terms of discomfort due to phase motions as shown in Section 8.6.2 the change of discomfort is associated with the minimum and maximum degree values where the subjects felt phase motion, as shown from Figure 8.14. This may suggest that discomfort due to phase motions is likely to be altered within a window of phase motions (i.e. min and max) where the subjects were able to detect the phase. So, the finding is consistent with the first assumption that the detectable out-of phase motions between the feet and the seat can alter the discomfort.

8.7.2 Effect of magnitude

The effect of vibration magnitude on phase motion detection was investigated with all three pairs of inputs (i.e. hands-feet, hands-seat, feet-seat) for three magnitudes at 4 and 8 Hz. As seen in Figures 8.8, 8.9 and 8.10, no significant effect of magnitude in thresholds at all three pairs of inputs were found. Jang and Griffin (1999) found greater sensitivity to phase changes of vertical vibration between the feet and the seat at the lowest vibration magnitude (i.e. 0.25 ms^{-2} r.m.s.) and the lowest frequency (i.e. 2.5 Hz) investigated. This finding is broadly consistent with the finding of this study, where there was a tendency of the phase threshold to reach 180 degrees (i.e. no sensation) as the magnitude increase. Although it may be expected that as vibration magnitude increases (with greater displacements of relative motions between the two input locations) the phase motions would be easier to detect. Lower magnitudes of vibration are influenced by the relative motion occurring around the two input locations, whereas judgements with higher magnitudes are more affected by vibration in the torso of the body (when one of the inputs involves vibration at the seat), as suggested by Jang and Griffin (1999).

8.7.3 Effect of location

As seen in Figure 8.11, the phase thresholds differed between the three combinations of pairs of inputs (i.e. hands-feet, hands-seat, feet-seat). Sensitivity to phase difference was significantly greater with the pairs of inputs involving vibration at the seat (i.e. hands-seat and feet-seat) than the pair of inputs not involving vibration at the seat (i.e. hands-feet) at 5 and 6.3 Hz. The fact that the resonance frequency for vertical vibration at the seat is known to be in the region of 5 Hz (depending on vibration magnitude and the sitting posture) where a significant effect of input location was found in this study.

For discomfort caused by phase motions between a pair of inputs, there was no change in discomfort with altering the degree of out-of-phase motions presented at the hands and the feet for all the examined frequencies (i.e. 2 to 12.5 Hz), except at 8 Hz. However, the discomfort caused by a pair of inputs involving vibration at the seat tended to increase with out-of-phase motions (at about 150-180 degrees) relative to in-phase (0 degree) motions.

Based on the finding from the localisation of sensation (see Table 8.9), the phase difference of a pair of inputs involving vibration at the seat and the feet was mostly perceived at the torso of the body at the frequencies around 5 Hz (resonance frequency of the body) and mostly perceived at the feet at frequencies around 8 Hz (resonance frequency of the feet). This may suggest that the sensitivity to phase differences caused by a pair of vibration inputs are associated with transmission of vibration to different body parts.

8.8 Conclusions

8.8.1 Effect of frequency

8.8.1.1 Hands and feet

Phase motions at lower frequencies (i.e. 2.5 to 5 Hz) were detected whereas as frequency increased (i.e. 5 and 12.5 Hz) there was no detection (i.e. 180 degrees phase between hands and feet). It can be supported from the localisation of sensation data (see Table 8.5 for the phase thresholds study) that as frequency increases the percentage of subjects that cannot detect of phase motions between the hands and the feet increases as well that phase motions are not altering the discomfort sensation compared to in phase motion.

8.8.1.2 Hands and seat

Phase motions between the hands and the seat were detectable at all frequencies (i.e. 4 to 12.5 Hz), the detection of out-of-phase differences of vertical vibration between the hands and the seat were associated with sensation at the hands and the arms. Discomfort due to phase motions is more likely to be altered between the minimum and maximum phase thresholds (see Section 8.6.4). So according to the first criterion out-of phase motions that can be detected and alter the discomfort between hands and seat

8.8.1.3 Feet and seat

Phase motion detection between the feet and the seat occurred for all frequencies (i.e. 4 to 12.5 Hz) except at 5 Hz due to body resonance. Phase motions altered the discomfort sensation between the minimum and maximum phase thresholds (see Section 8.6.4). So according to the first criterion out-of phase motions that can be detected and alter the discomfort between feet and seat.

8.8.2 Effect of magnitude

Phase motion detection is not altered between hands and feet as magnitude increases, subjects are still unable to detect any differences between in-phase and out-of phase motions. When phase motions occur between the hands-seat or the feet-seat, phase motions were detectable at lower magnitudes due to the relative motion between the two input location but as magnitudes increases phase motions are not easy to be detect since the discomfort sensation is masking any differences between in-phase and out-of phase motions.

8.8.3 Effect of location

The ability to detect vertical vibration phase motions presented to a pair of inputs (i.e. hands-feet, hands-seat, feet-seat) is related to the the location where the vibration is applied. Phase motions between the hands and the feet can only be detected at low frequencies (i.e. 2 to 5 Hz) but discomfort is not altered in any frequency, except at 8 Hz. Phase motions presented to a pair of inputs where one of the inputs is the seat (i.e. hands-seat, feet-seat) were detectable at all frequencies (i.e. 4 to 12.5 Hz) and discomfort due to phase motions was altered.

Chapter 9

General Discussion

9.1 Introduction

This chapter aims to create a logical discussion on the findings from all four experiments in order to identify which of the initial objectives (Chapter 3) are met.

9.2 Is the perception thresholds (sensitivity) for vertical vibration at the hands and the feet at low frequencies (i.e. 2 to 12.5 Hz) frequency dependent ?

At frequencies between 2 and 5 Hz, perception thresholds at the hands and the feet are independent of vibration frequency when expressed in terms of velocity. At frequencies greater than 5 Hz (up to 12.5 Hz), with the thresholds of the hands increased significantly the frequency dependence in threshold at the hands and the feet differed: possibly due to different tactile channel mediation or different sensory mechanism. Although no related literature is available to support the speculation of the difference of sensation between 5 to 12.5 Hz there are studies from Morioka and Griffin (2008) that found difference at vibration thresholds between hand and foot at 8 and 10 Hz as discussed at Chapter 5.

9.3 Are the comfort contours for vibration at the hands frequency dependent and magnitude dependent ?

Comfort contours at the hands for vertical transmitted vibration present a decrease of sensitivity to acceleration as frequency increases up to 5 Hz. There is no dependence of vibration magnitude and this can be supported from the fact that the shape of the contours is similar to the shape of the absolute thresholds as it was shown at Chapter 5. This means that probably the same tactile channels or the same sensory mechanism is involved in the perception of vibration thresholds and supra-thresholds levels within this frequency range.

9.4 Are the comfort contours for vibration at the feet frequency dependent and magnitude dependent ?

Comfort contours at the feet for vertical transmitted vibration present a decrease in sensitivity to acceleration as frequency increases up to 6.3 Hz as shown in Chapter 6 As frequency increases from 6.3 Hz up to 12.5 Hz there is a magnitude dependence possibly due to the non-linear biodynamic response as found by Kitazaki and Griffin (1997) and Nawayseh and Griffin (2004)

9.5 How the contact location affects the vertical vibration comfort contours, for low frequencies (i.e. 2 to 12.5 Hz) at the hands and the feet ?

As vibration magnitude increases it was found that the vibration is likely to be detected at the body locations other than the body location in direct contact (depending from the vibration input i.e. hands or feet). For vertical transmitted vibration at the feet between 8 to 12.5 Hz the discomfort was perceived not only at the area of direct contact (i.e. the feet) but also at other parts of the body in all three vibration magnitudes.

9.6 What is the sensitivity difference relation for vertical vibration transmitted to the hands, the feet and the seat at low frequencies ?

With increasing magnitude vertical vibration at low frequencies (i.e. 4 to 12.5 Hz) is detected at first at the seat, then at the feet and last at the hands. The seat has a greater sensitivity overall compared with the other two inputs. In greater detail the ratio of the vibration magnitude between the seat and the feet decreases from 6.3 to 12.5 Hz and from 4 to 6.3 Hz between the seat and the hands

9.7 Is the equivalence of sensation between the hands, the feet and the seat magnitude dependent ?

The absence of a magnitude-dependence in the relative sensitivity at the hands and the feet at 4 and 8 Hz vibration indicates that at these two frequencies the hands and the feet have similar rates of growth of discomfort with increasing magnitude of vibration. On the other hand a magnitude-dependence in the relative sensitivity found between the hands and the seat at 4-Hz vibration indicates that the hands and the seat have different rates of growth of discomfort with increasing vibration magnitude as found in chapter 7.

9.8 Can out-of phase motions between two vibration inputs affect the discomfort compared to in-phase motions ?

In order to evaluate and conclude if out-of phase motions between two inputs can be detected and maybe alter the discomfort compared to an in-phase motion it is necessary to examine the findings in pairs (i.e. hands-feet, hands-seat, feet-seat). So out-of phase motions on vertical transmitted vibration between hands and feet can be detected at low frequencies (i.e. 2 to 5 Hz) but they will not affect the discomfort compared to an in-phase motion. On the other hand out-of phase motions between the feet and the seat and the hands and the seat can be detected by some and the discomfort can be increased compared to in-phase motions. The sensitivity to phase differences caused by a pair of vibration inputs may be associated with transmission of vibration to different body parts.

Chapter 10

Conclusions

10.1 Introduction

This chapter aims to draw an overall conclusion based on the three main research questions raised in Chapter 3 (see section 3.4)

10.2 How does the sensitivity of detecting vibration or judging discomfort differ between the hands, the seat and the feet ?

The magnitudes required, for vertical transmitted vibration at the three examined inputs (i.e. the hands, the feet and the seat), in order to produce equivalent sensations presented a greater sensitivity at the seat, followed by the feet and lastly the hands for frequencies 4 to 12.5 Hz. As shown at Chapter 7 the seat presents greater sensitivity that can be explained by factors such as body location,weight support, vibration contact area, as well as applied pressure of the contact area.

10.3 What mechanisms are involved in detecting or judging discomfort caused by vibration at the hands, the seat and feet?

The absolute thresholds for vertical vibration transmitted to the hands and the feet at low frequencies between 2 to 12.5 Hz were frequency dependent. The thresholds at the hands and the feet differed for frequencies greater than 5 Hz, this may occur due to different tactile channels involvement in the detection of the vibration at the hands and the feet. In addition each input has different positioning of the human body, since the hands when are in contact with the vibrating surface the only pressure they apply is due to their own weight, compared to the feet that they act as supports for the lower half of the human body when the subject is adapting the seated posture. So factors as vibration transmission through the human body may explain the differences between the hands and the feet.

The fact that the comfort contours at the hands were independent from vibration magnitude as well as their similarity of their shape to the absolute thresholds as determined at Chapter 5, suggests that the perception of vertical vibration at the hands starting from threshold levels up to supra threshold level is detected from the same sensory mechanism for frequencies between 2 to 12.5 Hz .On the other hand comfort contours for vertical vibration transmitted at the feet present higher vibration acceleration values as frequency increased from 2 to 6.3 Hz. For frequencies greater than 6.3 Hz the increased vibration sensitivity can partly be explained from factors such as vibration localisation and the non linear biodynamic response. In terms of physiology, vibration transmitted at the feet presents differences compared to the hands. The weight differences for example that each input supports alters the pressure of the contact location (i.e. palm of the hand, sole of the foot).

Vertical vibration at low frequencies (i.e. 4 to 12.5 Hz) is detected at first at the seat, then at the feet and last at the hands. The seat has a greater sensitivity overall than the other two inputs. In greater detail the ratio of the vibration magnitude between the seat and the feet decreases from 6.3 to 12.5 Hz and from 4 to 6.3 Hz between the seat and the hands. The other two vibration inputs (i.e. the hands and the feet) present similar rates of growth of discomfort, as well as in terms of physiological differences compared to the seat input (i.e. smaller vibration contact area, lower pressure on the vibration surface due to lower weigh support). These two facts make it clear that their vibration sensitivity was expected to differ compared to the seat.

10.4 How the amount of discomfort caused by phases between vibration at pairs of inputs is associated with the ability of detecting the phases?

Out-of phase motions between two inputs can be detected and maybe alter the discomfort compared to an in-phase motion when presented at pairs of inputs (i.e. hands-feet, hands-seat, feet-seat). So out-of phase motions on vertical transmitted vibration between hands and feet can be detected at low frequencies (i.e. 2 to 12.5 Hz) but they will not affect the discomfort compared to an in-phase motion. On the other hand out-of phase motions between the feet and the seat and the hands and the seat can be detected by some and the discomfort can be increased compared to in-phase motions. The sensitivity to phase differences caused by a pair of vibration inputs may be associated with transmission of vibration to different body parts.

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Appendix A

Instructions for subjects

A.1 Experiment reported in Chapter 5

The purpose of this experiment is to explore your perception on threshold of vibration and the quivalent comfort contours at the hands and the feet. The experiment is divided in four sessions,vibration transmitted at the hands (2 sessions); at the feet (2 sessions). Each session will last approximately one hour and they will be held on different days. Please read carefully and follow the instructions below.

TABLE A.1: Sessions of the experiment

Experiment sessions		
Part 1	Session 1	*Perception Thresholds at the hands*
	Session 2	*Perception Thresholds at the feet*
Part 2	Session 3	*Equivalent comfort contours at the hands*
	Session 4	*Equivalent comfort contours at the feet*

Before the tests

- 1. You will be kindly asked to remove your shoes (keep your shocks on), your watch and jewels. You will also be asked to roll your trousers up to the knees.
- 2. Sit comfortably on the saddle, resting your feet on the foot pedals and grasping the handles (at your comfortable grip force).
- 3. You will be asked to wear a pair of headphones that present white noise.
- 4. Please maintain your body posture: (i) **sit upright** (ii)**look straight ahead**

During Part 1

A series of two motions (2 seconds each in duration with 1 sec pause between them) will be presented accompanied by a light indicator.

Your task is to indicate:

”WHICH OF THE TWO MOTIONS YOU FELT”

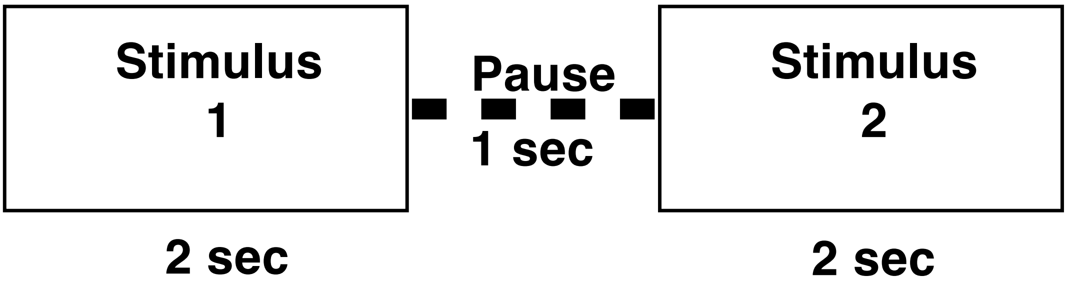
Please reply by saying **”FIRST or SECOND”**

It is important that all your judgements are derived from vibration, ignoring any audible noise. Say **”REPEAT”** if unsure.

The tests will be repeated with changed vibration frequency and magnitude.

Your task is to indicate:

”WHICH OF THE TWO MOTIONS YOU FELT ””



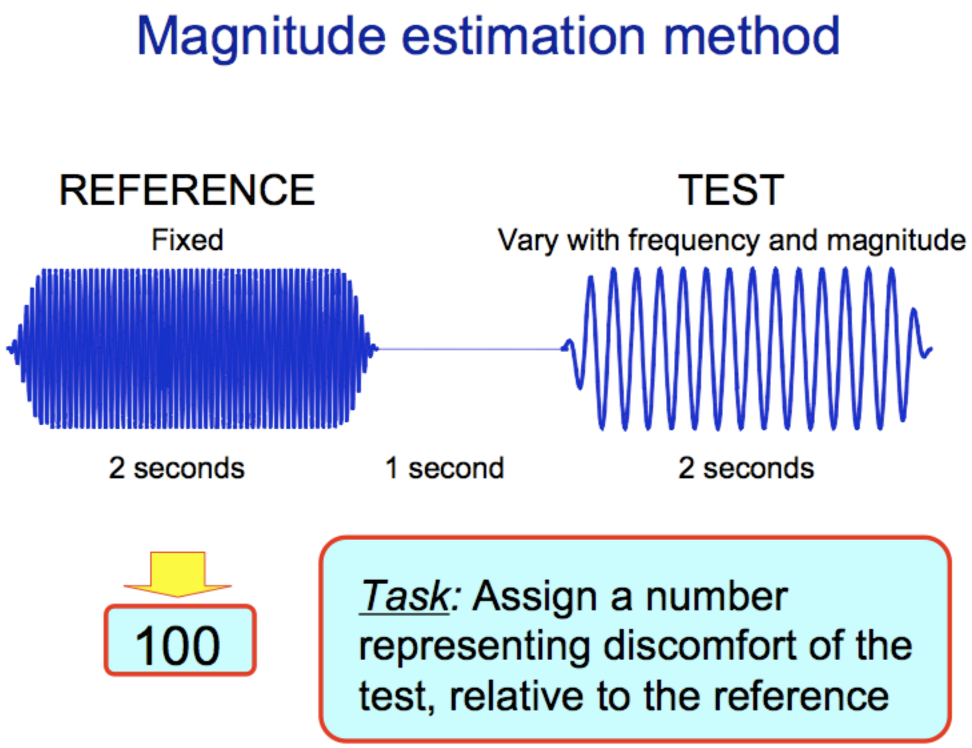
It is important that all your judgements are influenced by vibration, ignoring any audible noise.

Say **”REPEAT”** if unsure.

During Part 2

A series of two motions (2 seconds each in duration with 1 sec pause between them) will be presented accompanied by a light indicator. You will be asked to judge the discomfort caused by the test motion relative to the discomfort of the reference motion. The discomfort of the reference motion is evaluated with '100'. For example : if the test motions causes double discomfort from the reference motion you should evaluate it with '200'.

Your task is to indicate:



It is important that all your judgements are derived from vibration, ignoring any audible noise. Say **"REPEAT"** if unsure.

The tests will be repeated with changed vibration frequency and input conditions.

A.2 Experiment reported in Chapter 6

The purpose of this experiment is to explore the quivalent comfort contours at the hands and the feet. The experiment is divided in two sessions,vibration transmitted at the hands (first session) and vibration transmitted at the feet (second session). Each session will last approximately one hour and they will be held on different days. Please read carefully and follow the instructions below.

Table A.2: Sessions of the experiment

Experiment sessions		
	Test 1	*Test 2*
Session A	*Judgement of vibration discomfort at the hands*	*Localisation of sensation*
Session B	*Judgement of vibration discomfort at the feet*	*Localisation of sensation*

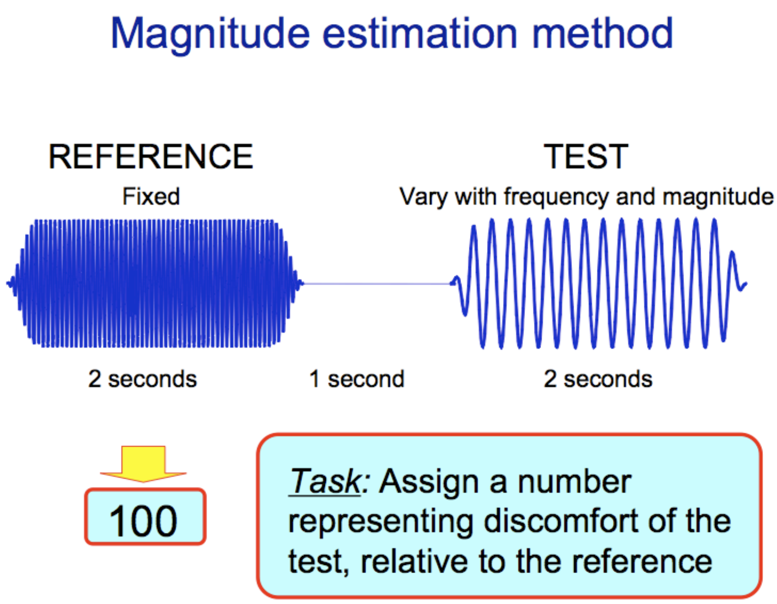
Before the tests

- You will be kindly asked to remove your shoes (keep your shocks on), your watch and jewels. You will also be asked to roll your trousers up to the knees.
- Sit comfortably on the saddle, resting your feet on the foot pedals and grasping the handles (at your comfortable grip force).
- You will be asked to wear a pair of headphones that present white noise.
- You will be asked to wear a pair of googles to make sure you cannot see your hands either your feet.
- Please maintain your body posture: (i) **sit upright** (ii)**look straight ahead**

During the tests

Test 1: Judgement of vibration discomfort

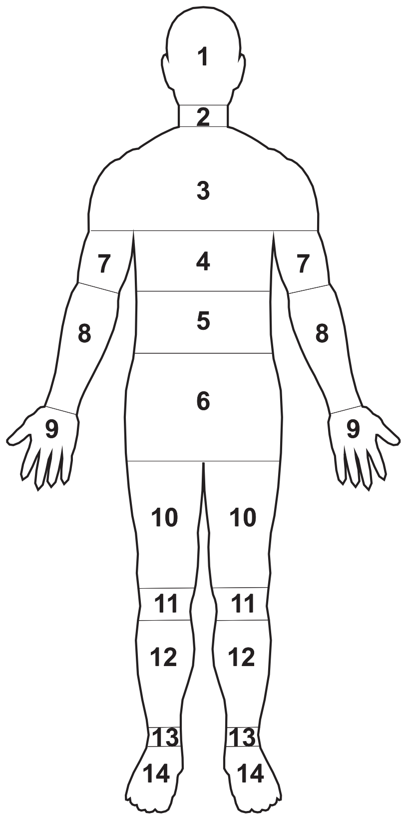
A series of two motions (2 seconds each in duration with 1 sec pause between them) will be presented. The discomfort of the **first motion** (reference motion) is evaluated with '100'. Your task is to judge the discomfort caused by the **second motion** (test motion) relative to the discomfort of the reference motion. For example : if the test motion is judged double the discomfort relative to the reference motion you should evaluate it as '200'.



It is important that all your judgements are derived from vibration, ignoring any audible noise. Say **"REPEAT"** if unsure.

Test 2: Localisation of sensation

A series of motions (2 seconds each in duration) will be presented. After each motion you will be asked to indicate on which part of your body you felt the vibration by replying with a number from the bodymap Indicate only one number. Each part of the body is represented by a number on an bodymap shown above. If you are unsure say ”**REPEAT**” If you felt the vibration in more than one part of the body, give only one more additional number.



A.3 Experiment reported in Chapter 7

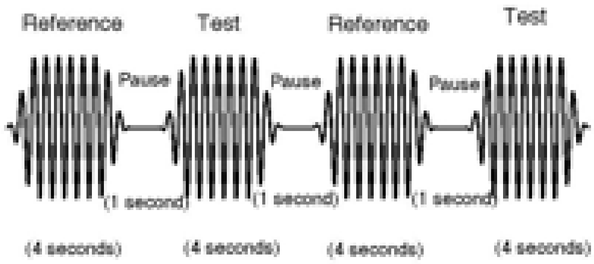
This experiment aims to measure your sensitivity to vibration at the hands, the seat, and feet at low frequencies (i.e. 2.0 to 12.5 Hz). You are requested to attend two sessions (on a different day), each session lasts approximately 1 hour. Please read the following instructions.

Before the tests

- You will be kindly asked to remove your shoes (keep your shocks on), your watch and jewels. You will also be asked to roll your trousers up to the knees.
- Sit comfortably on the saddle, resting your feet on the foot pedals and grasping the handles (at your comfortable grip force).
- You will be asked to wear a pair of headphones that present white noise.
- You will be asked to wear a pair of googles to make sure you cannot see your hands either your feet.
- Please maintain your body posture: (i) **sit upright** (ii)**look straight ahead**

During the tests

A series of two motions (4 seconds each in duration) will be presented twice. The first motion is **Reference** and the second motion is **Test**, as seen in the figure below:



The reference stimulus will be presented at the hands and the test stimulus will be presented at the seat or at the feet (the experimenter will inform you). Your task is to indicate,

Which of the two motions you would most like to be reduced if you were to be presented with them again for the same period in the laboratory

Please reply by saying **"FIRST or SECOND"**

It is important that all your judgements are derived from vibration, ignoring any audible noise. Say **"REPEAT"** if unsure.

The tests will be repeated with changed vibration frequency and magnitude.

A.4 Experiment reported in Chapter 8

This experiment aims to determine the difference thresholds (just noticeable difference, JND) of phase between vertical motions between two inputs (i.e. hands-feet, hands-seat, seat-feet) at low frequencies (i.e. 2.0 to 12.5 Hz). You are requested to attend three sessions (on a different day), each session lasts approximately 1 hour. Please read the following instructions

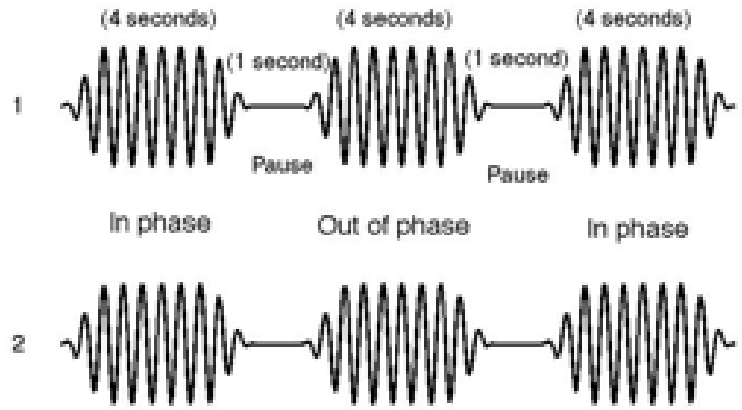
Before the tests

- You will be kindly asked to remove your shoes (keep your shocks on), your watch and jewels. You will also be asked to roll your trousers up to the knees.
- Sit comfortably on the saddle, resting your feet on the foot pedals and grasping the handles (at your comfortable grip force).
- You will be asked to wear a pair of headphones that present white noise.
- You will be asked to wear a pair of googles to make sure you cannot see your hands either your feet.
- Please maintain your body posture: (i) **sit upright** (ii)**look straight ahead**

During the tests

Session A

et of three motions (4 seconds each in duration) will be presented. Please see Figure below for an example of presenting three motions:



Your task is to indicate,

Which of the three motions you felt different from the other two motions.

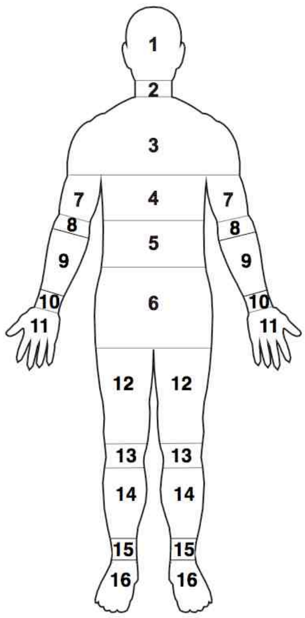
Please reply by saying **"First, Second or Third"**

It is important that all your judgements are derived from vibration, ignoring any audible noise. Say **"REPEAT"** if unsure.

The tests will be repeated with changed vibration frequency .

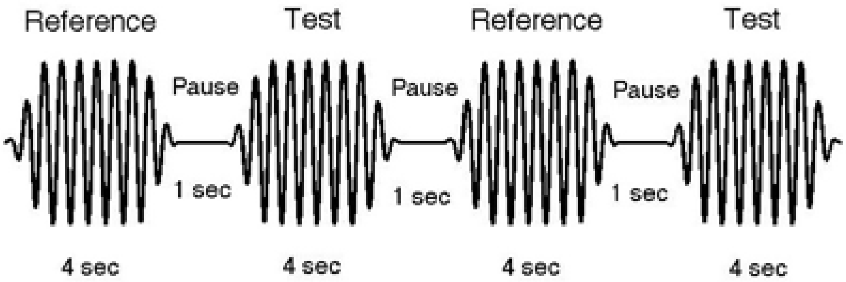
After each test you will be asked to indicate which part of the body you detected the motion that differed from the rest of the motions by referring to the bodymap (see Figure below)

The following figure of the human body segments with numbers is provided in front of you.



Session B

A set of two motions (4 seconds each in duration) will be presented. Please see Figure below for an example of presenting two motions, the first motion is the Reference and it is valuated with 100 in terms of discomfort :



Your task is to

Assign a number representing discomfort of the test relative to the reference

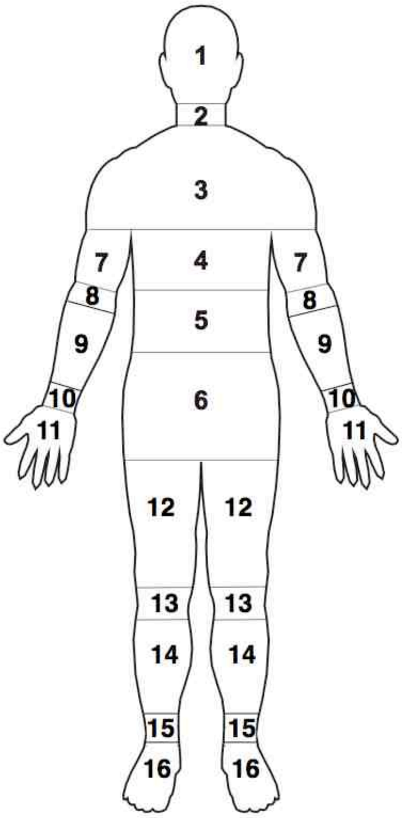
1. If the test motion caused double discomfort relative to reference give a rating of 200, if the test motion caused half discomfort relative to the reference give rating of 50, etc

2. Reply, after referring to the bodymap shown in front of you with a number

3. It is important that all your judgements are influenced by vibration, ignoring any audible noise. Say epeatf unsure.

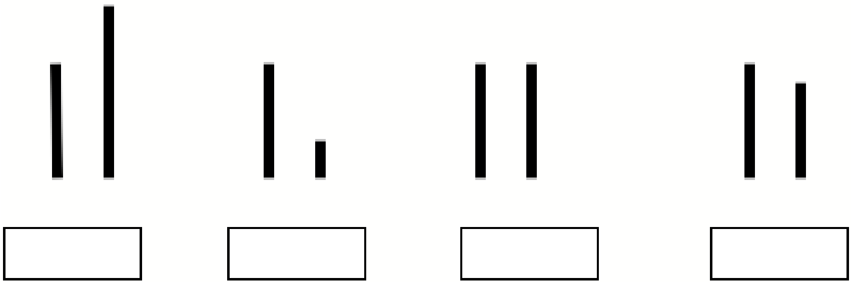
4. After each test you will be asked to indicate on the bodymap where you felt the discomfort (see Figure below)

The test will be repeated with changed vibration frequency



Practise

To practise the method of magnitude estimation rate the length of the second line, assuming that the length of the first line is 100.



Appendix B

Health questionnaire

This is a presentation of the health questionnaire each subject was asked to fill before considering to take part to any of the experiments

HEALTH QUESTIONNAIRE

Ref. No.

Please answer the questions below.

All information will be treated as **CONFIDENTIAL**

Section A: Personal information

Name: Age: Date of Birth:

Email:

Nationality: Height: cm Weight: kg

Dominant hand: Right [ ] Left [ ]

Occupation: Student [ ] Staff [ ] Other [ ]

Section B: Health information

1. Do you smoke ?

YES [ ] NO [ ] If yes, please specify the number :[ ] of cigarettes a day

2. How much alcohol do you consume weekly?

Never [ ] 1-3 units* [ ] 4-6 units [ ] More than 6 units [ ]

*1 unit for a glass of wine, 2 units for a pint of beer

3. Do you drive?

YES [ ] NO [ ] If yes, please specify how frequent :[ ] hours a week

4. Do you exercise regularly?

YES [ ] NO [ ] If yes, what sports do you participate in :[ ]

5. Do you take any drugs or medication?

YES [ ] NO [ ] If yes, please specify :[ ]

6. Have you had any hand, wrist or feet surgery?

YES [ ] NO [ ] If yes, please specify :[ ]

7. Have you had any burn or scars on your hands or feet?

YES [ ] NO [ ] If yes, please specify :[ ]

8. Have you had trouble (such as ache, pain, discomfort, numbness) in your body? YES [ ] NO [ ] If yes, please specify where in your body:

Elbows[ ] Wrists/hands[ ] Back[ ] Neck[ ]
Shoulder[ ] Hips/thighs[ ] Knees[ ] Ankles/feet[ ]

9. Do you suffer from the following disorders?

Diabetes[ ] Digestive disorders[ ] Vascular problems[ ] Neuropathy problems[ ]
Urinary disorders [ ] Vestibular disorders[ ] Others[ ] None[ ]

10. Have you been exposed to severe or long periods of vibration such as:

Vibration tools[ ] Off-road vehicles[ ] Trucks[ ]
Motorbikes[ ] Others [ ] Never[ ]

Appendix C

Raw data

C.1 Experiment 1 threshold data reported in Chapter 5

Table C.1: Vertical vibration thresholds at the hands for all 12 subjects

HANDS	**Frequency (Hz)**								
Subjects	**2**	**2.5**	**3.15**	**4**	**5**	**6.3**	**8**	**10**	**12.5**
S1	0.028	0.025	0.052	0.043	0.046	0.048	0.054	0.056	0.056
S2	0.023	0.022	0.043	0.058	0.035	0.033	0.058	0.052	0.079
S3	0.012	0.020	0.021	0.037	0.051	0.030	0.036	0.046	0.076
S4	0.036	0.037	0.034	0.051	0.034	0.020	0.049	0.036	0.057
S5	0.035	0.033	0.034	0.041	0.031	0.050	0.054	0.055	0.057
S6	0.017	0.022	0.017	0.029	0.039	0.041	0.037	0.026	0.052
S7	0.024	0.015	0.038	0.045	0.036	0.026	0.032	0.041	0.064
S8	0.024	0.040	0.032	0.054	0.040	0.064	0.082	0.082	0.100
S9	0.027	0.034	0.047	0.044	0.055	0.043	0.067	0.068	0.063
S10	0.016	0.029	0.034	0.051	0.043	0.043	0.066	0.076	0.090
S11	0.015	0.028	0.026	0.056	0.027	0.035	0.052	0.062	0.065
S12	0.032	0.036	0.048	0.064	0.037	0.071	0.046	0.077	0.072
MEDIAN	0.024	0.028	0.034	0.048	0.038	0.042	0.053	0.055	0.065
25th percerntile	0.017	0.022	0.030	0.042	0.035	0.032	0.044	0.045	0.057
75th percentile	0.029	0.035	0.044	0.055	0.044	0.048	0.060	0.070	0.077

Table C.2: Vertical vibration thresholds at the feet for all 12 subjects

FEET	**Frequency (Hz)**								
Subjects	**2**	**2.5**	**3.15**	**4**	**5**	**6.3**	**8**	**10**	**12.5**
S1	0.011	0.026	0.037	0.025	0.055	0.043	0.028	0.039	0.034
S2	0.016	0.029	0.033	0.042	0.070	0.068	0.062	0.040	0.035
S3	0.007	0.018	0.020	0.028	0.049	0.031	0.036	0.033	0.035
S4	0.018	0.026	0.041	0.041	0.041	0.025	0.024	0.030	0.029
S5	0.027	0.035	0.032	0.054	0.043	0.031	0.038	0.029	0.035
S6	0.025	0.017	0.025	0.045	0.042	0.033	0.027	0.027	0.033
S7	0.012	0.016	0.012	0.021	0.022	0.026	0.015	0.017	0.024
S8	0.020	0.030	0.056	0.034	0.054	0.040	0.021	0.024	0.019
S9	0.013	0.027	0.021	0.058	0.054	0.056	0.041	0.028	0.025
S10	0.012	0.013	0.014	0.030	0.030	0.032	0.021	0.027	0.024
S11	0.010	0.007	0.014	0.014	0.018	0.017	0.018	0.016	0.018
S12	0.019	0.020	0.053	0.034	0.049	0.051	0.032	0.019	0.022
MEDIAN	0.015	0.023	0.029	0.034	0.046	0.033	0.028	0.027	0.027
25th percentile	0.011	0.017	0.018	0.027	0.038	0.030	0.021	0.023	0.023
75th percentile	0.019	0.028	0.038	0.042	0.054	0.045	0.037	0.031	0.034

C.2 Experiment 2 vertical vibration acceleration values and sensation magnitudes reported in Chapter 6

TABLE C.3: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 1

Frequency (Hz)	Hands		Feet	
Subject 1	**Acceleration** ms^{-2}	**Sensation**	**Acceleration** ms^{-2}	**Sensation**
2	0.05	20	0.04	60
2	0.06	40	0.05	70
2	0.08	50	0.07	80
2	0.11	75	0.09	100
2	0.16	80	0.13	120
2	0.23	75	0.20	150
2	0.32	100	0.28	180
2	0.47	200	0.41	200
2.5	0.06	20	0.05	50
2.5	0.08	20	0.07	60
2.5	0.11	25	0.10	90
2.5	0.16	80	0.14	90
2.5	0.23	80	0.20	90
2.5	0.33	150	0.29	180
2.5	0.47	125	0.42	190
2.5	0.66	175	0.62	200
3.15	0.07	20	0.06	40
3.15	0.10	20	0.08	80
3.15	0.14	50	0.12	70
3.15	0.19	50	0.17	80
3.15	0.27	75	0.24	140
3.15	0.38	100	0.34	140
3.15	0.54	200	0.50	150
3.15	0.76	200	0.71	200
3.15	1.10	200	1.05	200
3.15	1.62	300	1.53	250
4	0.09	10	0.07	40
4	0.12	20	0.11	40
4	0.18	25	0.16	80
4	0.25	40	0.22	90
4	0.36	80	0.32	120
4	0.51	100	0.47	180
4	0.71	180	0.66	150
4	1.04	200	0.97	200
4	1.48	200	1.36	240
4	2.17	200	1.97	240
5	0.14	10	0.13	60
5	0.20	20	0.19	80
5	0.28	40	0.26	100
5	0.41	75	0.38	100
5	0.58	100	0.55	120
5	0.82	150	0.80	100
5	1.28	170	1.24	190
5	1.68	175	1.63	200
5	2.33	250	2.22	200
5	2.94	300	3.02	200
6.3	0.15	25	0.14	40
6.3	0.21	25	0.21	40
6.3	0.29	80	0.29	90
6.3	0.42	80	0.43	90
6.3	0.59	150	0.60	120
6.3	0.85	125	0.88	180
6.3	1.30	200	1.38	200
6.3	1.69	200	1.83	240
6.3	2.36	250	2.53	240
6.3	3.28	300	3.37	300
8	0.15	40	0.16	90
8	0.21	50	0.23	90
8	0.29	40	0.32	100
8	0.42	75	0.47	120
8	0.59	80	0.67	150
8	0.85	125	0.97	190
8	1.34	200	1.51	250
8	1.77	200	1.96	200
8	2.43	250	2.57	250
8	3.46	200	3.36	280
10	0.15	40	0.13	90
10	0.21	50	0.18	80
10	0.30	80	0.26	140
10	0.42	80	0.37	120
10	0.60	125	0.54	190
10	0.85	100	0.77	180
10	1.32	200	1.16	150
10	1.72	200	1.54	200
10	2.42	200	2.08	200
10	3.46	250	2.92	280
12.5	0.15	25	0.10	80
12.5	0.21	50	0.13	80
12.5	0.29	80	0.18	80
12.5	0.42	80	0.26	100
12.5	0.58	100	0.36	100
12.5	0.84	125	0.52	140
12.5	1.27	150	0.78	180
12.5	1.66	200	1.00	200
12.5	2.35	250	1.30	200
12.5	3.39	200	1.88	200

Table C.4: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 2

Frequency (Hz)	Hands		Frequency (Hz)	Feet	
Subject 2	Acceleration ms^{-2}	Sensation	Subject 2	Acceleration ms^{-2}	Sensation
2	0.06	5	2	0.04	10
2	0.08	10	2	0.05	5
2	0.11	30	2	0.06	30
2	0.16	10	2	0.09	40
2	0.23	90	2	0.12	30
2	0.32	80	2	0.19	70
2	0.47	110	2	0.28	130
2.5	0.11	20	2	0.42	140
2.5	0.16	10	2.5	0.05	30
2.5	0.23	60	2.5	0.07	10
2.5	0.32	60	2.5	0.10	10
2.5	0.47	70	2.5	0.14	50
2.5	0.68	150	2.5	0.21	60
3.15	0.14	5	2.5	0.30	90
3.15	0.20	5	2.5	0.43	110
3.15	0.27	40	2.5	0.62	160
3.15	0.38	60	3.15	0.09	5
3.15	0.55	80	3.15	0.12	5
3.15	0.77	240	3.15	0.17	40
3.15	1.12	250	3.15	0.25	50
3.15	1.65	260	3.15	0.35	130
4	0.18	5	3.15	0.51	90
4	0.25	30	3.15	0.71	150
4	0.36	90	3.15	1.06	140
4	0.51	80	3.15	1.53	270
4	0.73	90	4	0.10	5
4	1.04	130	4	0.17	10
4	1.49	190	4	0.23	30
4	2.17	300	4	0.35	90
5	0.28	30	4	0.49	120
5	0.41	70	4	0.71	120
5	0.57	100	4	1.04	150
5	0.83	90	4	1.46	150
5	1.28	170	4	2.07	250
5	1.70	180	5	0.14	10
5	2.36	300	5	0.21	5
5	2.95	300	5	0.30	40
6.3	0.20	10	5	0.43	60
6.3	0.30	10	5	0.62	120
6.3	0.43	30	5	0.92	100
6.3	0.60	80	5	1.43	160
6.3	0.87	120	5	1.88	180
6.3	1.33	160	5	2.59	250
6.3	1.77	200	5	3.32	240
6.3	2.46	290	6.3	0.18	10
6.3	3.29	300	6.3	0.27	30
8	0.15	5	6.3	0.37	100
8	0.22	10	6.3	0.54	60
8	0.31	10	6.3	0.77	120
8	0.44	10	6.3	1.10	150
8	0.62	30	6.3	1.63	200
8	0.90	50	6.3	2.10	200
8	1.39	130	6.3	2.78	250
8	1.84	190	6.3	3.60	290
8	2.54	220	8	0.14	20
8	3.50	300	8	0.20	30
10	0.32	5	8	0.28	30
10	0.45	20	8	0.39	80
10	0.62	40	8	0.57	110
10	0.91	150	8	0.81	150
10	1.38	150	8	1.34	160
10	1.83	200	8	1.77	280
10	2.52	220	8	2.29	260
10	3.49	280	8	3.12	260
12.5	0.29	20	10	0.14	5
12.5	0.43	10	10	0.20	20
12.5	0.60	50	10	0.26	20
12.5	0.85	150	10	0.35	130
12.5	1.31	120	10	0.49	130
12.5	1.70	200	10	0.68	120
12.5	2.35	190	10	0.91	140
12.5	3.31	250	10	1.15	220
			10	1.69	220
			12.5	0.05	5
			12.5	0.09	10
			12.5	0.13	20
			12.5	0.19	20
			12.5	0.27	40
			12.5	0.37	150
			12.5	0.52	120
			12.5	0.68	150
			12.5	0.93	200

Table C.5: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 3

Frequency (Hz)	Hands		Frequency (Hz)	Feet	
Subject 3	Acceleration ms^{-2}	Sensation	Subject 3	Acceleration ms^{-2}	Sensation
2	0.07	5	2	0.05	40
2	0.09	20	2	0.06	60
2	0.12	60	2	0.09	5
2	0.16	80	2	0.12	110
2	0.23	120	2	0.18	110
2	0.32	120	2	0.26	120
2	0.47	200	2	0.40	200
2.5	0.07	5	2.5	0.06	20
2.5	0.09	30	2.5	0.09	60
2.5	0.12	60	2.5	0.13	60
2.5	0.17	80	2.5	0.19	80
2.5	0.23	120	2.5	0.27	120
2.5	0.32	150	2.5	0.40	120
2.5	0.46	120	2.5	0.58	160
2.5	0.65	150	3.15	0.08	5
3.15	0.09	5	3.15	0.11	20
3.15	0.11	5	3.15	0.16	100
3.15	0.15	40	3.15	0.23	100
3.15	0.20	80	3.15	0.32	100
3.15	0.27	80	3.15	0.46	130
3.15	0.37	120	3.15	0.66	130
3.15	0.53	120	3.15	1.00	180
3.15	0.75	120	3.15	1.44	200
3.15	1.08	200	4	0.10	5
3.15	1.58	200	4	0.22	10
4	0.11	5	4	0.31	70
4	0.19	5	4	0.45	100
4	0.26	60	4	0.65	160
4	0.37	80	4	0.92	110
4	0.51	100	4	1.36	150
4	0.71	100	4	1.91	200
4	1.02	150	5	0.13	5
4	1.45	200	5	0.20	10
4	2.10	250	5	0.26	40
5	0.22	10	5	0.39	100
5	0.30	10	5	0.54	80
5	0.42	100	5	0.80	150
5	0.58	100	5	1.24	130
5	0.82	120	5	1.66	180
5	1.25	150	5	2.26	250
5	1.64	250	5	3.05	300
5	2.26	350	6.3	0.16	5
5	2.91	300	6.3	0.21	30
6.3	0.16	5	6.3	0.31	40
6.3	0.22	10	6.3	0.44	30
6.3	0.30	10	6.3	0.63	130
6.3	0.42	30	6.3	0.92	100
6.3	0.60	80	6.3	1.40	160
6.3	0.83	100	6.3	2.10	200
6.3	1.29	150	6.3	2.51	250
6.3	1.69	200	6.3	3.33	300
6.3	2.33	200	8	0.15	5
6.3	3.24	300	8	0.21	5
8	0.23	20	8	0.27	50
8	0.32	10	8	0.39	120
8	0.45	40	8	0.56	80
8	0.62	80	8	0.88	110
8	0.88	120	8	1.37	140
8	1.33	120	8	1.95	150
8	1.75	200	8	2.39	250
8	2.44	200	8	3.20	250
8	3.36	300	10	0.11	5
10	0.23	5	10	0.16	10
10	0.30	40	10	0.21	20
10	0.45	5	10	0.30	80
10	0.61	80	10	0.44	60
10	0.89	120	10	0.63	80
10	1.36	120	10	0.85	150
10	1.71	120	10	1.10	130
10	2.28	190	10	1.43	200
10	3.46	250	10	1.95	200
12.5	0.23	5	12.5	0.06	5
12.5	0.30	10	12.5	0.09	5
12.5	0.42	40	12.5	0.12	5
12.5	0.59	10	12.5	0.17	5
12.5	0.89	80	12.5	0.22	10
12.5	1.36	150	12.5	0.31	10
12.5	1.60	200	12.5	0.45	110
12.5	2.18	150	12.5	0.61	80
12.5	3.41	150	12.5	0.79	120
			12.5	1.12	160

Table C.6: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 4

Frequency (Hz)	**Hands**		**Frequency (Hz)**	**Hands**	
Subject 4	**Acceleration ms^{-2}**	**Sensation**	**Subject 4**	**Acceleration ms^{-2}**	**Sensation**
2	0.08	10	2	0.04	10
2	0.09	10	2	0.05	20
2	0.12	40	2	0.07	10
2	0.17	20	2	0.09	70
2	0.24	90	2	0.13	35
2	0.32	110	2	0.19	100
2	0.46	250	2	0.27	150
2.5	0.13	15	2	0.41	170
2.5	0.18	90	2.5	0.07	40
2.5	0.25	100	2.5	0.10	30
2.5	0.33	110	2.5	0.13	5
2.5	0.46	250	2.5	0.20	100
2.5	0.65	230	2.5	0.28	120
3.15	0.16	20	2.5	0.41	120
3.15	0.21	70	2.5	0.60	140
3.15	0.28	130	3.15	0.08	10
3.15	0.39	100	3.15	0.12	10
3.15	0.54	140	3.15	0.17	130
3.15	0.74	200	3.15	0.23	80
3.15	1.05	300	3.15	0.33	120
3.15	1.55	300	3.15	0.47	110
4	0.14	5	3.15	0.69	70
4	0.20	20	3.15	1.01	170
4	0.26	60	3.15	1.49	220
4	0.37	90	4	0.16	20
4	0.51	90	4	0.22	40
4	0.70	150	4	0.32	120
4	1.00	300	4	0.46	110
4	1.42	350	4	0.66	100
4	2.08	300	4	0.96	160
5	0.22	20	4	1.46	200
5	0.30	12	4	1.96	240
5	0.42	80	5	0.19	25
5	0.57	110	5	0.26	90
5	0.82	300	5	0.39	25
5	1.23	160	5	0.55	110
5	1.62	200	5	0.80	170
5	2.23	300	5	1.24	160
5	2.88	400	5	1.62	180
6.3	0.16	5	5	2.25	200
6.3	0.22	50	5	3.09	400
6.3	0.30	85	6.3	0.30	10
6.3	0.43	90	6.3	0.44	100
6.3	0.60	120	6.3	0.62	160
6.3	0.85	200	6.3	0.90	130
6.3	1.29	280	6.3	1.43	200
6.3	1.67	400	6.3	1.89	270
6.3	2.29	400	6.3	2.59	300
6.3	3.21	280	6.3	3.49	400
8	0.15	5	8	0.16	80
8	0.22	20	8	0.24	8
8	0.30	15	8	0.34	60
8	0.44	30	8	0.47	150
8	0.60	100	8	0.69	160
8	0.85	200	8	0.96	220
8	1.29	300	8	1.50	250
8	1.73	280	8	2.00	280
8	2.36	400	8	2.66	400
8	3.39	350	8	3.38	450
10	0.15	5	10	0.12	25
10	0.31	10	10	0.17	100
10	0.42	90	10	0.23	80
10	0.59	140	10	0.35	150
10	0.88	100	10	0.47	200
10	1.34	180	10	0.68	280
10	1.83	200	10	1.02	150
10	2.37	350	10	1.36	280
10	3.38	350	10	1.77	300
12.5	0.29	5	10	2.37	400
12.5	0.41	15	12.5	0.08	5
12.5	0.60	60	12.5	0.11	10
12.5	0.83	150	12.5	0.16	15
12.5	1.30	180	12.5	0.23	20
12.5	1.71	150	12.5	0.30	150
12.5	2.35	260	12.5	0.44	180
12.5	3.29	400	12.5	0.62	200
			12.5	0.80	300
			12.5	1.08	200
			12.5	1.53	450

Table C.7: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 5

Frequency (Hz)	**Hands**		**Feet**	
Subject 5	**Acceleration ms^{-2}**	**Sensation**	**Acceleration ms^{-2}**	**Sensation**
2	0.04	30	0.04	30
2	0.06	50	0.05	80
2	0.09	50	0.07	100
2	0.12	50	0.09	100
2	0.17	80	0.13	100
2	0.24	100	0.19	150
2	0.32	150	0.28	180
2	0.46	200	0.40	200
2.5	0.06	20	0.05	20
2.5	0.08	20	0.07	30
2.5	0.12	50	0.10	100
2.5	0.17	50	0.14	100
2.5	0.23	100	0.19	120
2.5	0.32	120	0.28	120
2.5	0.47	150	0.41	120
2.5	0.67	150	0.60	250
3.15	0.07	10	0.06	20
3.15	0.10	10	0.08	50
3.15	0.14	30	0.11	40
3.15	0.19	50	0.17	120
3.15	0.27	100	0.22	120
3.15	0.37	130	0.32	100
3.15	0.54	150	0.47	150
3.15	0.76	150	0.68	150
3.15	1.08	200	1.03	200
3.15	1.57	250	1.47	280
4	0.09	10	0.07	20
4	0.12	20	0.10	30
4	0.18	20	0.15	50
4	0.25	80	0.20	100
4	0.37	100	0.32	120
4	0.51	120	0.46	150
4	0.72	120	0.67	150
4	1.03	180	0.95	150
4	1.45	250	1.33	200
4	2.14	200	1.88	250
5	0.14	20	0.12	20
5	0.20	20	0.18	80
5	0.29	50	0.25	100
5	0.41	80	0.37	80
5	0.58	120	0.50	120
5	0.83	150	0.75	120
5	1.25	250	1.17	150
5	1.66	200	1.55	200
5	2.30	250	2.16	280
5	2.94	250	2.98	300
6.3	0.15	10	0.13	50
6.3	0.21	40	0.19	30
6.3	0.29	30	0.27	50
6.3	0.42	40	0.38	50
6.3	0.59	100	0.56	120
6.3	0.85	120	0.81	150
6.3	1.31	150	1.28	250
6.3	1.72	180	1.66	180
6.3	2.39	150	2.29	200
6.3	3.28	180	3.19	350
8	0.15	20	0.13	80
8	0.22	40	0.20	100
8	0.30	50	0.28	120
8	0.42	80	0.42	120
8	0.60	100	0.69	130
8	0.85	150	0.86	150
8	1.31	200	1.32	150
8	1.75	180	1.78	200
8	2.44	200	2.25	250
8	3.39	250	3.07	250
10	0.14	50	0.12	100
10	0.20	80	0.16	80
10	0.29	80	0.23	50
10	0.41	50	0.32	70
10	0.57	100	0.47	120
10	0.82	150	0.68	150
10	1.30	150	1.00	180
10	1.68	200	1.24	150
10	2.33	200	1.65	200
10	3.33	180	2.26	350
12.5	0.15	30	0.08	80
12.5	0.22	40	0.12	50
12.5	0.27	50	0.16	100
12.5	0.39	40	0.21	100
12.5	0.57	30	0.31	120
12.5	0.79	120	0.41	150
12.5	1.27	100	0.60	120
12.5	1.63	220	0.78	180
12.5	2.25	180	1.01	150
12.5	3.26	200	1.56	250

TABLE C.8: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 6

Frequency (Hz)	Hands		Frequency (Hz)	Feet	
Subject 6	Acceleration ms^{-2}	Sensation	Subject 6	Acceleration ms^{-2}	Sensation
2	0.05	10	2	0.03	5
2	0.07	5	2	0.05	5
2	0.09	10	2	0.06	50
2	0.12	20	2	0.09	70
2	0.17	70	2	0.13	150
2	0.24	100	2	0.19	150
2	0.33	150	2	0.28	400
2	0.48	200	2	0.43	300
2.5	0.09	5	2.5	0.05	10
2.5	0.12	5	2.5	0.06	20
2.5	0.17	50	2.5	0.09	20
2.5	0.24	50	2.5	0.14	20
2.5	0.34	150	2.5	0.19	200
2.5	0.47	200	2.5	0.28	200
2.5	0.68	200	2.5	0.42	200
3.15	0.20	5	2.5	0.62	300
3.15	0.28	50	3.15	0.06	20
3.15	0.39	100	3.15	0.08	5
3.15	0.55	150	3.15	0.12	60
3.15	0.77	100	3.15	0.16	100
3.15	1.11	300	3.15	0.24	200
3.15	1.63	300	3.15	0.33	100
4	0.13	5	3.15	0.49	200
4	0.18	10	3.15	0.70	300
4	0.25	10	3.15	1.04	300
4	0.37	20	3.15	1.50	400
4	0.52	150	4	0.08	5
4	0.73	200	4	0.10	20
4	1.04	200	4	0.16	50
4	1.48	300	4	0.21	70
4	2.15	400	4	0.33	100
5	0.14	5	4	0.45	150
5	0.21	10	4	0.67	300
5	0.29	30	4	0.96	200
5	0.42	50	4	1.40	400
5	0.58	100	4	1.98	400
5	0.83	150	5	0.12	5
5	1.29	300	5	0.18	20
5	1.69	400	5	0.26	70
5	2.32	300	5	0.38	150
5	2.96	400	5	0.59	150
6.3	0.21	10	5	0.86	200
6.3	0.30	5	5	1.27	200
6.3	0.43	20	5	1.73	400
6.3	0.60	50	5	2.16	300
6.3	0.87	150	5	3.19	500
6.3	1.33	250	6.3	0.15	10
6.3	1.76	200	6.3	0.22	30
6.3	2.44	300	6.3	0.30	50
6.3	3.29	500	6.3	0.44	70
8	0.31	10	6.3	0.62	200
8	0.45	20	6.3	0.91	400
8	0.63	20	6.3	1.39	300
8	0.90	100	6.3	1.84	400
8	1.39	150	6.3	2.64	300
8	1.84	200	6.3	3.50	500
8	2.56	300	8	0.13	10
8	3.43	500	8	0.20	10
10	0.15	5	8	0.27	100
10	0.22	5	8	0.40	50
10	0.31	20	8	0.59	150
10	0.45	10	8	0.82	150
10	0.63	40	8	1.30	200
10	0.90	100	8	1.69	300
10	1.40	100	8	2.21	300
10	1.84	200	8	3.08	300
10	2.54	200	10	0.12	70
10	3.47	400	10	0.16	10
12.5	0.16	5	10	0.23	20
12.5	0.22	10	10	0.31	90
12.5	0.30	10	10	0.45	150
12.5	0.43	20	10	0.64	150
12.5	0.60	40	10	0.95	200
12.5	0.86	50	10	1.18	300
12.5	1.31	100	10	1.55	300
12.5	1.73	200	10	2.05	300
12.5	2.31	200	12.5	0.07	5
12.5	3.32	200	12.5	0.10	20
			12.5	0.17	10
			12.5	0.24	70
			12.5	0.34	150
			12.5	0.47	200
			12.5	0.62	200
			12.5	0.83	200
			12.5	1.16	200

Table C.9: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 7

Frequency (Hz)	Hands		Frequency (Hz)	Feet	
Subject 7	Acceleration ms^{-2}	Sensation	Subject 7	Acceleration ms^{-2}	Sensation
2	0.05	20	2	0.03	50
2	0.07	5	2	0.05	80
2	0.09	50	2	0.06	120
2	0.12	50	2	0.09	40
2	0.18	80	2	0.13	150
2	0.25	60	2	0.19	200
2	0.35	180	2	0.28	180
2	0.50	140	2	0.43	250
2.5	0.09	20	2.5	0.04	30
2.5	0.13	10	2.5	0.07	120
2.5	0.18	40	2.5	0.10	80
2.5	0.25	80	2.5	0.14	120
2.5	0.35	80	2.5	0.20	170
2.5	0.49	120	2.5	0.29	140
2.5	0.70	150	2.5	0.43	150
3.15	0.07	20	2.5	0.64	200
3.15	0.10	20	3.15	0.06	20
3.15	0.15	20	3.15	0.08	20
3.15	0.20	80	3.15	0.12	20
3.15	0.28	80	3.15	0.18	50
3.15	0.40	120	3.15	0.24	80
3.15	0.56	120	3.15	0.35	150
3.15	0.78	120	3.15	0.51	150
3.15	1.13	150	3.15	0.73	200
3.15	1.64	150	3.15	1.08	250
4	0.13	5	3.15	1.59	250
4	0.18	10	4	0.08	5
4	0.26	20	4	0.11	10
4	0.37	40	4	0.16	20
4	0.52	100	4	0.24	80
4	0.73	140	4	0.35	100
4	1.05	150	4	0.50	100
4	1.50	200	4	0.68	120
4	2.17	200	4	1.01	170
5	0.21	20	4	1.45	220
5	0.29	40	4	2.04	250
5	0.42	100	5	0.13	15
5	0.58	100	5	0.19	50
5	0.83	120	5	0.28	40
5	1.27	140	5	0.41	50
5	1.68	160	5	0.58	120
5	2.32	180	5	0.87	160
5	2.94	200	5	1.32	200
6.3	0.14	5	5	1.78	250
6.3	0.20	30	5	2.40	250
6.3	0.29	40	5	3.20	250
6.3	0.42	80	6.3	0.16	15
6.3	0.58	100	6.3	0.24	70
6.3	0.85	130	6.3	0.33	50
6.3	1.30	140	6.3	0.47	120
6.3	1.71	130	6.3	0.66	120
6.3	2.38	160	6.3	0.97	130
6.3	3.28	250	6.3	1.55	150
8	0.14	10	6.3	1.99	140
8	0.21	10	6.3	2.69	200
8	0.30	5	6.3	3.50	300
8	0.42	100	8	0.14	80
8	0.59	50	8	0.23	40
8	0.85	120	8	0.29	80
8	1.33	160	8	0.43	100
8	1.76	160	8	0.63	100
8	2.43	200	8	0.92	150
8	3.43	200	8	1.41	150
10	0.21	20	8	1.89	150
10	0.30	40	8	2.64	200
10	0.42	120	8	3.51	300
10	0.60	80	10	0.11	40
10	0.87	110	10	0.19	30
10	1.32	150	10	0.23	100
10	1.75	150	10	0.34	60
10	2.42	180	10	0.47	100
10	3.45	180	10	0.69	140
12.5	0.15	10	10	1.09	100
12.5	0.28	30	10	1.37	200
12.5	0.41	80	10	1.75	200
12.5	0.58	110	10	2.18	240
12.5	0.82	120	12.5	0.10	10
12.5	1.28	130	12.5	0.14	30
12.5	1.66	160	12.5	0.21	50
12.5	2.29	120	12.5	0.25	80
12.5	3.28	180	12.5	0.34	120
			12.5	0.49	140
			12.5	0.68	130
			12.5	0.90	120
			12.5	1.30	150

Table C.10: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 8

Frequency (Hz)	Hands		Frequency (Hz)	Feet	
Subject 8	Acceleration ms^{-2}	Sensation	Subject 8	Acceleration ms^{-2}	Sensation
2	0.07	20	2	0.05	70
2	0.09	50	2	0.07	20
2	0.12	30	2	0.09	30
2	0.17	50	2	0.13	90
2	0.24	60	2	0.19	100
2	0.34	60	2	0.28	70
2	0.48	110	2	0.42	100
2.5	0.06	10	2.5	0.05	40
2.5	0.09	5	2.5	0.07	10
2.5	0.12	60	2.5	0.10	50
2.5	0.17	40	2.5	0.14	10
2.5	0.24	50	2.5	0.20	100
2.5	0.33	70	2.5	0.28	100
2.5	0.47	50	2.5	0.42	60
2.5	0.66	50	2.5	0.61	100
3.15	0.10	5	3.15	0.06	10
3.15	0.14	30	3.15	0.08	40
3.15	0.19	50	3.15	0.12	20
3.15	0.27	50	3.15	0.17	50
3.15	0.38	80	3.15	0.24	80
3.15	0.55	80	3.15	0.34	50
3.15	0.76	150	3.15	0.49	70
3.15	1.08	100	3.15	0.71	60
3.15	1.57	200	3.15	1.02	200
4	0.09	80	3.15	1.49	250
4	0.12	15	4	0.11	30
4	0.25	30	4	0.16	10
4	0.36	40	4	0.23	80
4	0.50	90	4	0.33	90
4	0.70	100	4	0.48	100
4	1.01	100	4	0.69	100
4	1.46	180	4	0.98	130
4	2.10	300	4	1.37	200
5	0.20	40	4	2.01	250
5	0.28	30	5	0.13	10
5	0.41	200	5	0.19	100
5	0.56	100	5	0.28	60
5	0.81	120	5	0.41	90
5	1.25	200	5	0.58	100
5	1.62	250	5	0.83	120
5	2.28	250	5	1.26	200
5	2.93	400	5	1.70	250
6.3	0.14	50	5	2.36	350
6.3	0.20	100	5	3.16	350
6.3	0.29	100	6.3	0.15	120
6.3	0.40	60	6.3	0.22	70
6.3	0.55	130	6.3	0.32	150
6.3	0.84	120	6.3	0.46	100
6.3	1.25	225	6.3	0.69	130
6.3	1.63	250	6.3	0.97	250
6.3	2.30	400	6.3	1.51	250
6.3	3.20	400	6.3	2.00	250
8	0.14	60	6.3	2.58	300
8	0.20	180	6.3	3.46	350
8	0.28	160	8	0.14	130
8	0.40	180	8	0.21	130
8	0.59	180	8	0.29	120
8	0.78	200	8	0.42	150
8	1.22	200	8	0.62	120
8	1.62	300	8	0.88	200
8	2.25	150	8	1.38	250
8	3.27	300	8	1.86	300
10	0.13	5	8	2.49	400
10	0.19	120	8	3.16	350
10	0.27	80	10	0.11	100
10	0.38	200	10	0.15	80
10	0.53	200	10	0.22	200
10	0.77	200	10	0.32	200
10	1.20	400	10	0.42	120
10	1.59	210	10	0.62	200
10	2.20	300	10	0.91	200
10	3.18	400	10	1.17	200
12.5	0.13	50	10	1.57	350
12.5	0.19	160	10	2.19	350
12.5	0.26	200	12.5	0.07	100
12.5	0.39	220	12.5	0.10	120
12.5	0.51	250	12.5	0.13	150
12.5	0.74	260	12.5	0.17	150
12.5	1.12	300	12.5	0.24	100
12.5	1.52	250	12.5	0.36	200
12.5	2.03	300	12.5	0.51	200
12.5	3.07	400	12.5	0.67	250
			12.5	0.91	300
			12.5	1.30	350

Table C.11: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 9

Frequency (Hz)	**Hands**		**Feet**	
Subject 9	**Acceleration** ms^{-2}	**Sensation**	**Acceleration** ms^{-2}	**Sensation**
2	0.05	20	0.04	30
2	0.07	30	0.05	60
2	0.09	10	0.07	90
2	0.12	60	0.09	110
2	0.17	60	0.13	120
2	0.25	40	0.20	130
2	0.34	110	0.29	120
2	0.48	80	0.43	160
2.5	0.06	20	0.05	40
2.5	0.09	70	0.07	40
2.5	0.12	80	0.10	50
2.5	0.17	20	0.14	70
2.5	0.25	70	0.20	130
2.5	0.34	130	0.29	100
2.5	0.48	120	0.43	130
2.5	0.69	130	0.62	160
3.15	0.07	10	0.06	20
3.15	0.10	20	0.08	40
3.15	0.15	50	0.12	50
3.15	0.20	70	0.17	90
3.15	0.28	110	0.24	110
3.15	0.39	50	0.34	120
3.15	0.56	120	0.50	130
3.15	0.77	140	0.72	90
3.15	1.11	150	1.06	170
3.15	1.61	200	1.57	170
4	0.09	10	0.07	10
4	0.13	10	0.11	70
4	0.18	20	0.16	100
4	0.25	50	0.22	100
4	0.37	100	0.32	120
4	0.52	120	0.47	110
4	0.72	140	0.66	80
4	1.03	150	0.98	180
4	1.48	160	1.42	150
4	2.14	170	2.06	220
5	0.14	10	0.12	20
5	0.20	40	0.18	40
5	0.29	60	0.26	80
5	0.41	60	0.38	100
5	0.58	130	0.55	100
5	0.83	140	0.81	130
5	1.26	130	1.26	170
5	1.63	140	1.66	200
5	2.25	160	2.29	250
5	2.91	230	3.12	270
6.3	0.15	20	0.14	40
6.3	0.21	20	0.20	90
6.3	0.29	30	0.28	120
6.3	0.42	90	0.42	110
6.3	0.59	120	0.59	120
6.3	0.84	120	0.86	150
6.3	1.29	130	1.35	200
6.3	1.70	170	1.79	190
6.3	2.34	180	2.52	200
6.3	3.22	210	3.42	210
8	0.15	30	0.14	50
8	0.20	40	0.21	80
8	0.29	70	0.29	120
8	0.43	120	0.43	110
8	0.58	120	0.61	120
8	0.87	140	0.88	170
8	1.30	140	1.37	190
8	1.74	210	1.81	180
8	2.38	200	2.38	180
8	3.40	200	3.21	250
10	0.14	60	0.12	110
10	0.19	90	0.17	110
10	0.29	40	0.26	120
10	0.39	120	0.35	120
10	0.55	120	0.50	120
10	0.80	140	0.77	150
10	1.29	130	1.14	200
10	1.64	190	1.36	200
10	2.28	190	1.92	180
10	3.37	150	2.68	220
12.5	0.15	20	0.09	30
12.5	0.21	30	0.13	60
12.5	0.27	40	0.17	140
12.5	0.40	70	0.25	140
12.5	0.55	110	0.34	130
12.5	0.79	120	0.49	120
12.5	1.22	130	0.69	120
12.5	1.58	170	0.88	180
12.5	2.21	150	1.17	180
12.5	3.17	200	1.69	200

Table C.12: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 10

Frequency (Hz)	Hands		Frequency (Hz)	Feet	
Subject 10	Acceleration ms^{-2}	Sensation	Subject 10	Acceleration ms^{-2}	Sensation
2	0.05	5	2	0.04	20
2	0.07	20	2	0.06	50
2	0.09	10	2	0.08	70
2	0.12	100	2	0.09	110
2	0.17	150	2	0.15	100
2	0.23	100	2	0.21	200
2	0.32	120	2	0.29	150
2	0.44	200	2	0.47	400
2.5	0.06	10	2.5	0.06	5
2.5	0.09	10	2.5	0.07	50
2.5	0.12	50	2.5	0.10	150
2.5	0.17	70	2.5	0.14	70
2.5	0.24	120	2.5	0.22	150
2.5	0.33	150	2.5	0.31	200
2.5	0.47	150	2.5	0.47	120
2.5	0.65	150	2.5	0.65	200
3.15	0.10	5	3.15	0.08	25
3.15	0.14	10	3.15	0.14	30
3.15	0.20	50	3.15	0.18	140
3.15	0.27	150	3.15	0.27	130
3.15	0.38	120	3.15	0.36	100
3.15	0.54	100	3.15	0.54	150
3.15	0.75	150	3.15	0.72	200
3.15	1.07	200	3.15	1.07	200
3.15	1.54	250	3.15	1.58	300
4	0.18	10	4	0.08	10
4	0.25	100	4	0.12	10
4	0.36	100	4	0.17	75
4	0.51	100	4	0.24	100
4	0.71	120	4	0.36	100
4	1.02	150	4	0.50	100
4	1.44	250	4	0.73	100
4	2.06	300	4	1.06	150
5	0.14	5	4	1.44	400
5	0.20	10	4	2.13	500
5	0.28	50	5	0.19	100
5	0.41	100	5	0.28	10
5	0.57	100	5	0.43	100
5	0.81	100	5	0.60	100
5	1.26	150	5	0.88	120
5	1.65	200	5	1.40	300
5	2.26	300	5	1.80	300
5	2.89	300	5	2.48	500
6.3	0.15	5	5	3.29	400
6.3	0.21	10	6.3	0.18	50
6.3	0.29	20	6.3	0.23	50
6.3	0.42	5	6.3	0.38	80
6.3	0.58	80	6.3	0.51	120
6.3	0.84	100	6.3	0.68	100
6.3	1.31	100	6.3	1.00	300
6.3	1.67	200	6.3	1.64	200
6.3	2.34	250	6.3	1.94	500
6.3	3.26	300	6.3	2.72	300
8	0.15	5	6.3	3.60	500
8	0.22	20	8	0.17	60
8	0.30	10	8	0.26	100
8	0.43	20	8	0.37	100
8	0.61	70	8	0.51	100
8	0.88	100	8	0.69	80
8	1.35	200	8	0.92	200
8	1.80	200	8	1.51	200
8	2.45	200	8	1.96	500
8	3.44	300	8	2.54	500
10	0.15	50	8	3.47	500
10	0.22	10	10	0.13	5
10	0.31	70	10	0.18	5
10	0.43	100	10	0.27	50
10	0.62	100	10	0.34	80
10	0.89	150	10	0.48	120
10	1.34	150	10	0.68	150
10	1.79	250	10	1.00	300
10	2.45	200	10	1.28	150
10	3.44	300	10	1.15	250
12.5	0.15	5	10	2.31	300
12.5	0.21	50	12.5	0.12	10
12.5	0.28	10	12.5	0.15	50
12.5	0.42	30	12.5	0.21	80
12.5	0.59	100	12.5	0.28	30
12.5	0.84	150	12.5	0.38	75
12.5	1.27	200	12.5	0.57	120
12.5	1.65	150	12.5	0.71	150
12.5	2.29	300	12.5	0.82	500
12.5	3.24	300	12.5	1.16	150

Table C.13: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 11

Frequency (Hz)	**Hands**		**Frequency (Hz)**	**Feet**	
Subject 11	**Acceleration ms^{-2}**	**Sensation**	**Subject 11**	**Acceleration ms^{-2}**	**Sensation**
2	0.05	30	2	0.04	10
2	0.07	20	2	0.05	30
2	0.09	30	2	0.07	20
2	0.12	80	2	0.09	50
2	0.17	50	2	0.13	30
2	0.24	50	2	0.19	50
2	0.32	120	2	0.29	80
2	0.45	130	2	0.40	80
2.5	0.07	10	2.5	0.05	10
2.5	0.09	20	2.5	0.07	20
2.5	0.13	30	2.5	0.10	30
2.5	0.17	80	2.5	0.15	20
2.5	0.24	80	2.5	0.21	20
2.5	0.33	80	2.5	0.29	50
2.5	0.46	130	2.5	0.43	30
2.5	0.65	120	2.5	0.62	80
3.15	0.07	10	3.15	0.08	20
3.15	0.10	20	3.15	0.13	50
3.15	0.15	20	3.15	0.18	80
3.15	0.20	50	3.15	0.24	50
3.15	0.28	80	3.15	0.34	50
3.15	0.38	100	3.15	0.51	100
3.15	0.54	80	3.15	0.72	80
3.15	0.74	120	3.15	1.02	150
3.15	1.06	150	3.15	1.47	150
3.15	1.51	150	4	0.08	10
4	0.13	10	4	0.11	10
4	0.19	20	4	0.16	10
4	0.25	50	4	0.24	10
4	0.36	80	4	0.33	20
4	0.51	80	4	0.45	50
4	0.71	100	4	0.69	100
4	1.01	120	4	0.94	80
4	1.42	120	4	1.33	120
4	2.05	150	4	1.89	120
5	0.14	10	5	0.19	10
5	0.20	80	5	0.27	10
5	0.28	50	5	0.41	20
5	0.41	100	5	0.53	80
5	0.57	100	5	0.81	120
5	0.80	120	5	1.19	100
5	1.22	120	5	1.66	150
5	1.60	180	5	2.26	150
5	2.20	180	5	2.98	150
5	2.88	200	6.3	0.14	10
6.3	0.14	20	6.3	0.22	10
6.3	0.20	50	6.3	0.32	10
6.3	0.28	80	6.3	0.44	20
6.3	0.41	20	6.3	0.64	80
6.3	0.57	100	6.3	0.94	100
6.3	0.81	100	6.3	1.40	100
6.3	1.25	120	6.3	1.90	150
6.3	1.66	120	6.3	2.60	180
6.3	2.28	150	6.3	3.32	200
6.3	3.17	150	8	0.18	20
8	0.14	30	8	0.26	50
8	0.20	20	8	0.33	50
8	0.29	30	8	0.47	30
8	0.41	80	8	0.64	80
8	0.58	80	8	0.91	120
8	0.83	120	8	1.52	100
8	1.28	80	8	1.89	180
8	1.70	150	8	2.33	180
8	2.34	180	8	3.20	200
8	3.32	200	10	0.12	10
10	0.14	10	10	0.17	20
10	0.20	10	10	0.25	30
10	0.29	10	10	0.33	80
10	0.41	80	10	0.46	100
10	0.56	100	10	0.73	80
10	0.82	80	10	1.06	120
10	1.25	120	10	1.39	150
10	1.69	150	10	1.96	200
10	2.30	150	10	2.72	200
10	3.33	150	12.5	0.10	10
12.5	0.15	10	12.5	0.13	10
12.5	0.20	10	12.5	0.18	20
12.5	0.27	20	12.5	0.27	10
12.5	0.41	20	12.5	0.35	50
12.5	0.56	80	12.5	0.50	80
12.5	0.82	50	12.5	0.70	120
12.5	1.24	80	12.5	0.94	80
12.5	1.60	150	12.5	1.19	150
12.5	2.22	120	12.5	1.66	180
12.5	3.23	180			

Table C.14: Vertical vibration acceleration values at the hands and the feet and sensation magnitudes for subject 12

Frequency (Hz)	Hands		Frequency (Hz)	Feet	
Subject 12	Acceleration ms^{-2}	Sensation	Subject 12	Acceleration ms^{-2}	Sensation
2	0.05	40	2	0.04	60
2	0.07	50	2	0.05	50
2	0.09	30	2	0.07	70
2	0.12	40	2	0.09	30
2	0.17	30	2	0.13	40
2	0.24	30	2	0.20	20
2	0.34	40	2	0.30	40
2	0.48	40	2	0.44	80
2.5	0.06	10	2.5	0.05	25
2.5	0.09	30	2.5	0.07	10
2.5	0.12	20	2.5	0.10	30
2.5	0.17	50	2.5	0.15	35
2.5	0.24	40	2.5	0.22	70
2.5	0.34	50	2.5	0.30	40
2.5	0.48	40	2.5	0.44	60
2.5	0.66	30	2.5	0.65	90
3.15	0.07	10	3.15	0.10	20
3.15	0.10	20	3.15	0.13	40
3.15	0.15	80	3.15	0.18	50
3.15	0.20	60	3.15	0.26	90
3.15	0.28	60	3.15	0.36	40
3.15	0.39	60	3.15	0.52	80
3.15	0.56	40	3.15	0.74	60
3.15	0.77	80	3.15	1.09	60
3.15	1.08	50	3.15	1.58	120
3.15	1.59	40	4	0.12	50
4	0.13	20	4	0.17	80
4	0.18	80	4	0.25	50
4	0.25	50	4	0.35	50
4	0.36	90	4	0.49	80
4	0.50	60	4	0.72	60
4	0.71	70	4	1.03	100
4	1.01	70	4	1.46	100
4	1.43	90	4	2.05	90
4	2.04	70	5	0.31	90
5	0.14	70	5	0.44	50
5	0.20	90	5	0.63	100
5	0.28	90	5	0.87	140
5	0.41	120	5	1.32	120
5	0.57	70	5	1.78	100
5	0.81	100	5	2.46	110
5	1.24	90	5	3.24	130
5	1.62	100	6.3	0.17	110
5	2.21	100	6.3	0.25	90
5	2.91	110	6.3	0.37	130
6.3	0.14	90	6.3	0.51	100
6.3	0.20	110	6.3	0.71	100
6.3	0.29	110	6.3	1.02	120
6.3	0.40	120	6.3	1.60	140
6.3	0.57	110	6.3	2.04	180
6.3	0.82	130	6.3	2.83	180
6.3	1.24	120	6.3	3.59	230
6.3	1.65	150	8	0.18	160
6.3	2.30	130	8	0.26	110
6.3	3.21	120	8	0.34	130
8	0.14	160	8	0.51	190
8	0.21	140	8	0.70	160
8	0.29	140	8	0.95	150
8	0.41	140	8	1.47	160
8	0.58	130	8	1.86	160
8	0.82	130	8	2.63	200
8	1.31	110	8	3.43	150
8	1.74	130	10	0.11	150
8	2.33	130	10	0.17	160
8	3.34	120	10	0.27	200
10	0.14	140	10	0.37	180
10	0.20	150	10	0.48	190
10	0.28	160	10	0.74	200
10	0.40	150	10	1.05	200
10	0.59	170	10	1.30	210
10	0.80	150	10	1.85	170
10	1.24	160	10	2.53	170
10	1.73	160	12.5	0.08	200
10	2.26	170	12.5	0.11	210
10	3.36	150	12.5	0.15	200
12.5	0.14	40	12.5	0.21	190
12.5	0.19	160	12.5	0.28	210
12.5	0.26	160	12.5	0.40	190
12.5	0.38	180	12.5	0.54	180
12.5	0.57	160	12.5	0.64	200
12.5	0.82	180	12.5	0.88	220
12.5	1.17	190	12.5	1.23	190
12.5	1.66	180			
12.5	2.30	170			
12.5	3.09	180			

C.3 Experiment 3 vibration acceleration magnitudes for equivalence of sensation reported in Chapter 7

Table C.15: Vertical vibration acceleration values at the hands (reference) for equivalence of sensation between hands and feet for all 12 subjects

HANDS	**Frequency (Hz)**												
	2	2.5	3.15	4(1)	4(2)	4(3)	5	6.3	8(1)	8(2)	8(3)	10	12.5
	Acceleration ms^{-2}												
s1	0.47	0.62	0.77	0.66	0.96	1.27	1.27	1.66	1.27	1.98	2.50	2.46	3.10
s2	0.49	0.67	0.81	0.63	1.00	1.29	1.33	1.58	1.37	1.96	2.70	2.40	2.95
s3	0.49	0.63	0.74	0.65	0.97	1.31	1.27	1.59	1.28	1.87	2.50	2.30	3.00
4s	0.49	0.67	0.74	0.71	0.95	1.28	1.30	1.64	1.31	2.00	2.60	2.38	3.10
s5	0.48	0.67	0.78	0.64	0.98	1.24	1.20	1.62	1.27	1.92	2.60	2.40	3.17
s6	0.48	0.66	0.75	0.64	0.96	1.29	1.19	1.62	1.30	1.99	2.49	2.50	2.97
s7	0.47	0.64	0.79	0.64	0.94	1.32	1.25	1.61	1.38	2.00	2.60	2.27	2.99
s8	0.49	0.63	0.79	0.65	0.95	1.29	1.23	1.58	1.28	1.95	2.59	2.38	2.00
s9	0.53	0.67	0.79	0.64	0.97	1.29	1.22	1.52	1.27	1.93	2.60	2.54	3.00
s10	0.51	0.67	0.75	0.67	0.97	1.32	1.29	1.53	1.30	1.92	2.52	2.38	3.00
s11	0.48	0.67	0.75	0.64	0.97	1.30	1.20	1.62	1.28	2.00	2.56	2.50	2.90
s12	0.50	0.68	0.76	0.65	1.00	1.32	1.26	1.57	1.30	2.00	2.58	2.54	3.00

Table C.16: Vertical vibration acceleration values at the feet for equivalence of sensation between hands and feet for all 12 subjects

FEET	**Frequency (Hz)**												
	2	2.5	3.15	4(1)	4(2)	4(3)	5	6.3	8(1)	8(2)	8(3)	10	12.5
	Acceleration ms^{-2}												
s1	0.31	0.44	0.55	0.49	0.78	0.90	1.00	1.10	0.55	0.96	1.64	1.09	0.98
s2	0.43	0.67	0.57	0.64	0.87	1.32	1.26	1.58	1.20	1.52	1.60	1.69	1.39
s3	0.23	0.32	0.52	0.44	0.85	0.81	0.63	1.41	1.14	1.39	1.85	2.20	1.39
4s	0.20	0.28	0.36	0.41	0.51	0.95	0.93	1.00	0.79	0.97	1.60	1.00	1.00
s5	0.54	0.61	0.73	0.63	0.81	1.05	1.27	1.81	1.18	1.68	1.89	1.15	0.74
s6	0.32	0.55	0.59	0.35	0.72	0.93	0.98	1.31	1.06	1.47	2.00	1.75	1.44
s7	0.28	0.46	0.50	0.46	0.65	0.89	0.93	1.55	0.87	1.12	1.38	1.15	0.75
s8	0.30	0.45	0.88	0.98	0.67	1.45	1.69	1.50	1.29	1.73	1.78	1.14	0.63
s9	0.34	0.36	0.60	0.27	0.68	1.37	1.13	0.99	0.61	0.89	1.60	1.14	0.50
s10	0.28	0.37	0.41	0.66	0.97	1.19	1.24	1.27	1.04	1.13	1.73	1.04	0.55
s11	0.26	0.30	0.26	0.39	0.54	0.75	0.79	1.23	0.51	0.72	1.20	1.14	0.81
s12	0.29	0.58	0.50	0.50	1.00	1.08	1.23	1.81	1.41	2.00	2.30	1.87	1.66

Table C.17: Vertical vibration acceleration values at the hands (reference) for equivalence of sensation between hands and seat for all 12 subjects

HANDS	**Frequency (Hz)**									
	4(1)	4(2)	4(3)	5	6.3	8(1)	8(2)	8(3)	10	12.5
	Acceleration ms^{-2}									
s1	0.65	0.95	1.24	1.29	1.54	1.26	1.92	2.52	2.47	3.1
s2	0.65	0.94	1.32	1.26	1.58	1.28	1.92	2.59	2.40	3.2
s3	0.64	0.98	1.27	1.3	1.54	1.26	1.92	2.6	2.32	2.84
s4	0.66	1	1.3	1.31	1.6	1.29	1.96	2.62	2.37	3.1
s5	0.64	0.98	1.36	1.29	1.6	1.31	1.84	2.59	2.40	3
s6	0.62	1	1.3	1.29	1.58	1.36	1.98	2.6	2.40	3
s7	0.65	0.89	1.3	1.22	1.49	1.29	1.89	2.6	2.37	3
s8	0.66	1	1.35	1.22	1.5	1.2	2	2.6	2.36	3.1
s9	0.64	0.93	1.28	1.32	1.52	1.3	2	2.6	2.40	3
s10	0.64	0.96	1.31	1.28	1.59	1.28	1.95	2.64	2.46	3
s11	0.65	0.98	1.27	1.19	1.58	1.35	1.93	2.6	2.38	3.16
s12	0.65	0.99	1.3	1.29	1.69	1.26	1.93	2.79	2.40	2.9

Table C.18: Vertical vibration acceleration values at the seat for equivalence of sensation between hands and seat for all 12 subjects

SEAT	**Frequency (Hz)**									
	4(1)	4(2)	4(3)	5	6.3	8(1)	8(2)	8(3)	10	12.5
	Acceleration ms^{-2}									
s1	0.2	0.18	0.17	0.15	0.23	0.11	0.23	0.32	0.32	0.4
s2	0.24	0.25	0.24	0.22	0.27	0.16	0.21	0.35	0.37	0.4
s3	0.24	0.27	0.19	0.26	0.18	0.13	0.32	0.38	0.28	0.27
s4	0.13	0.2	0.24	0.2	0.17	0.13	0.28	0.39	0.26	0.37
s5	0.16	0.22	0.28	0.22	0.16	0.2	0.25	0.25	0.24	0.37
s6	0.13	0.14	0.19	0.15	0.1	0.15	0.2	0.3	0.28	0.31
s7	0.22	0.2	0.29	0.24	0.15	0.23	0.32	0.34	0.25	0.21
s8	0.15	0.19	0.27	0.17	0.19	0.14	0.23	0.23	0.30	0.28
s9	0.29	0.17	0.26	0.2	0.19	0.18	0.31	0.37	0.28	0.26
s10	0.14	0.2	0.22	0.16	0.15	0.13	0.18	0.2	0.24	0.3
s11	0.14	0.27	0.26	0.23	0.12	0.11	0.15	0.22	0.22	0.34
s12	0.19	0.19	0.17	0.17	0.21	0.18	0.24	0.25	0.16	0.2

C.4 Experiment 4 data reported in Chapter 8

Table C.19: Phase threshold detection values in degrees for phase motions between hands and feet for all 12 subjects

HANDS FEET	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
Frequency (Hz)	Phase threshold (degrees)											
2	82.5	56.25	180	180	63.75	180	37.5	67.5	97.5	37.5	97.5	75
2.5	120	131.25	180	180	180	180	67.5	180	71.25	60	180	75
3.15	108.75	180	180	180	180	180	82.5	180	180	71.25	116.25	180
4(1)	150	180	180	180	180	180	157.5	127.5	150	131.25	180	180
4(2)	71.25	180	180	180	180	180	123.75	180	180	93.75	180	180
4(3)	86.25	180	180	180	127.5	180	180	180	180	146.25	180	180
5	180	180	180	180	180	180	180	180	180	127.5	180	180
6.3	180	180	180	180	180	180	180	180	180	180	180	180
8(1)	180	180	180	180	180	180	112.5	180	180	180	180	180
8(2)	180	180	180	180	180	180	93.75	180	180	180	180	180
8(3)	180	180	180	180	180	180	75	180	180	180	180	180
10	180	180	180	180	180	180	131.25	180	180	180	180	180
12.5	180	180	180	180	180	180	116.25	180	180	180	180	180

Table C.20: Phase threshold detection values in degrees for phase motions between hands and seat for all 12 subjects

HANDS SEAT	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
Frequency (Hz)	Phase threshold (degrees)											
4(1)	71.25	180	180	180	146.25	153.75	116.25	150	101.25	78.75	180	86.25
4(2)	180	180	120	180	93.75	180	131.25	180	161.25	180	180	135
4(3)	78.75	180	142.5	180	180	138.75	112.5	180	180	93.75	180	180
5	180	180	101.25	180	97.5	123.75	180	180	97.5	108.75	97.5	105
6.3	142.5	180	142.5	142.5	142.5	116.25	142.5	146.25	180	56.25	142.5	180
8(1)	180	180	127.5	180	142.5	138.75	150	180	180	138.75	180	146.25
8(2)	146.25	157.5	180	180	180	180	142.5	180	180	142.5	180	142.5
8(3)	180	135	180	142.5	142.5	142.5	142.5	180	180	131.25	180	142.5
10	180	180	127.5	180	127.5	142.5	116.25	180	180	180	142.5	123.75
12.5	142.5	180	131.25	180	180	52.5	142.5	142.5	180	138.75	90	142.5

Table C.21: Phase threshold detection values in degrees for phase motions between feet and seat for all 12 subjects

FEET SEAT	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
Frequency (Hz)	Phase threshold (degrees)											
4(1)	37.5	180	116.25	112.5	180	180	180	165	52.5	180	146.25	80
4(2)	97.5	180	180	146.25	180	135	180	172.5	37.5	101.25	180	180
4(3)	93.75	180	78.75	180	180	180	142.5	180	78.75	108.75	180	180
5	105	180	120	142.5	180	180	180	180	180	116.25	180	157.5
6.3	138.75	180	142.5	180	138.75	142.5	142.5	142.5	180	138.75	142.5	180
8(1)	180	180	142.5	180	138.75	180	180	180	180	131.25	180	180
8(2)	142.5	180	180	180	116.25	180	142.5	131.25	180	120	180	180
8(3)	142.5	180	180	180	142.5	180	180	142.5	180	131.25	180	180
10	142.5	180	142.5	180	142.5	180	180	142.5	180	180	180	180
12.5	142.5	142.5	142.5	180	138.75	180	180	142.5	142.5	116.25	180	180

Table C.22: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 2 Hz

Phase	**Discomfort rating**											
Hands Feet	**2 Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	90	110	100	120	120	115	100	100	100	90
30	100	100	80	120	100	120	120	100	120	100	100	120
60	140	90	100	80	111	120	60	110	100	102	100	120
90	150	110	80	90	125	100	80	110	110	110	110	90
120	150	110	70	90	128	90	40	120	110	125	130	100
150	150	110	100	70	105	120	50	100	120	110	100	70
180	160	110	110	60	110	110	50	100	120	110	120	80

Table C.23: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 2.5 Hz

Phase	**Discomfort rating**											
Hands Feet	**2.5 Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	100	80	100	90	100	100	100	100	110	50
30	100	100	100	100	100	110	100	100	100	100	110	80
60	120	100	100	90	100	120	100	105	100	90	100	90
90	130	100	100	110	100	120	80	90	120	75	110	100
120	150	100	100	90	100	90	50	100	130	130	100	90
150	130	100	100	110	104	100	60	115	120	120	110	100
180	150	100	80	120	100	110	50	105	120	107	100	70

Table C.24: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 3.15 Hz

Phase	**Discomfort rating**											
Hands Feet	**3.15 Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
30	100	100	100	100	100	110	90	100	100	100	90	120
60	100	100	100	110	100	110	100	100	100	95	100	110
90	100	100	100	110	100	100	100	100	110	105	90	110
120	120	100	80	100	97	100	90	115	100	100	90	80
150	150	100	100	110	101	100	90	100	100	205	120	50
180	130	100	100	120	90	120	80	105	110	120	130	70
180	130	100	100	100	93	120	100	110	110	120	100	100

Table C.25: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 4(1) Hz

Phase	**Discomfort rating**											
Hands Feet	**4(1) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	110	100	100	100	100	110	90	110	120	90	110	90
30	100	100	100	100	100	100	100	100	100	115	100	120
60	90	100	100	110	100	100	110	105	100	100	100	90
90	120	100	90	80	100	90	100	100	90	100	90	110
120	130	100	80	120	100	70	70	105	100	105	100	100
150	130	100	70	80	100	90	90	100	110	85	100	70
180	120	100	100	70	100	110	100	90	110	70	120	120

Table C.26: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 4(2) Hz

Phase	**Discomfort rating**											
Hands Feet	**4(2) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	100	90	100	110	90	100	110	100	100	120
30	100	100	130	110	100	80	100	100	100	103	100	130
60	110	100	110	100	100	110	90	100	100	105	110	110
90	110	100	110	120	109	80	100	100	100	100	90	70
120	120	100	100	110	100	100	80	110	110	100	100	70
150	130	100	100	110	106	100	80	85	100	110	120	90
180	120	100	100	110	91	90	90	90	110	115	110	80

Table C.27: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 4(3) Hz

Phase	**Discomfort rating**											
Hands Feet	**4(3) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	100	100	107	100	100	100	100	100	100	90
30	100	100	100	100	105	90	100	100	100	100	120	80
60	100	100	100	100	105	110	90	115	100	90	120	120
90	100	100	100	110	102	120	110	105	100	100	120	100
120	130	100	120	90	123	110	130	110	100	100	120	50
150	150	100	100	100	113	90	120	100	110	105	120	80
180	150	100	100	90	113	100	110	110	100	115	110	70

Table C.28: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 5 Hz

Phase	Discomfort rating											
Hands Feet	**5 Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	100	110	100	90	100	105	100	85	100	80
30	120	100	80	110	108	120	100	110	100	100	100	110
60	100	100	100	120	105	110	90	100	110	105	100	70
90	100	100	100	100	100	110	100	100	110	90	100	80
120	90	100	120	100	105	120	80	105	100	85	90	110
150	140	100	80	110	105	110	100	115	120	110	100	90
180	120	100	100	80	112	100	100	90	90	90	100	100

Table C.29: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 6.3 Hz

Phase	Discomfort rating											
Hands Feet	**6.3 Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	110	100	100	120	100	100	110	100	100	100	120	130
30	90	100	100	100	100	90	100	100	100	95	120	90
60	100	100	100	110	106	110	90	100	100	100	90	90
90	100	100	100	120	105	120	90	100	100	100	100	110
120	110	100	100	100	100	80	100	110	100	100	110	100
150	90	100	100	80	100	120	90	105	100	100	110	70
180	110	100	100	110	100	110	100	100	100	100	100	100

Table C.30: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 8(1) Hz

Phase	Discomfort rating											
Hands Feet	**8(1) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	90	100	100	100	100	110	100	100	100	100	100	70
30	120	100	100	110	108	120	110	110	100	100	100	100
60	100	100	100	100	100	90	100	105	100	90	100	90
90	110	100	100	120	100	110	90	100	100	100	120	80
120	120	100	90	110	102	110	100	110	110	95	110	70
150	100	100	100	110	100	70	120	100	130	120	110	60
180	90	100	100	100	100	100	90	100	100	85	100	70

Table C.31: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 8(2) Hz

Phase	**Discomfort rating**											
Hands Feet	**8(2) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	110	100	102	100	80	100	100	100	110	90
30	110	100	120	90	100	120	110	100	100	100	100	80
60	120	100	100	110	105	120	80	100	100	100	110	100
90	100	100	110	110	100	90	90	100	100	95	100	60
120	90	100	100	100	112	100	50	100	100	95	100	70
150	120	100	100	95	108	120	60	105	110	100	100	120
180	100	100	100	100	100	110	50	100	100	95	100	60

Table C.32: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 8(3) Hz

Phase	**Discomfort rating**											
Hands Feet	**8(3) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	120	100	120	100	100	100	80	120	100	90	120	120
30	90	100	100	120	100	120	100	100	80	115	100	110
60	100	100	100	110	100	120	100	110	100	100	100	80
90	100	100	100	110	100	110	70	100	100	110	120	120
120	120	100	100	100	100	90	60	125	120	110	100	90
150	120	100	110	100	100	110	50	120	90	90	120	100
180	90	100	100	120	100	120	100	110	110	90	100	100

Table C.33: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 10 Hz

Phase	**Discomfort rating**											
Hands Feet	**10 Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	100	90	105	110	100	100	100	100	100	100
30	100	100	100	100	100	70	100	100	100	100	100	100
60	120	100	100	100	107	110	110	100	100	100	120	80
90	110	100	100	110	100	100	70	100	100	95	90	80
120	100	100	110	100	100	90	50	90	100	95	120	70
150	90	100	100	110	100	90	50	105	100	100	90	120
180	110	100	100	120	100	120	60	110	100	100	90	90

Table C.34: Discomfort rating values for phase motions between hands and feet for all 12 subjects at 12.5 Hz

Phase	Discomfort rating											
Hands Feet	**12.5 Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	120	100	120	110	103	120	90	100	110	100	100	90
30	100	100	110	100	100	110	100	100	100	100	120	70
60	120	100	100	120	100	100	120	100	100	100	120	100
90	120	100	120	120	111	90	80	100	100	105	100	80
120	100	100	120	100	100	110	70	105	100	95	100	80
150	100	100	120	110	109	90	70	100	100	100	120	100
180	130	100	130	120	103	100	60	100	100	102	100	110

Table C.35: Discomfort rating values for phase motions between hands and seat for all 12 subjects at 4(1) Hz

Phase	Discomfort rating											
Hands Seat	**4(1) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	90	100	100	110	100	100	60	100	110	100	100	100
30	100	105	120	110	91	120	60	100	100	100	100	120
60	120	100	100	100	93	120	70	110	100	100	100	120
90	150	110	100	120	96	40	90	105	110	75	80	110
120	150	95	100	120	85	90	80	120	100	70	60	60
150	120	90	120	80	57	40	50	100	80	60	80	70
180	130	110	130	140	60	110	100	150	100	90	90	70

Table C.36: Discomfort rating values for phase motions between hands and seat for all 12 subjects at 4(2) Hz

Phase	Discomfort rating											
Hands Seat	**4(2) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	120	100	89	120	100	100	100	100	90	110
30	120	100	100	110	84	110	100	100	100	85	100	70
60	90	95	80	120	91	70	90	100	100	100	100	120
90	120	100	110	120	77	90	80	110	110	50	110	110
120	150	100	100	110	81	100	50	105	110	45	70	90
150	110	90	70	90	78	70	50	115	90	45	70	60
180	110	90	90	110	100	110	60	110	110	40	70	100

Table C.37: Discomfort rating values for phase motions between hands and seat for all 12 subjects at 4(3) Hz

Phase	**Discomfort rating**											
Hands Seat	**4(3) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	120	110	100	110	100	120	100	90	100	90	110	90
30	100	100	100	140	99	110	100	100	100	105	100	100
60	100	110	120	100	95	100	110	100	100	90	100	100
90	150	100	100	120	86	110	80	115	100	60	80	110
120	150	90	70	130	78	90	50	110	100	60	80	120
150	130	100	70	100	84	70	80	100	100	35	60	60
180	130	100	80	120	87	90	70	100	110	35	50	60

Table C.38: Discomfort rating values for phase motions between hands and seat for all 12 subjects at 5 Hz

Phase	**Discomfort rating**											
Hands Seat	**5 Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	120	90	110	110	100	100	90	100	100	50	100	100
30	100	100	120	150	98	110	100	100	100	55	90	120
60	100	100	100	100	97	120	100	100	100	100	90	100
90	150	90	90	100	94	60	90	100	110	45	100	90
120	130	90	100	110	90	70	50	90	110	35	70	70
150	150	80	100	120	103	130	80	100	120	40	110	120
180	120	90	80	80	92	90	60	90	90	40	80	90

Table C.39: Discomfort rating values for phase motions between hands and seat for all 12 subjects at 6.3 Hz

Phase	**Discomfort rating**											
Hands Seat	**6.3 Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	100	100	109	90	80	100	100	100	100	110
30	120	100	100	100	110	90	100	100	100	70	100	90
60	120	100	110	90	111	110	100	100	100	75	100	80
90	140	100	90	100	95	110	110	100	100	70	80	90
120	120	90	100	90	88	70	100	85	100	75	50	110
150	100	120	150	120	127	120	150	150	110	135	160	150
180	100	100	100	70	100	90	120	90	100	60	80	100

Table C.40: Discomfort rating values for phase motions between hands and seat for all 12 subjects at 8(1) Hz

Phase	**Discomfort rating**											
Hands Seat	**8(1) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	130	100	110	100	105	130	100	100	100	85	100	110
30	100	100	100	100	112	100	100	105	100	100	110	100
60	130	100	110	90	100	110	130	100	100	100	110	80
90	110	100	100	110	117	120	100	100	100	90	90	70
120	100	100	140	100	120	100	100	100	100	80	100	110
150	90	110	150	130	141	150	160	120	110	150	130	150
180	150	100	120	120	100	110	120	110	100	135	80	90

Table C.41: Discomfort rating values for phase motions between hands and seat for all 12 subjects at 8(2) Hz

Phase	**Discomfort rating**											
Hands Seat	**8(2) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	120	100	100	120	100	150	100	100	100	100	100	90
30	120	100	120	110	101	140	120	100	110	90	110	100
60	100	100	100	140	102	240	100	100	100	65	100	150
90	120	100	140	140	106	120	130	100	100	60	100	110
120	100	105	100	140	113	110	100	110	100	85	80	120
150	150	115	130	180	137	150	160	120	130	210	120	100
180	120	100	100	150	111	160	120	100	100	130	90	130

Table C.42: Discomfort rating values for phase motions between hands and seat for all 12 subjects at 8(3) Hz

Phase	**Discomfort rating**											
Hands Seat	**8(3) Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	120	100	100	90	100	100	100	100	130	100
30	120	100	120	110	100	120	110	100	100	110	130	80
60	100	100	100	100	105	150	150	110	100	100	90	130
90	90	100	150	110	102	110	120	110	100	110	100	100
120	90	100	140	110	107	130	100	100	100	105	110	110
150	100	120	200	180	99	130	170	140	110	115	150	150
180	120	110	170	130	110	140	170	125	100	110	110	120

Table C.43: Discomfort rating values for phase motions between hands and seat for all 12 subjects at 10 Hz

Phase	**Discomfort rating**											
Hands Seat	**10 Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	110	100	110	110	100	110	100	120	100	100	120	90
30	100	100	100	110	100	120	110	110	100	100	100	80
60	120	100	100	110	101	110	90	100	100	85	120	100
90	100	100	80	110	105	100	100	100	100	100	130	110
120	120	110	200	150	118	100	140	130	100	100	120	80
150	150	120	200	180	163	160	170	150	120	250	170	150
180	140	100	150	140	133	140	100	100	100	130	110	110

Table C.44: Discomfort rating values for phase motions between hands and seat for all 12 subjects at 12.5 Hz

Phase	**Discomfort rating**											
Hands Seat	**12.5 Hz**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	140	110	100	100	100	100	100	115	110	120
30	100	110	150	110	110	140	110	100	100	95	120	100
60	120	110	100	100	104	160	140	100	100	110	120	130
90	120	110	140	120	113	140	120	100	100	105	110	90
120	130	110	150	120	115	110	110	100	120	100	120	120
150	150	105	80	180	193	170	150	170	150	170	200	170
180	150	110	110	120	111	150	100	100	110	120	130	110

Table C.45: Discomfort rating values for phase motions between feet and seat for all 12 subjects at 4(1) Hz

Phase	**Discomfort rating**											
Feet Seat	**4(1)**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	100	100	100	100	100	100	100	100	100	80
30	100	90	110	110	96	100	100	100	100	105	100	110
60	100	100	130	100	107	90	90	100	100	100	80	130
90	130	110	120	100	100	100	100	112	110	95	120	100
120	150	110	100	120	104	100	90	100	100	100	110	150
150	100	100	100	110	100	90	60	100	110	120	70	110
180	150	100	120	150	103	120	80	100	120	130	110	130

Table C.46: Discomfort rating values for phase motions between feet and seat for all 12 subjects at 4(2) Hz

Phase	**Discomfort rating**											
Feet Seat	**4(2)**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	120	100	100	90	102	110	100	100	100	100	90	90
30	100	90	100	120	100	100	100	100	100	95	90	120
60	100	110	110	140	100	100	110	120	120	90	100	110
90	130	100	100	100	100	90	120	100	120	75	120	110
120	120	110	90	150	105	90	90	120	140	115	110	130
150	150	110	90	150	100	110	90	110	120	90	90	110
180	150	100	120	180	113	110	80	100	120	65	100	140

Table C.47: Discomfort rating values for phase motions between feet and seat for all 12 subjects at 4(3) Hz

Phase	**Discomfort rating**											
Feet Seat	**4(3)**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	100	120	100	90	110	100	100	100	90	80
30	100	100	110	90	100	130	100	100	100	100	110	90
60	110	100	120	100	100	110	90	110	110	100	110	120
90	120	100	120	150	100	120	100	105	110	100	110	130
120	120	105	130	120	105	70	110	105	110	90	100	120
150	150	100	120	110	100	100	150	110	110	85	100	110
180	150	100	130	120	112	110	150	115	120	130	130	135

Table C.48: Discomfort rating values for phase motions between feet and seat for all 12 subjects at 5 Hz

Phase	**Discomfort rating**											
Feet Seat	**5**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	110	100	110	100	120	90	100	100	95	100	100
30	100	100	110	120	100	140	110	100	100	100	110	100
60	150	100	100	110	100	130	100	125	100	100	90	135
90	120	100	130	180	93	170	110	112	100	110	80	140
120	80	100	120	150	100	150	100	100	100	115	90	120
150	150	105	150	200	100	160	100	100	110	140	110	120
180	150	110	130	180	96	150	100	110	100	115	90	135

Table C.49: Discomfort rating values for phase motions between feet and seat for all 12 subjects at 6.3 Hz

Phase	**Discomfort rating**											
Feet Seat	**6.3**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	100	100	95	110	100	100	100	100	100	100
30	100	100	100	80	100	100	100	100	100	100	110	90
60	120	100	90	120	100	110	100	100	110	90	100	90
90	120	100	120	120	100	90	60	100	100	60	90	70
120	100	100	100	180	100	110	70	120	100	85	110	80
150	150	150	200	200	129	150	180	160	120	170	140	140
180	100	100	160	150	100	120	100	125	100	100	100	110

Table C.50: Discomfort rating values for phase motions between feet and seat for all 12 subjects at 8(1) Hz

Phase	**Discomfort rating**											
Feet Seat	**8(1)**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	110	100	100	120	100	100	100	100	100	125
30	100	100	100	110	100	100	110	110	100	100	100	90
60	110	100	100	100	100	90	150	100	100	80	100	100
90	120	100	140	150	100	100	110	100	100	70	100	120
120	100	100	120	120	100	120	150	100	100	80	70	120
150	90	110	130	130	110	150	200	130	110	80	150	150
180	100	100	130	100	100	110	180	120	100	90	110	100

Table C.51: Discomfort rating values for phase motions between feet and seat for all 12 subjects at 8(2) Hz

Phase	Discomfort rating											
Feet Seat	**8(2)**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	100	100	100	110	100	120	100	100	100	100	90	110
30	90	100	100	90	100	110	100	100	110	95	110	115
60	90	110	100	90	100	90	110	110	100	90	90	80
90	80	100	100	150	100	70	140	120	100	110	100	100
120	100	110	120	100	115	90	120	120	100	80	80	80
150	80	115	170	130	123	120	190	132	110	150	140	120
180	90	105	110	120	110	110	160	110	100	165	100	120

Table C.52: Discomfort rating values for phase motions between feet and seat for all 12 subjects at 8(3) Hz

Phase	Discomfort rating											
Feet Seat	**8(3)**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	110	110	110	100	100	100	110	100	100	110	100	100
30	100	100	120	100	102	90	100	100	100	100	120	80
60	100	100	100	120	105	110	100	100	100	85	100	100
90	120	100	100	90	105	90	120	100	100	110	100	90
120	90	100	120	100	102	110	70	100	100	100	110	70
150	120	105	150	150	111	100	190	130	110	140	140	115
180	120	110	130	120	102	70	140	110	100	140	120	110

Table C.53: Discomfort rating values for phase motions between feet and seat for all 12 subjects at 10 Hz

Phase	Discomfort rating											
Feet Seat	**10**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	90	100	100	150	100	110	100	160	100	115	100	120
30	100	100	100	120	112	100	100	110	100	100	100	110
60	100	100	100	80	100	110	100	110	100	100	100	100
90	90	100	90	160	100	90	100	100	100	90	100	100
120	120	100	120	110	110	90	200	100	100	170	120	70
150	120	120	180	200	147	150	200	120	110	150	120	140
180	90	100	120	150	100	100	130	110	100	150	120	110

Table C.54: Discomfort rating values for phase motions between feet and seat for all 12 subjects at 12.5 Hz

Phase	**Discomfort rating**											
Feet Seat	**12.5**											
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12
0	110	100	100	110	100	100	120	100	120	100	100	110
30	100	100	120	100	100	110	110	115	110	90	110	100
60	100	105	110	110	100	70	100	110	100	110	100	100
90	120	100	120	110	100	110	140	100	110	100	120	100
120	100	100	110	180	106	120	150	100	120	115	100	125
150	150	130	200	250	137	170	200	105	140	200	100	200
180	100	110	120	130	100	140	150	110	100	120	110	120

C.4.1 Comparison of the bodymap localisation of phase thresholds-discomfort

C.4.1.1 Hands-Feet

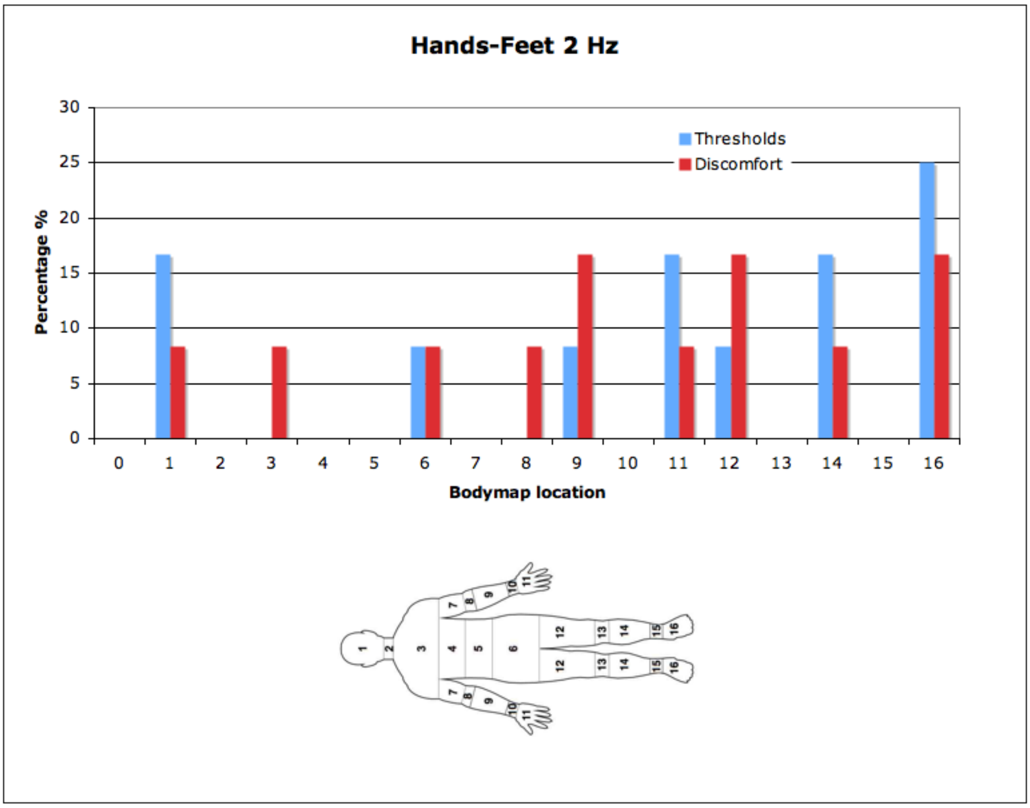


FIGURE C.1: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

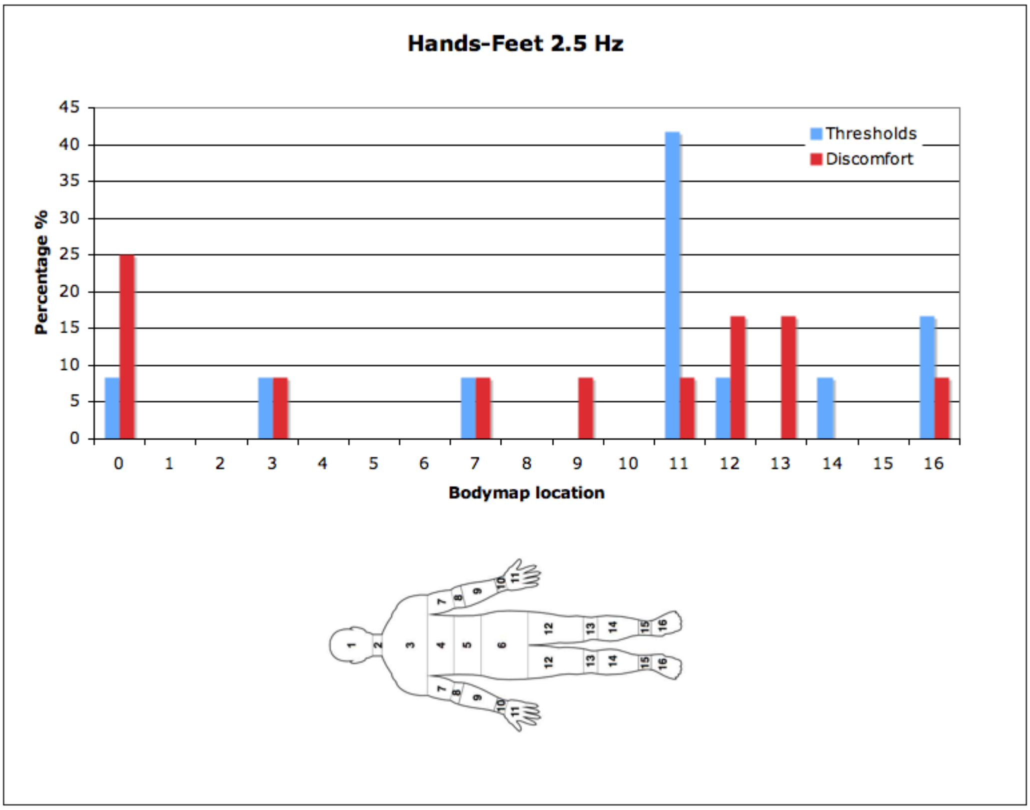


FIGURE C.2: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

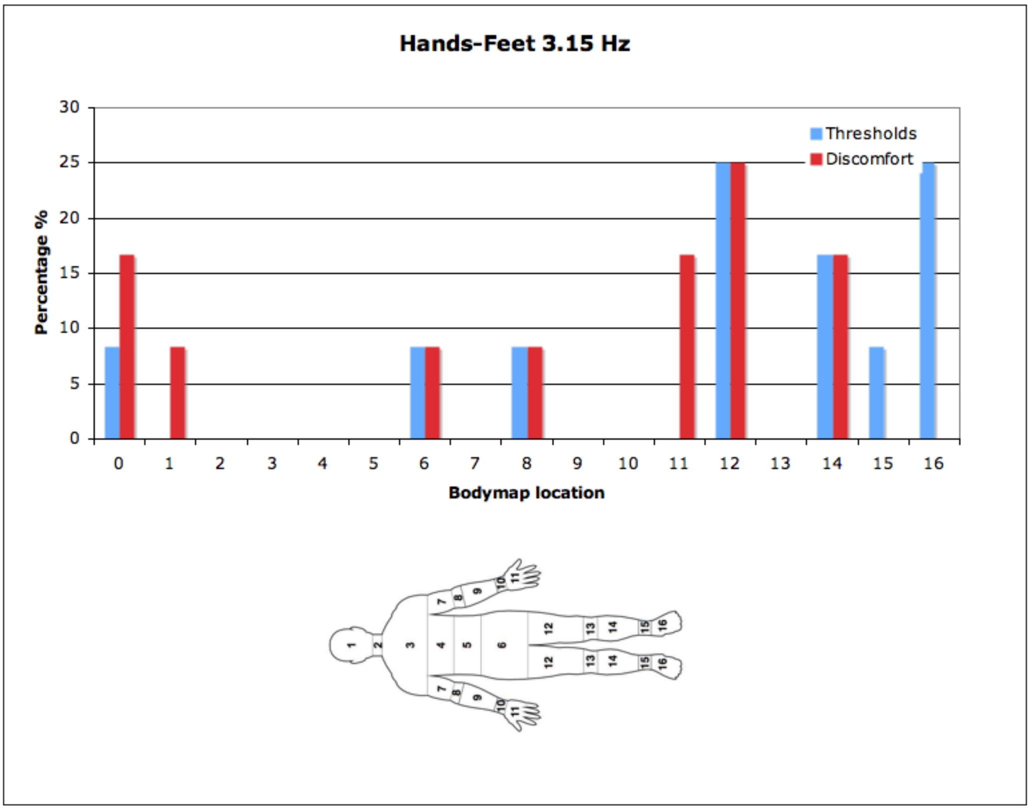


FIGURE C.3: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

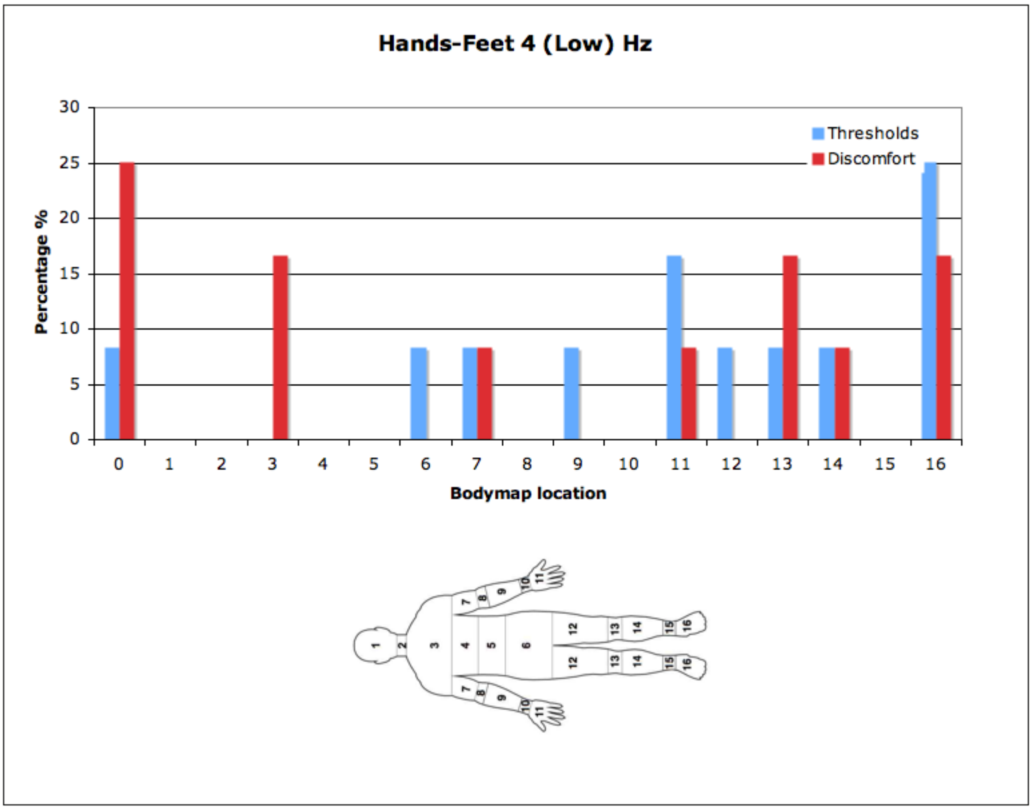


FIGURE C.4: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

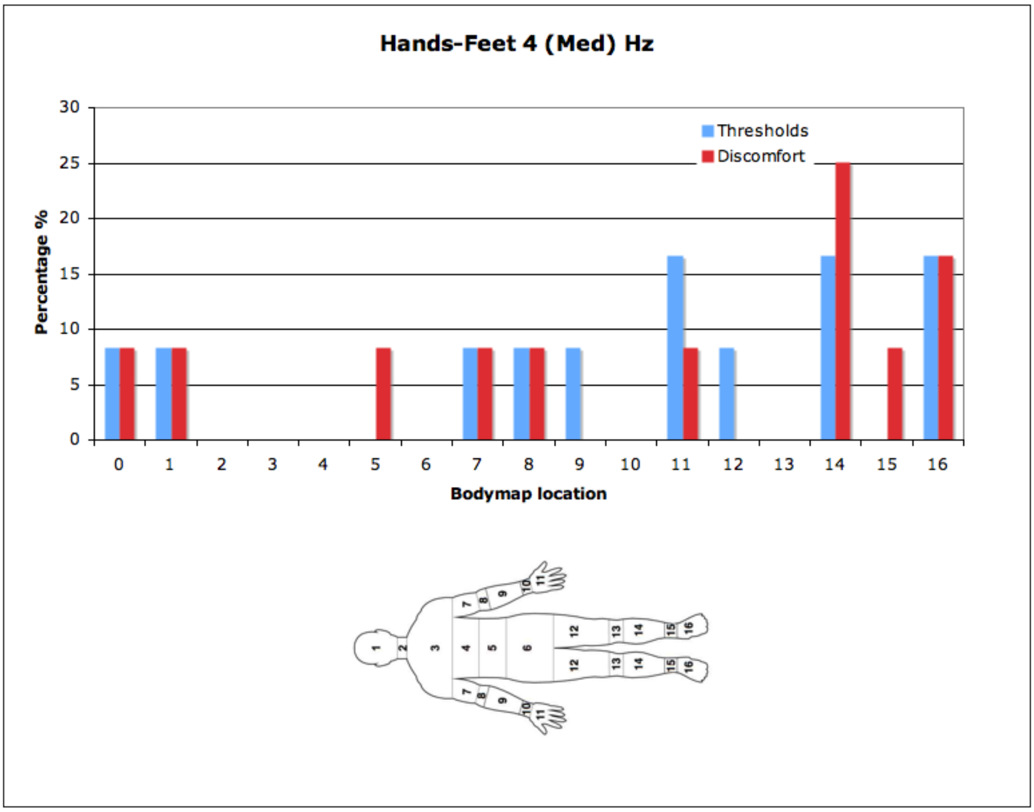


Figure C.5: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

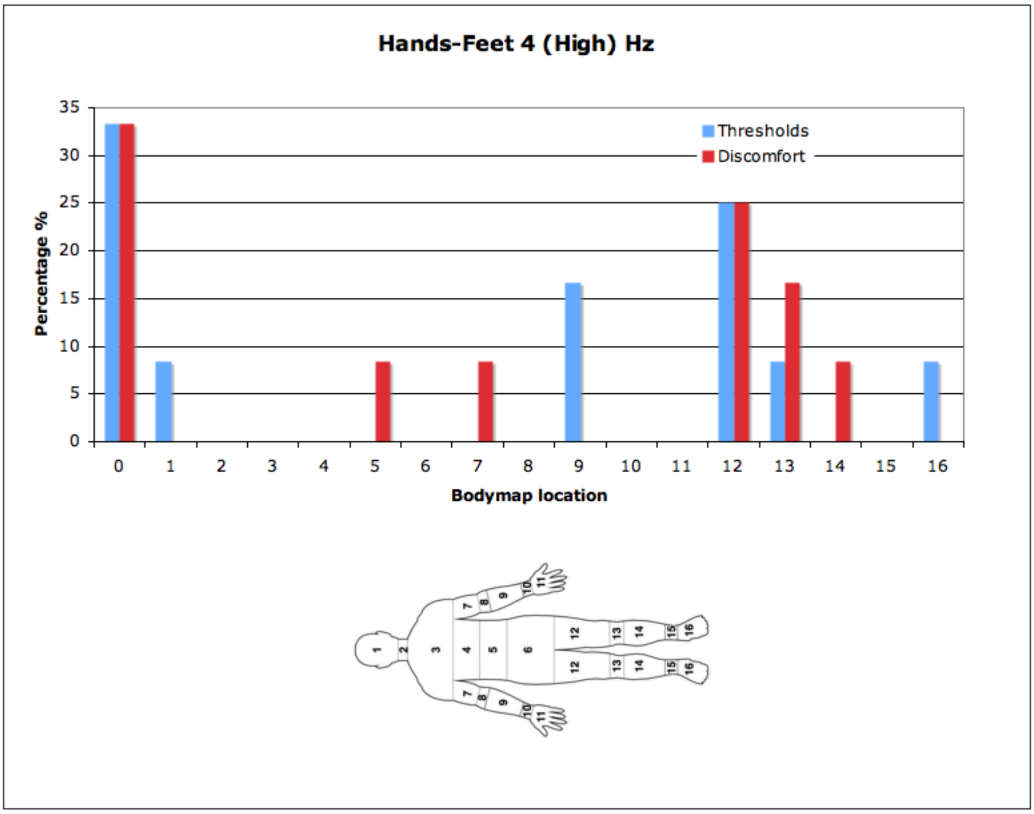


Figure C.6: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

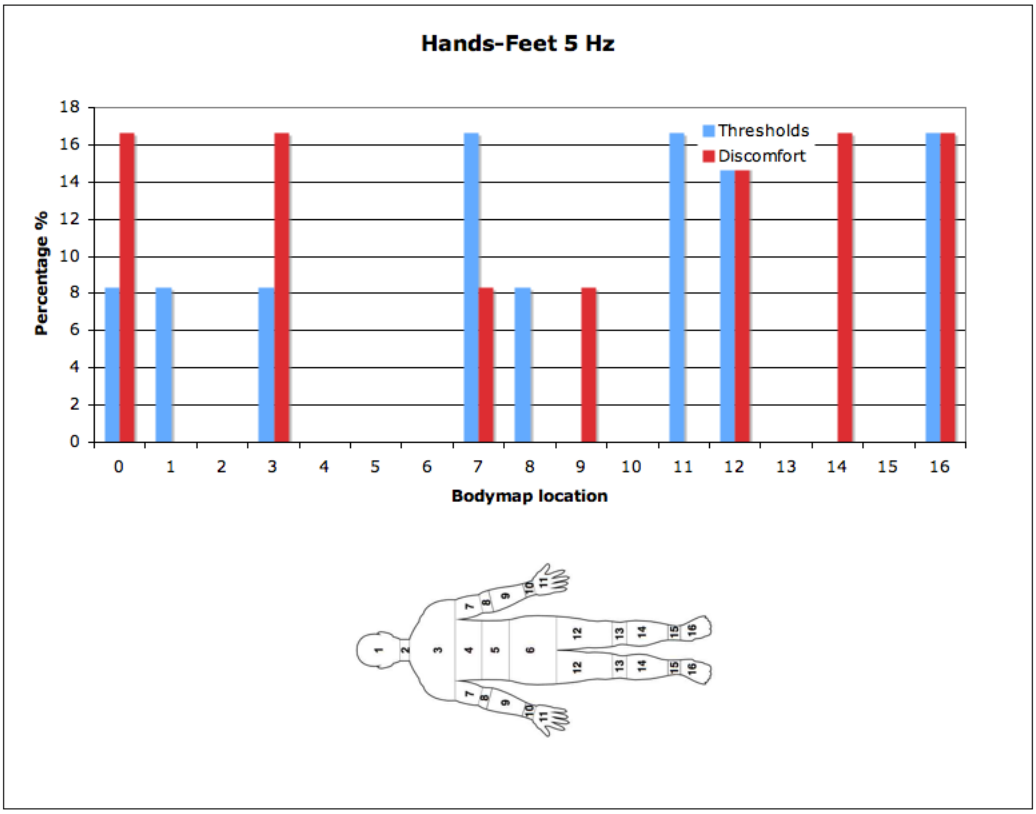


Figure C.7: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

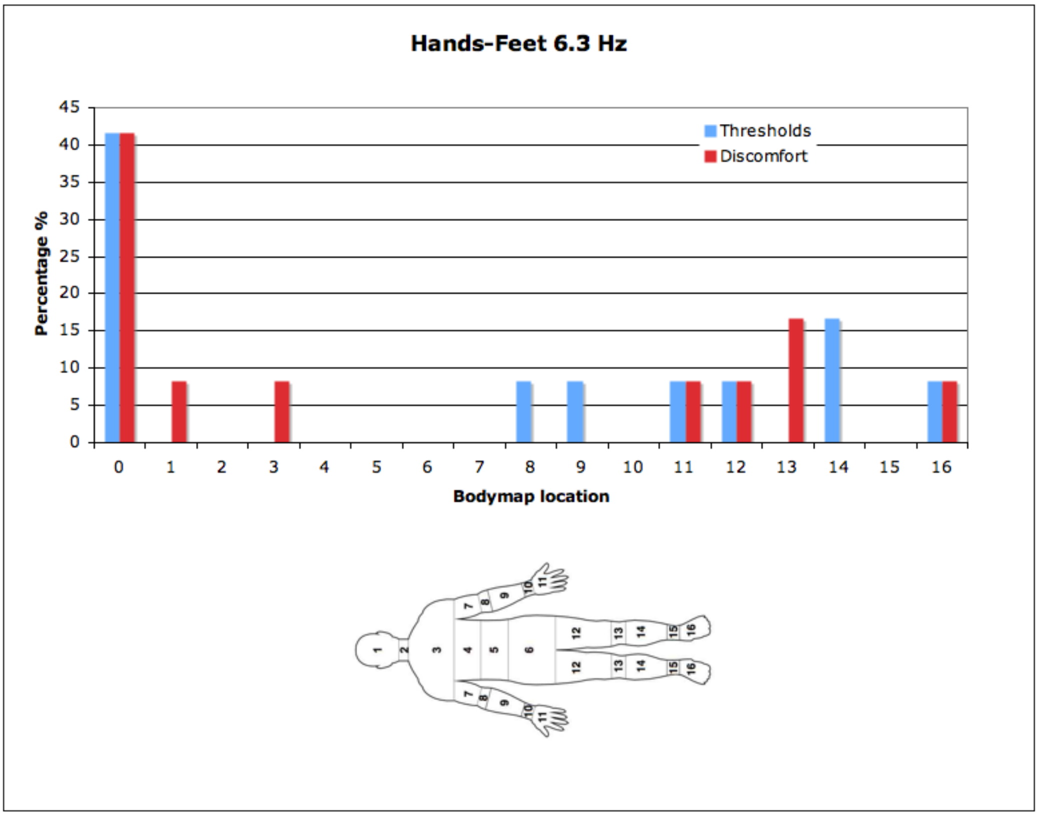


Figure C.8: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

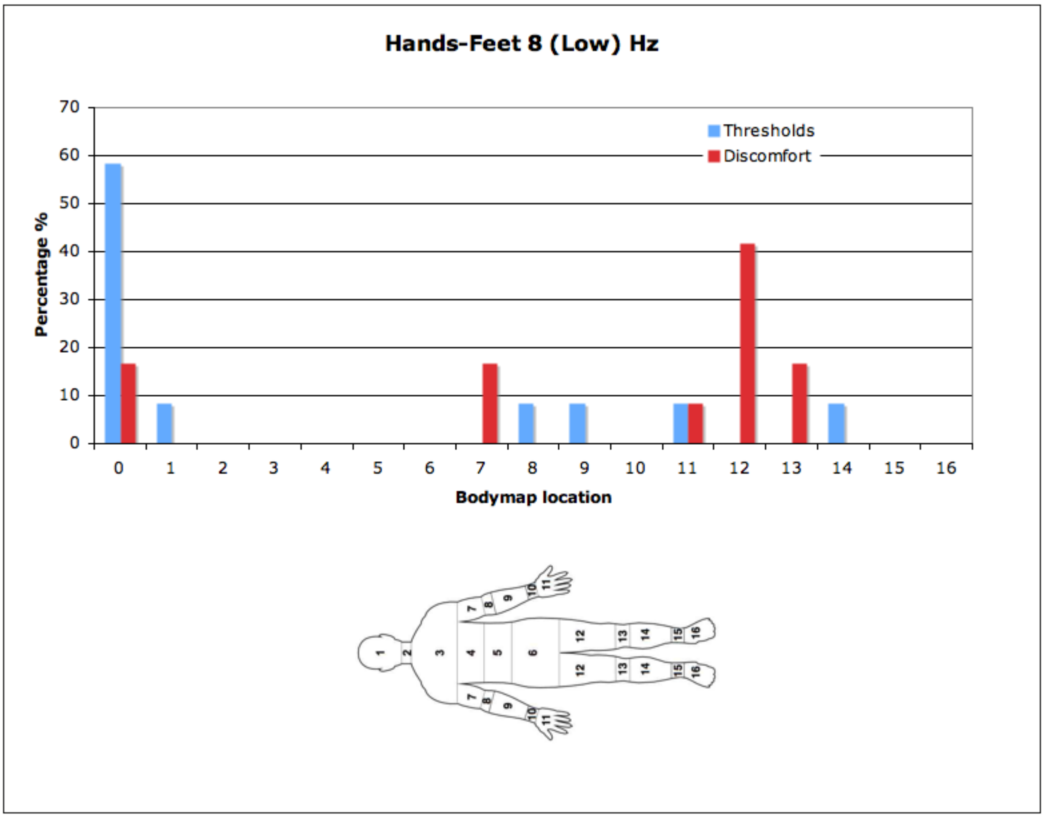


FIGURE C.9: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

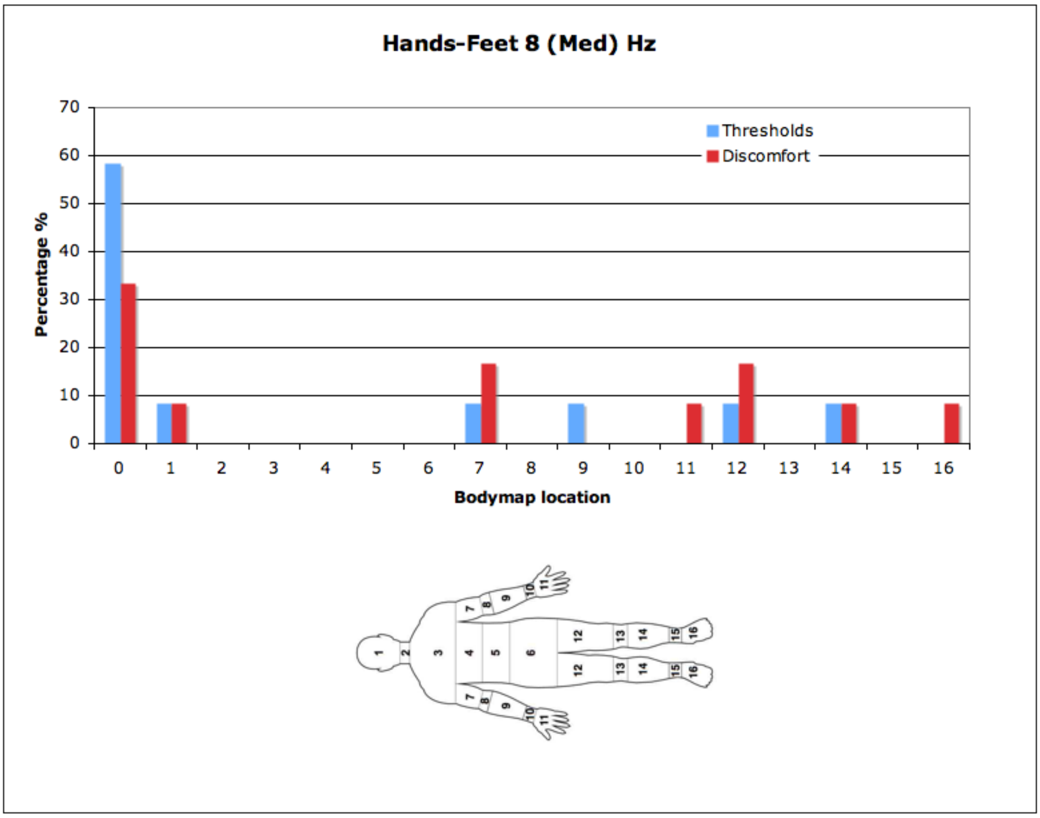


FIGURE C.10: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

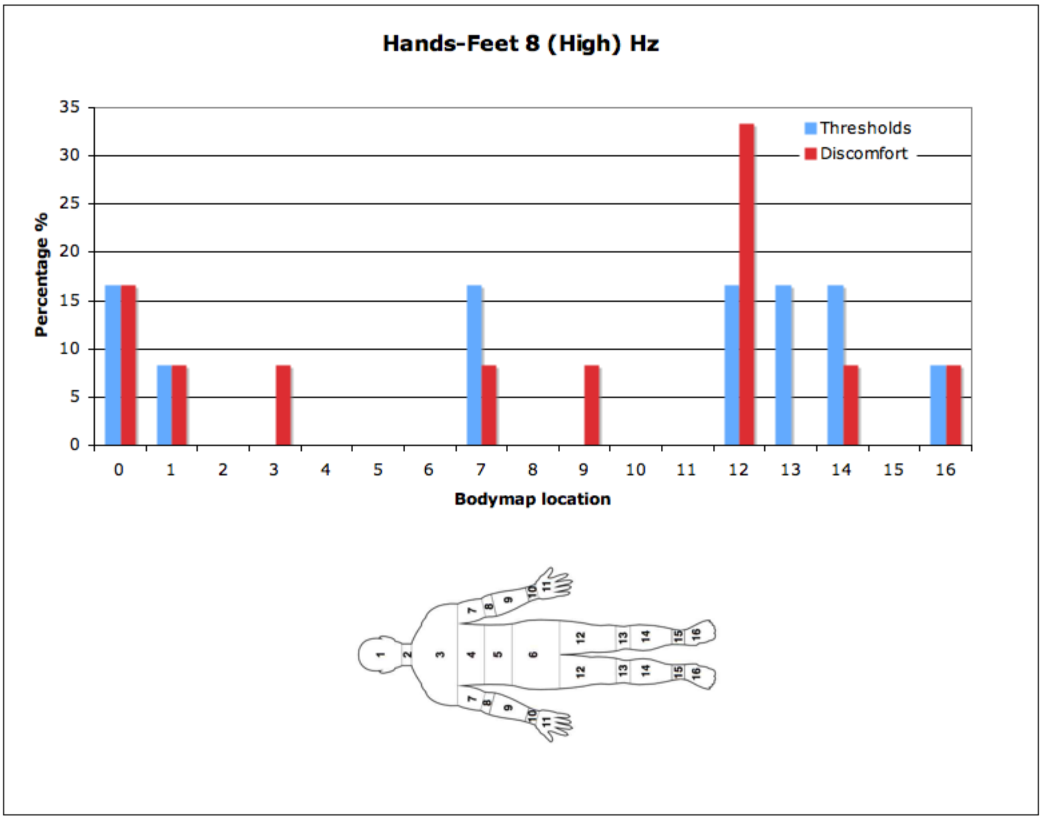


FIGURE C.11: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

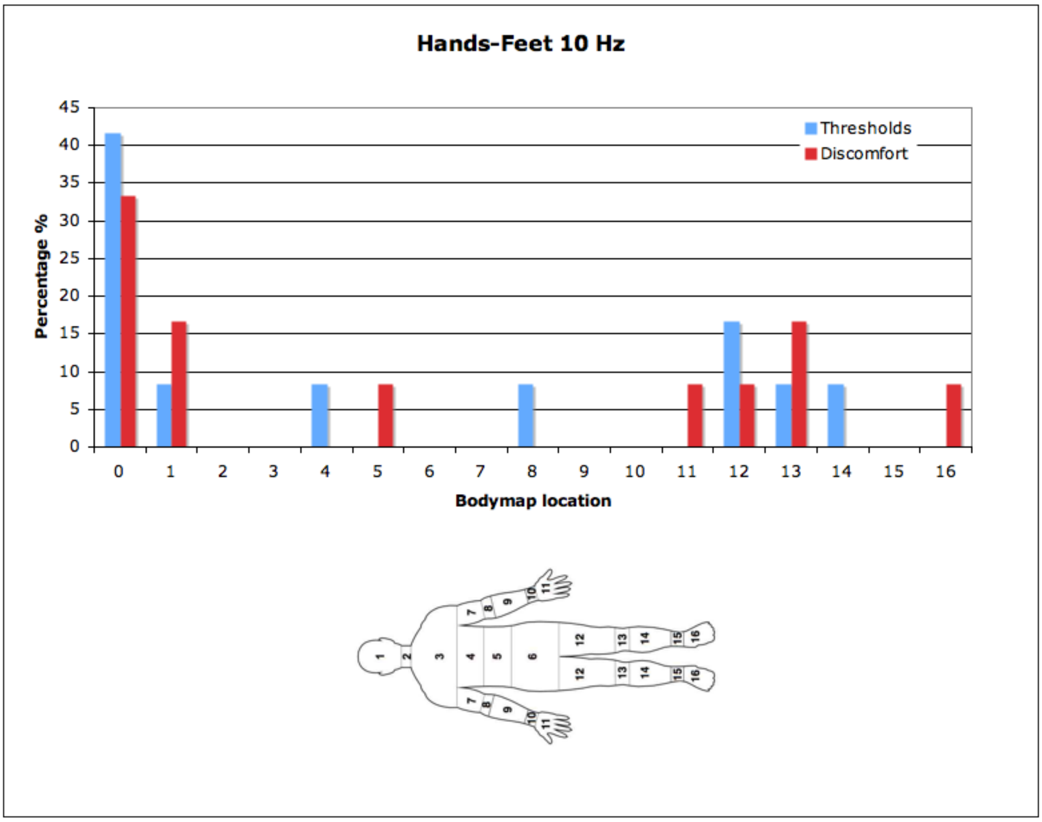


Figure C.12: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body

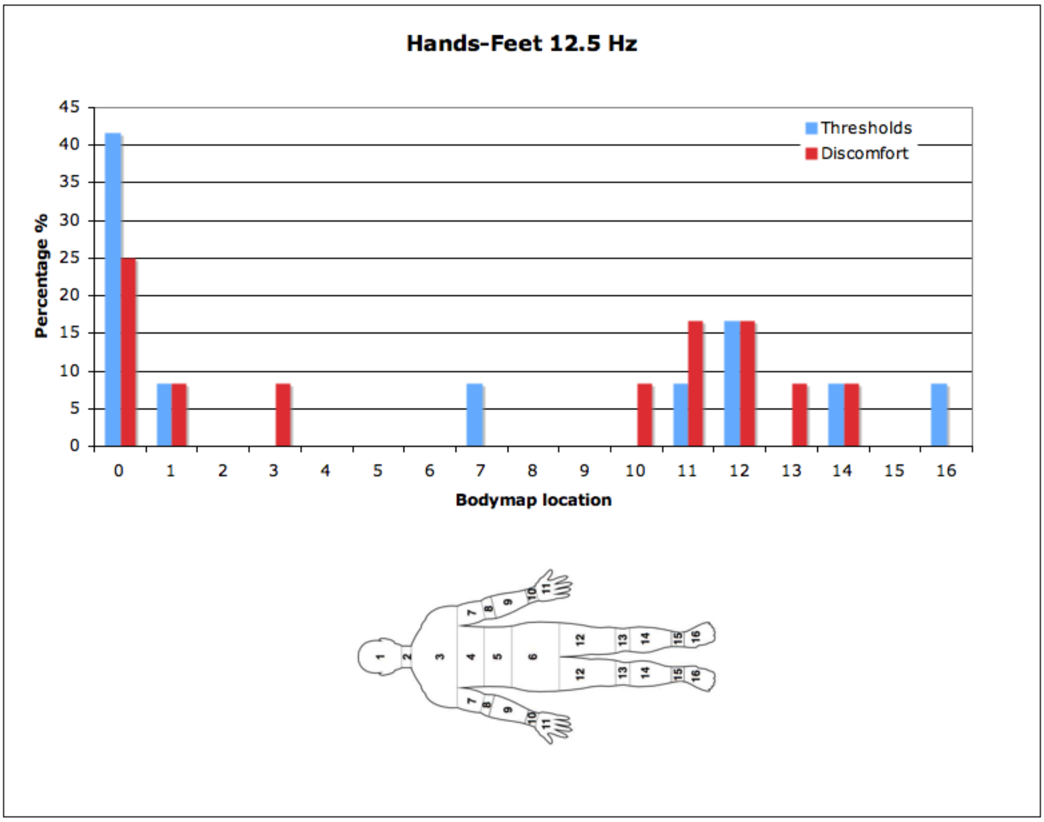


FIGURE C.13: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

C.4.1.2 Hands-Seat

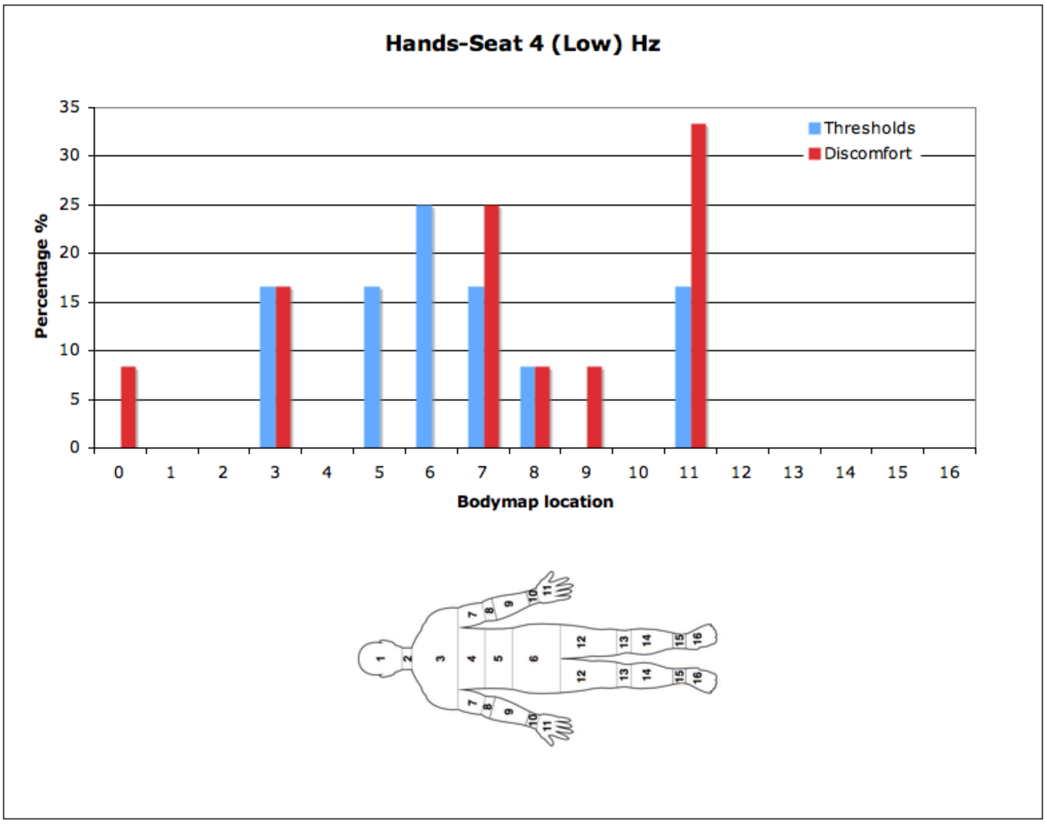


FIGURE C.14: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

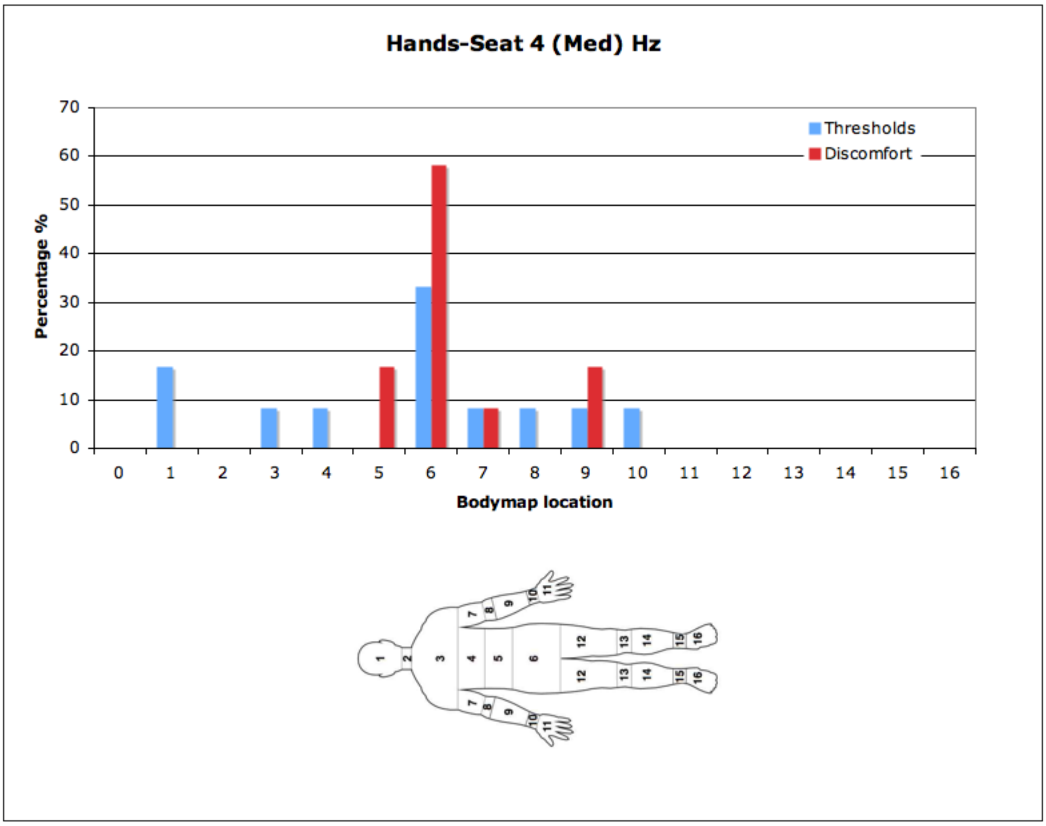


Figure C.15: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

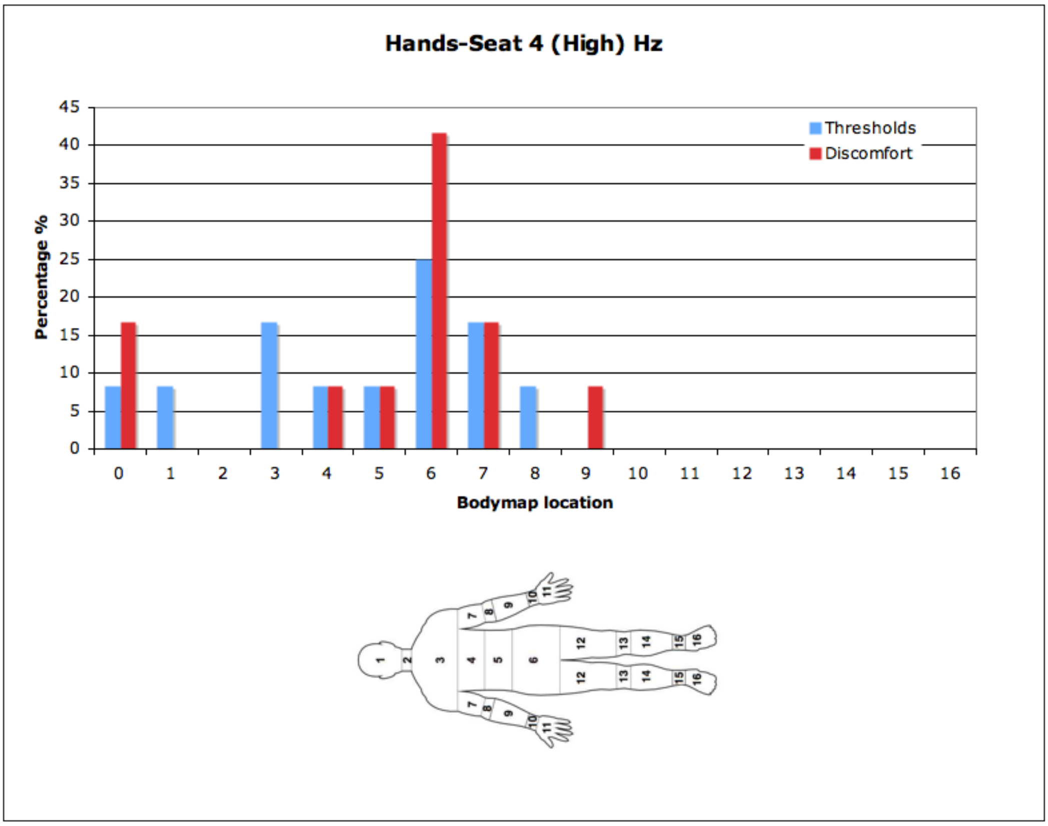


FIGURE C.16: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

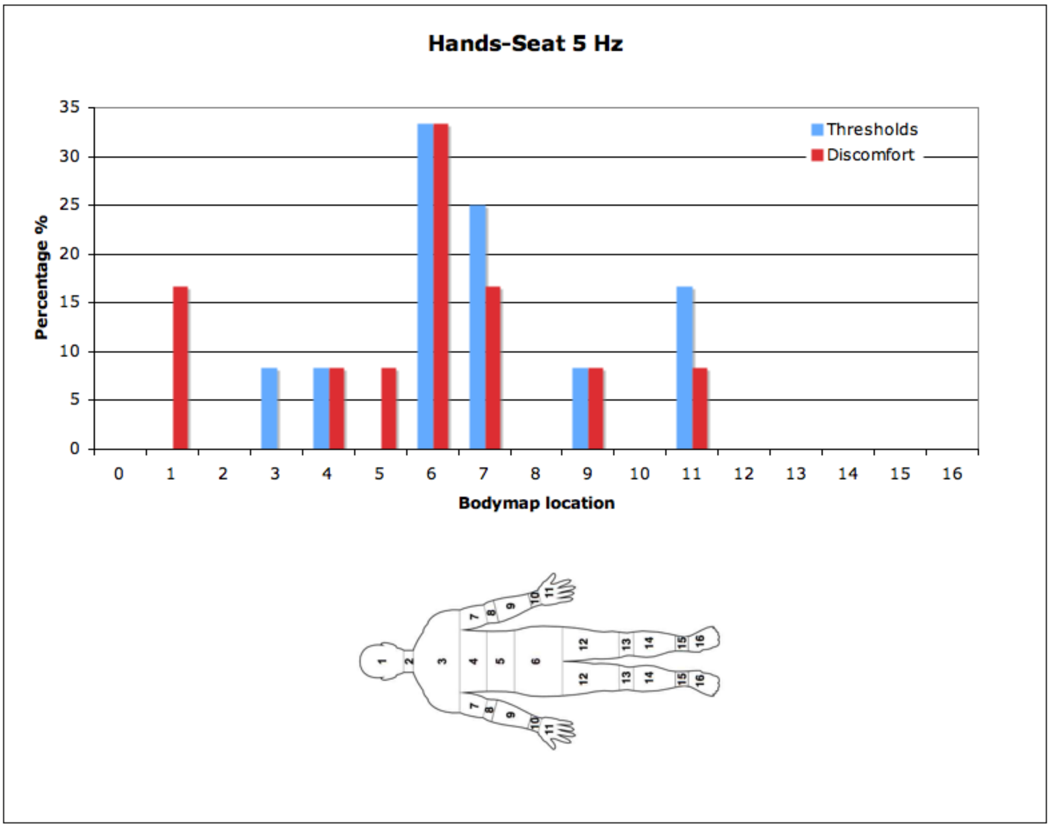


FIGURE C.17: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

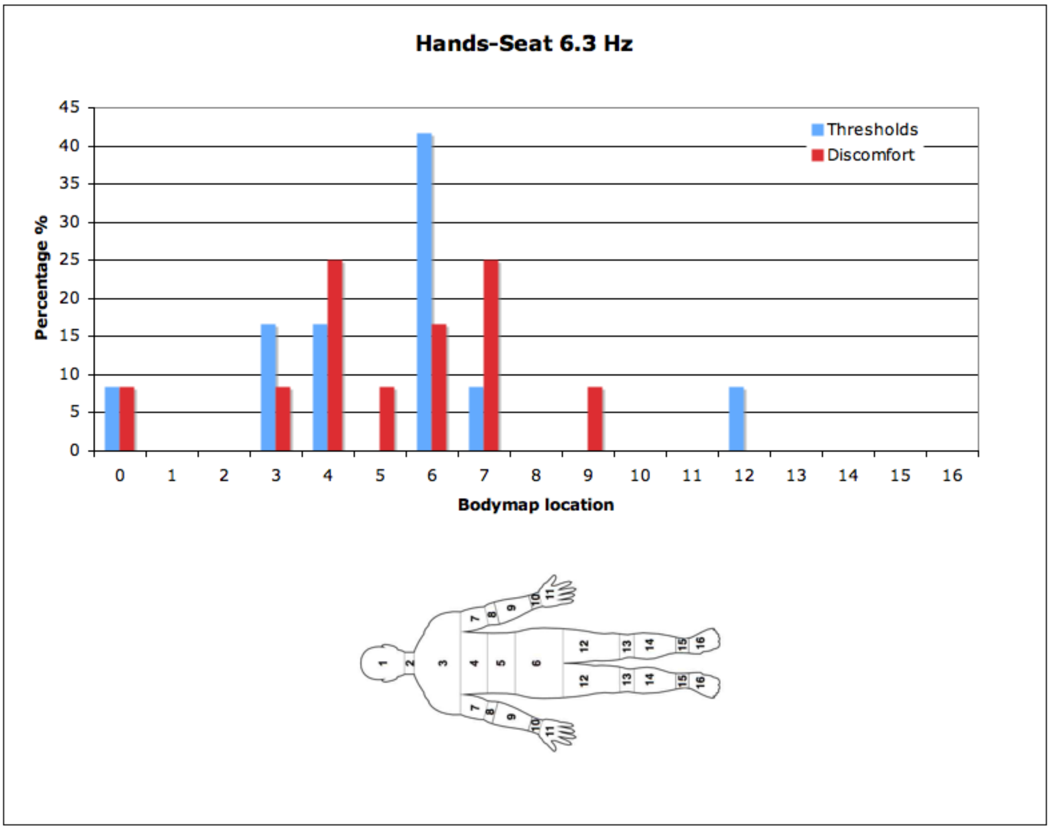


Figure C.18: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

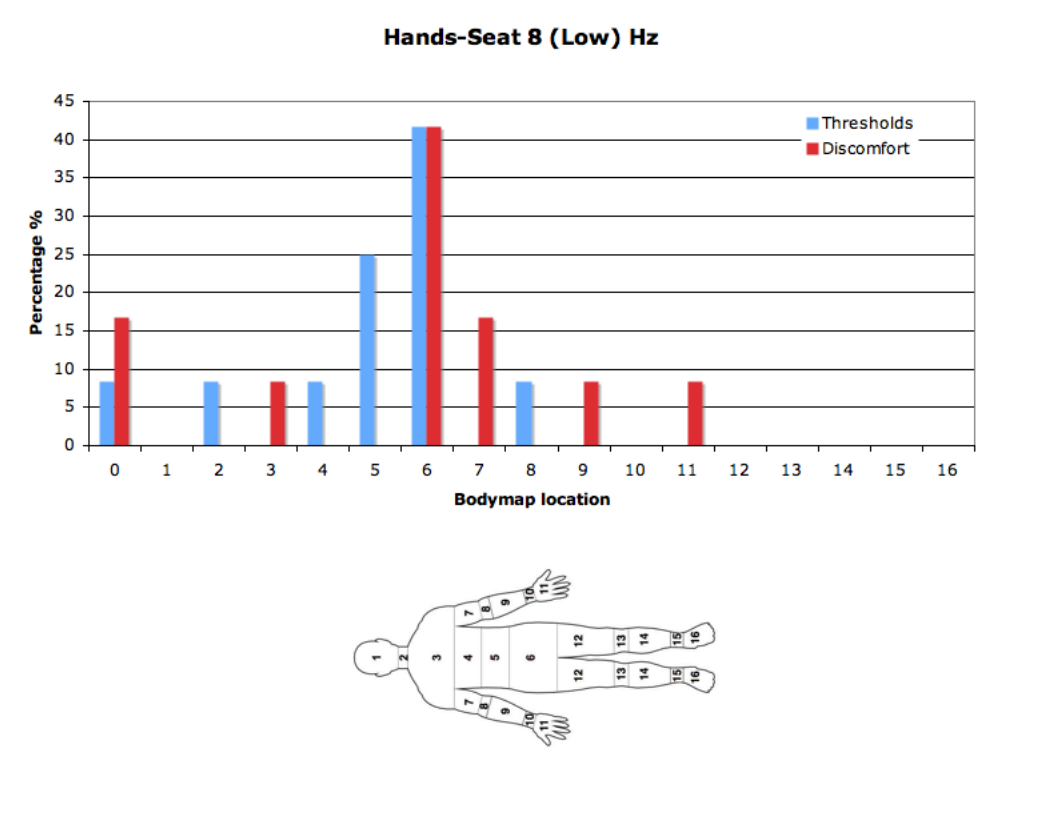


FIGURE C.19: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

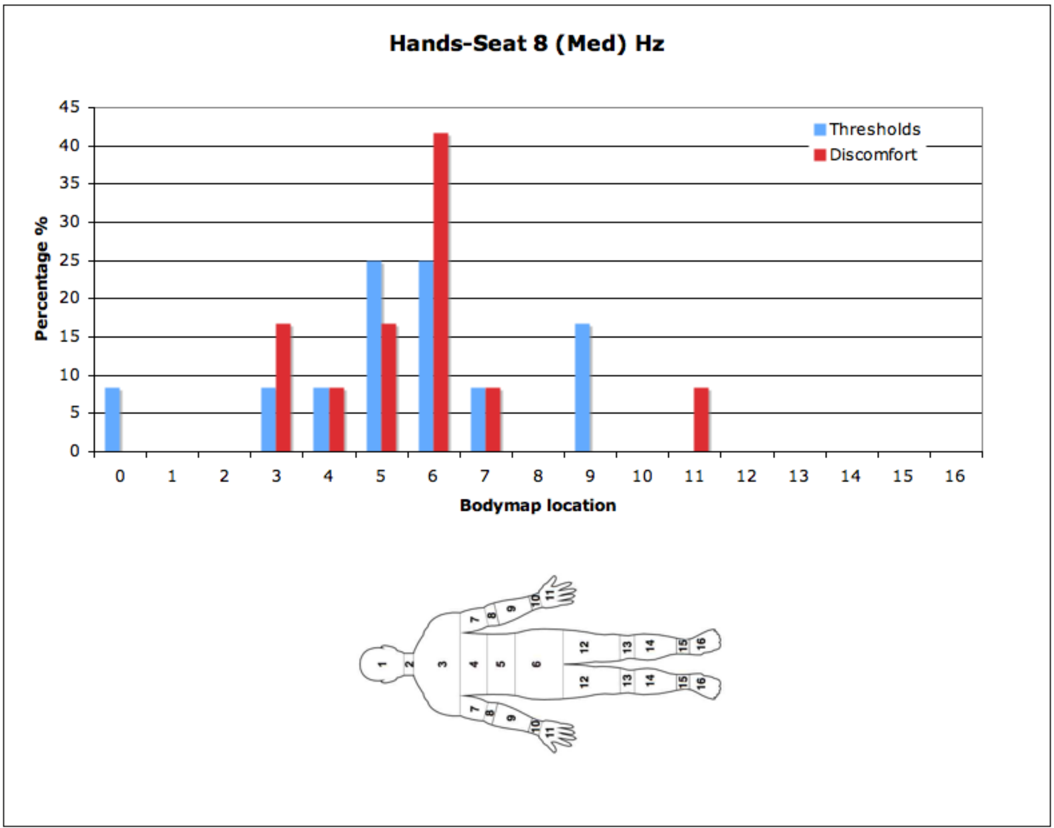


FIGURE C.20: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

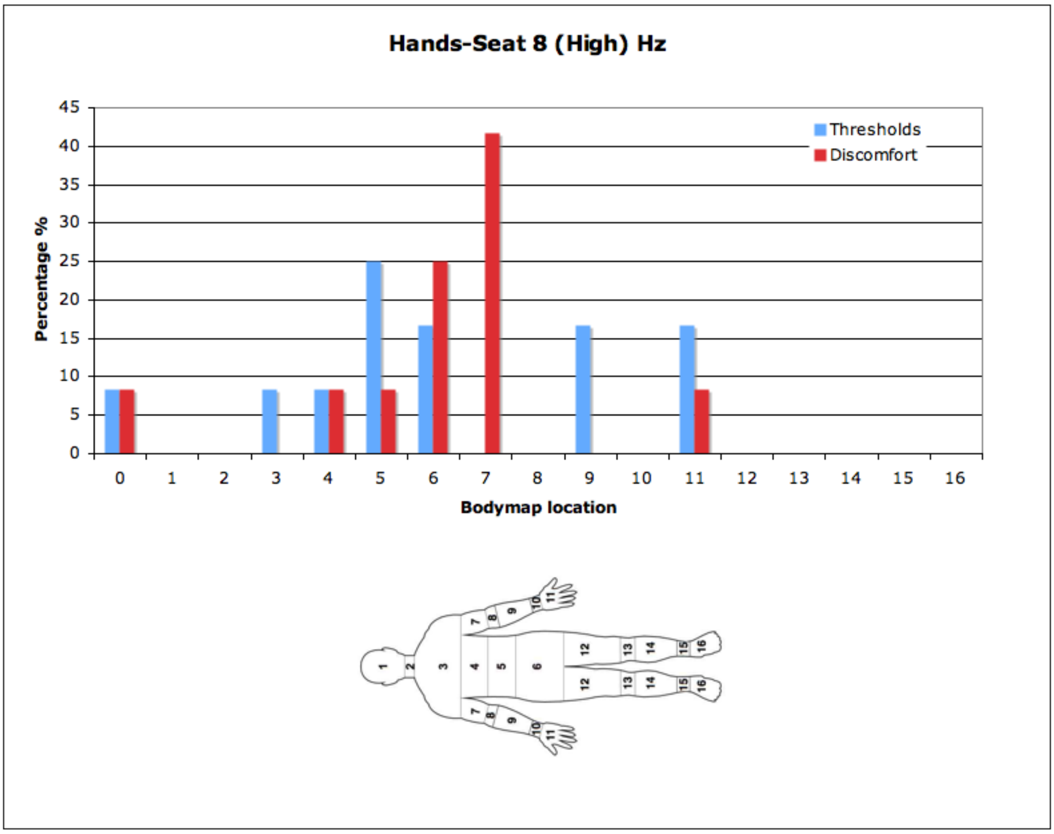


FIGURE C.21: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

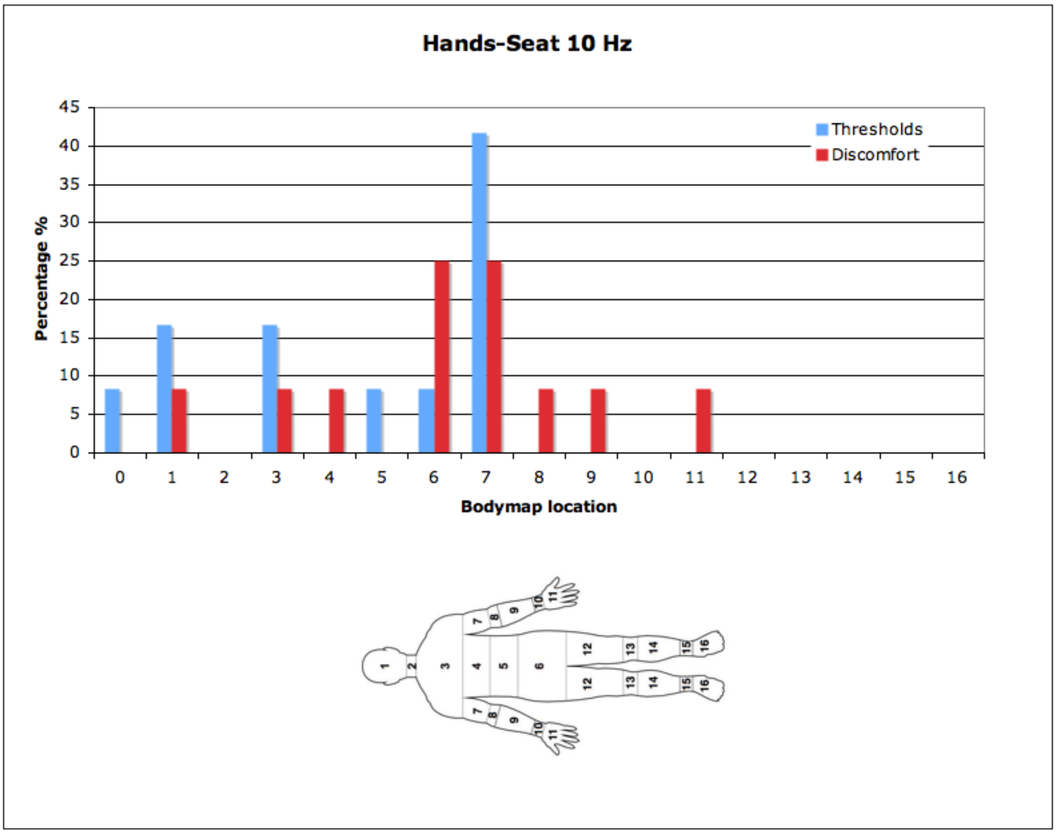


FIGURE C.22: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

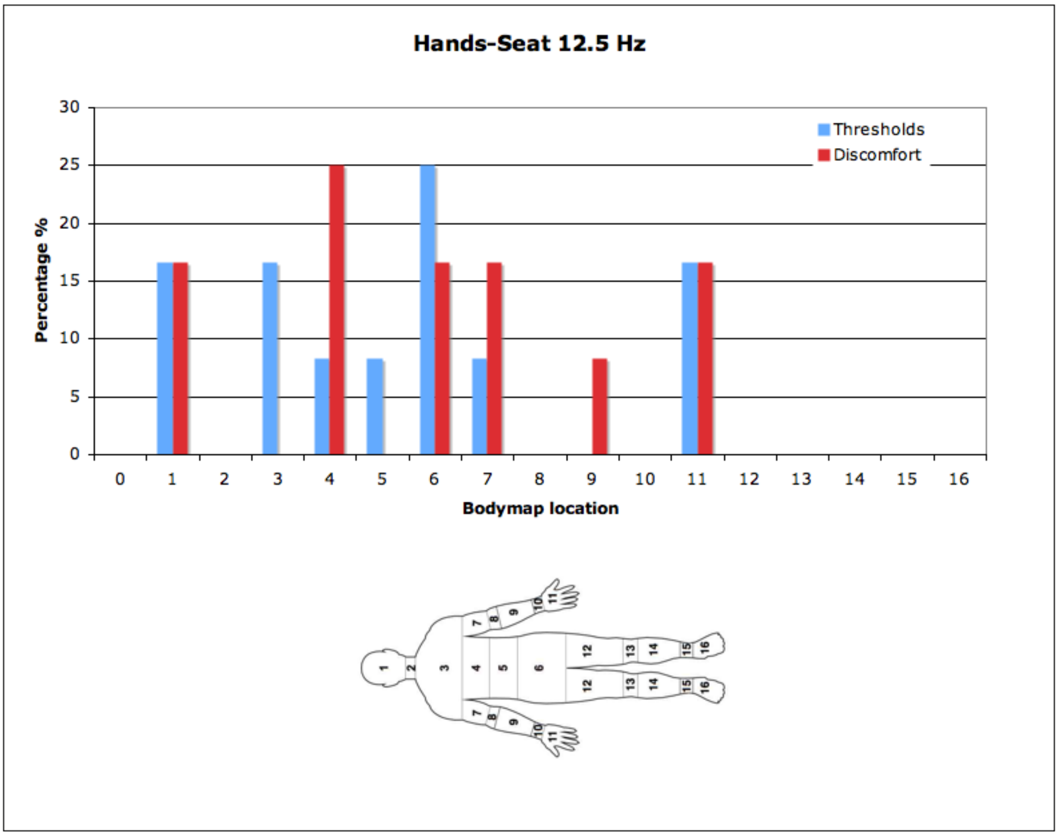


FIGURE C.23: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

C.4.1.3 Feet-Seat

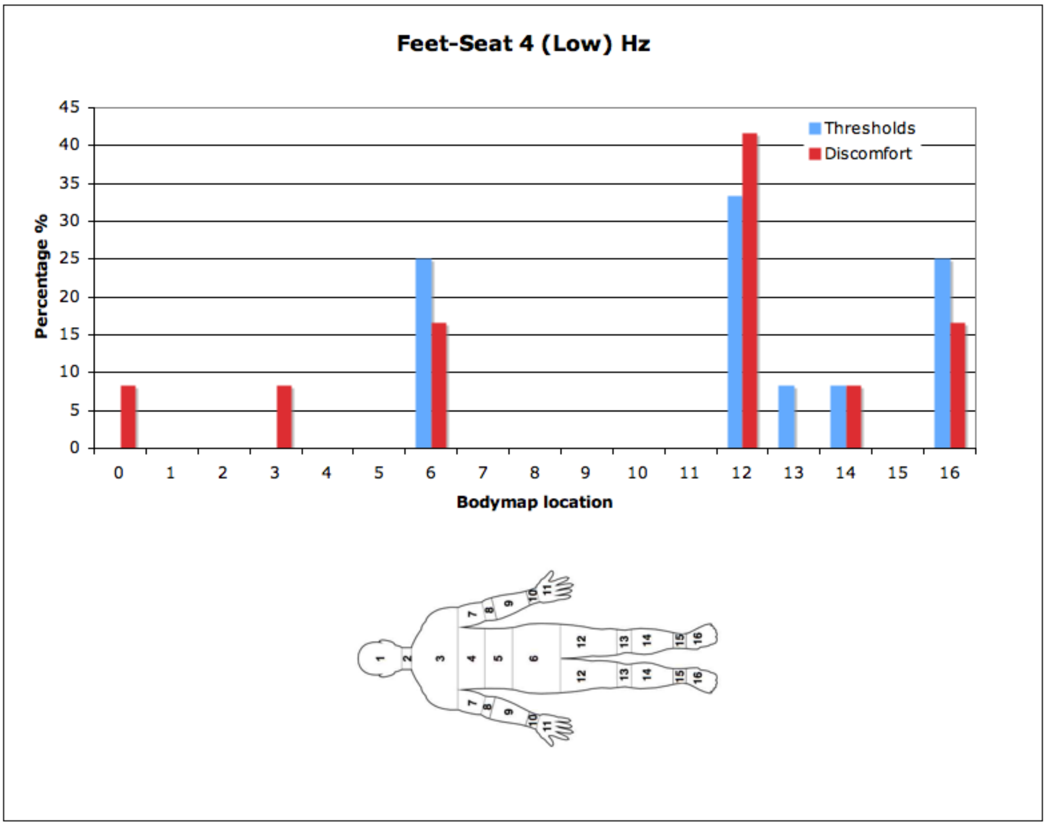


FIGURE C.24: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

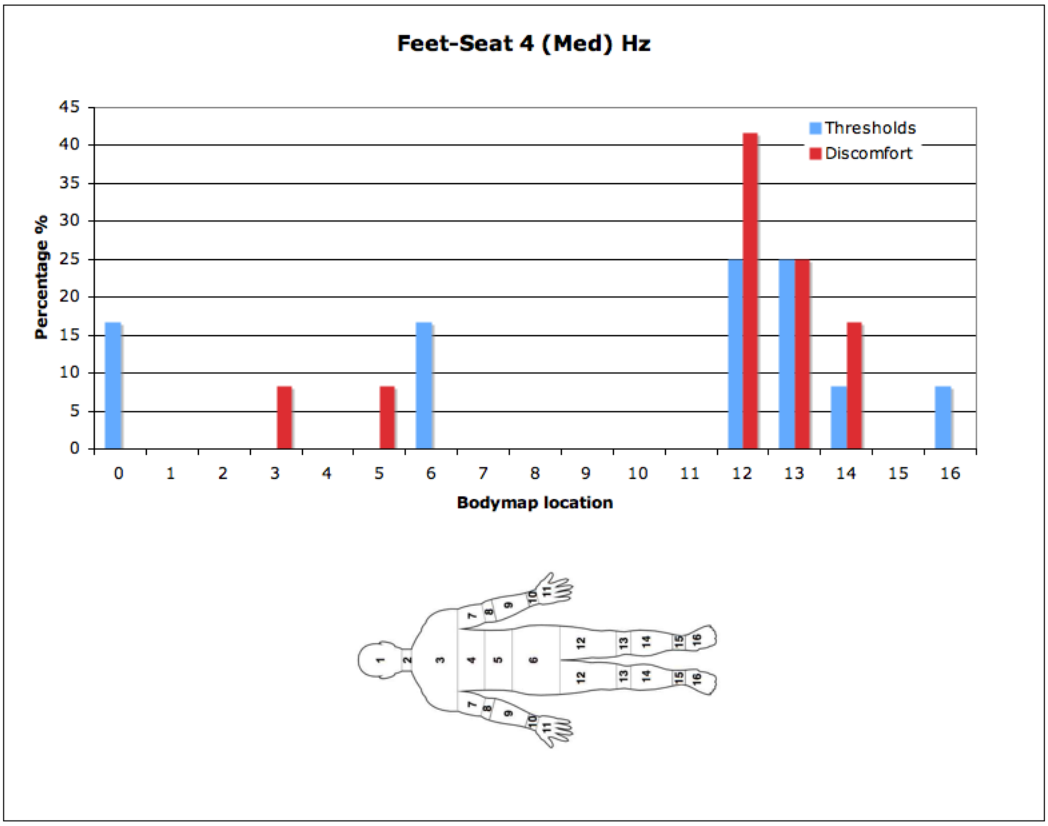


FIGURE C.25: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

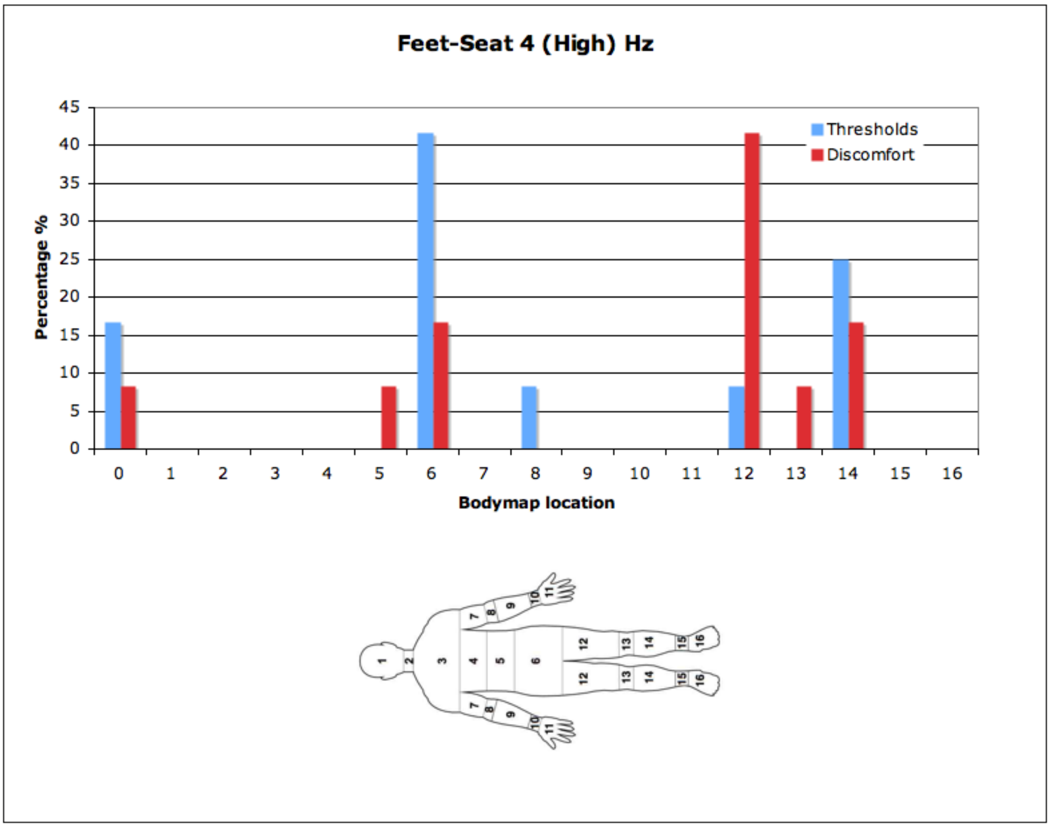


FIGURE C.26: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

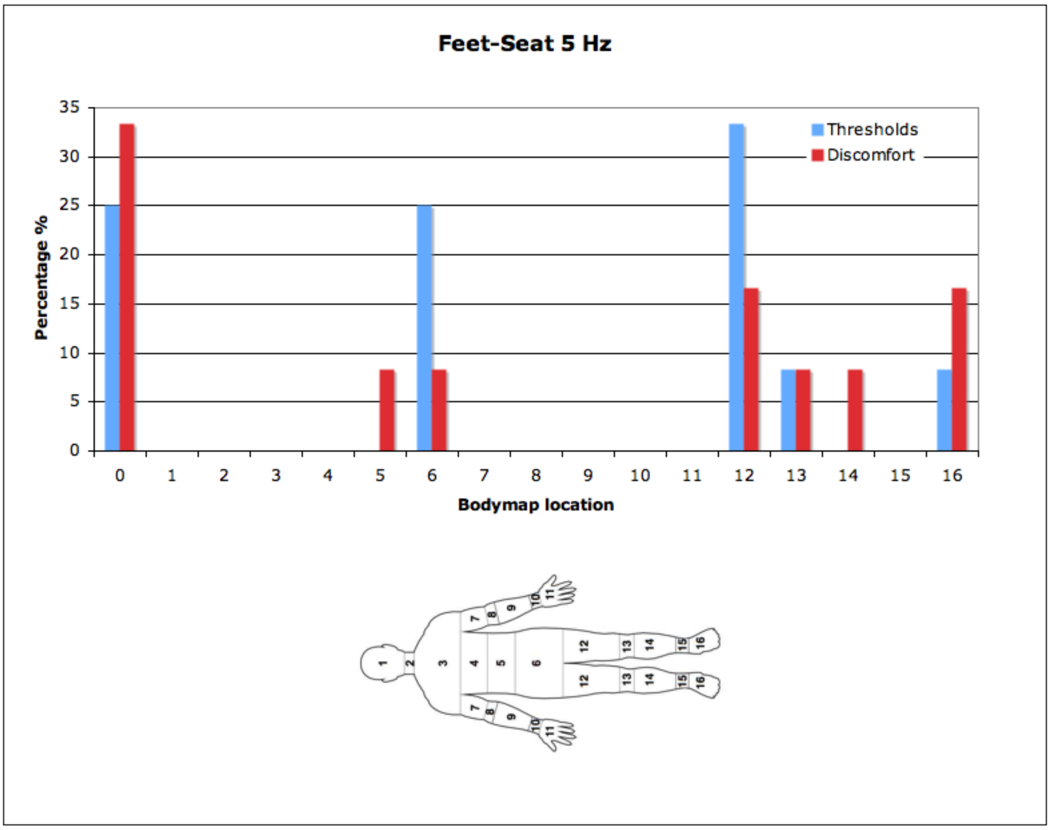


FIGURE C.27: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

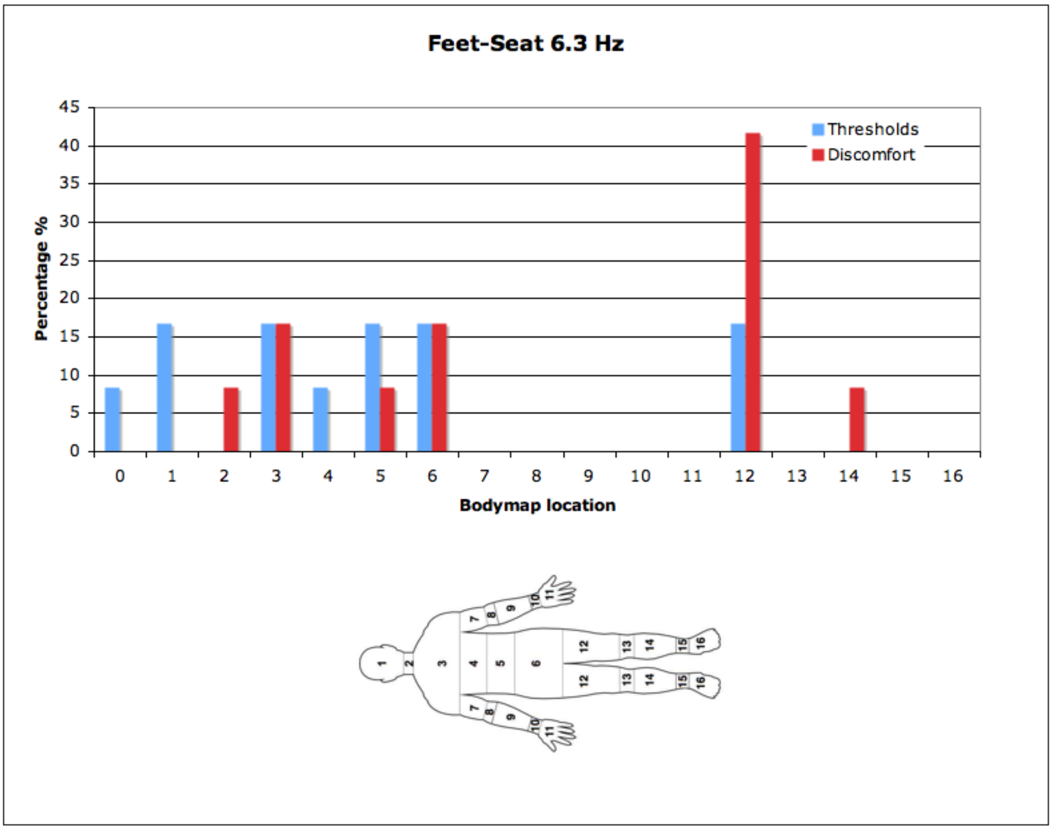


Figure C.28: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

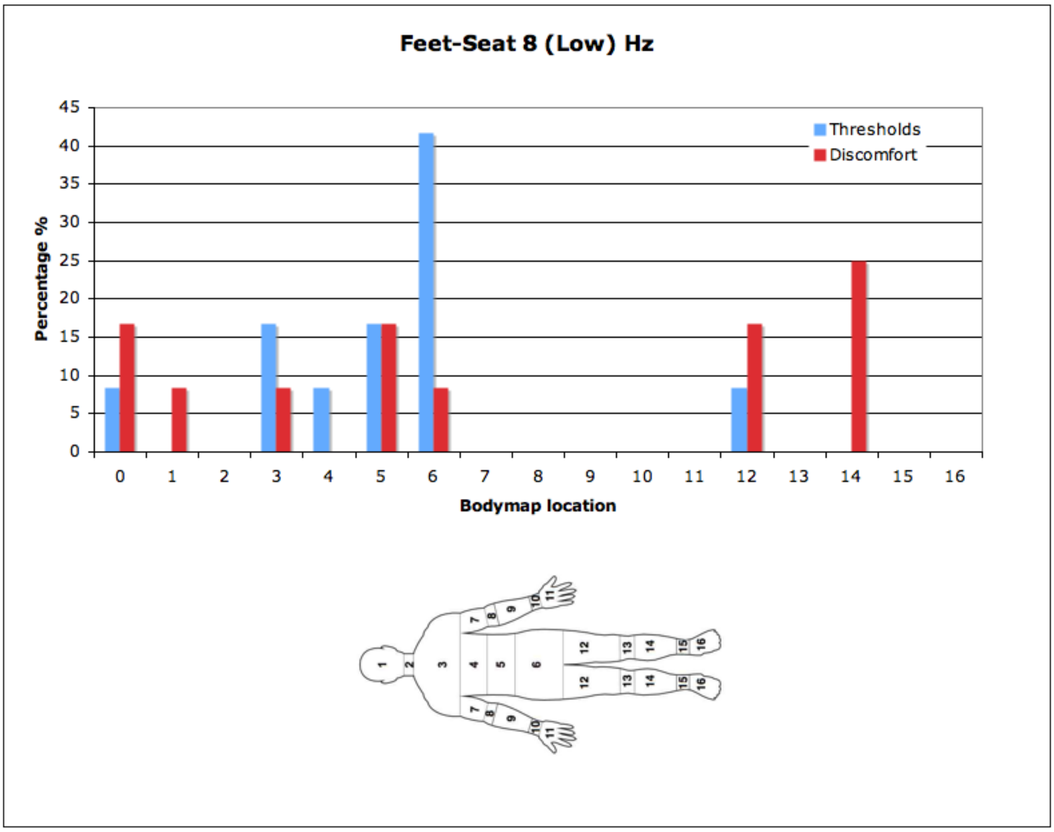


FIGURE C.29: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

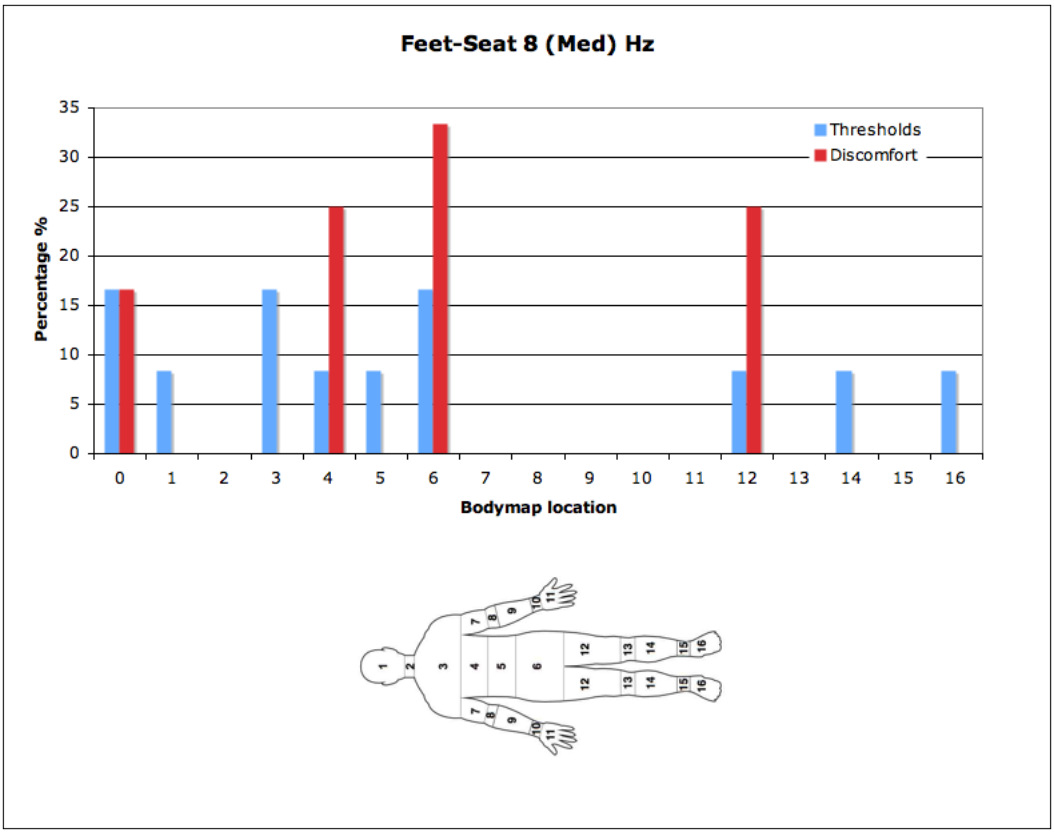


FIGURE C.30: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

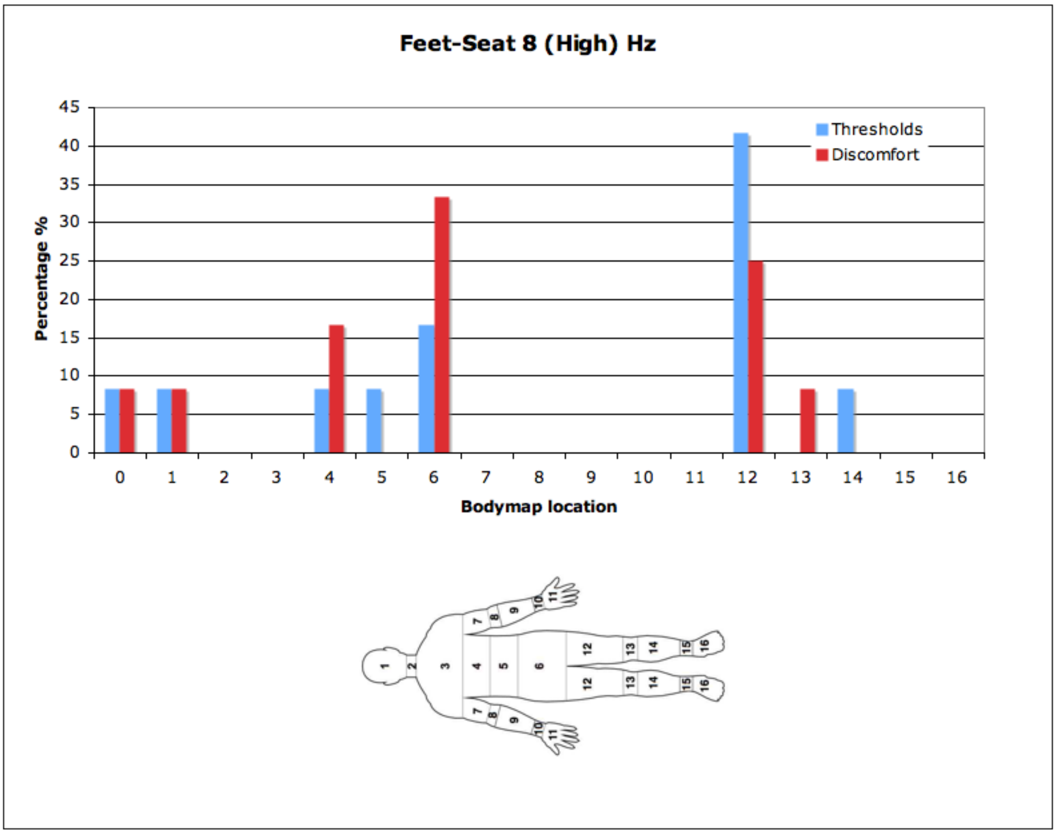


Figure C.31: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

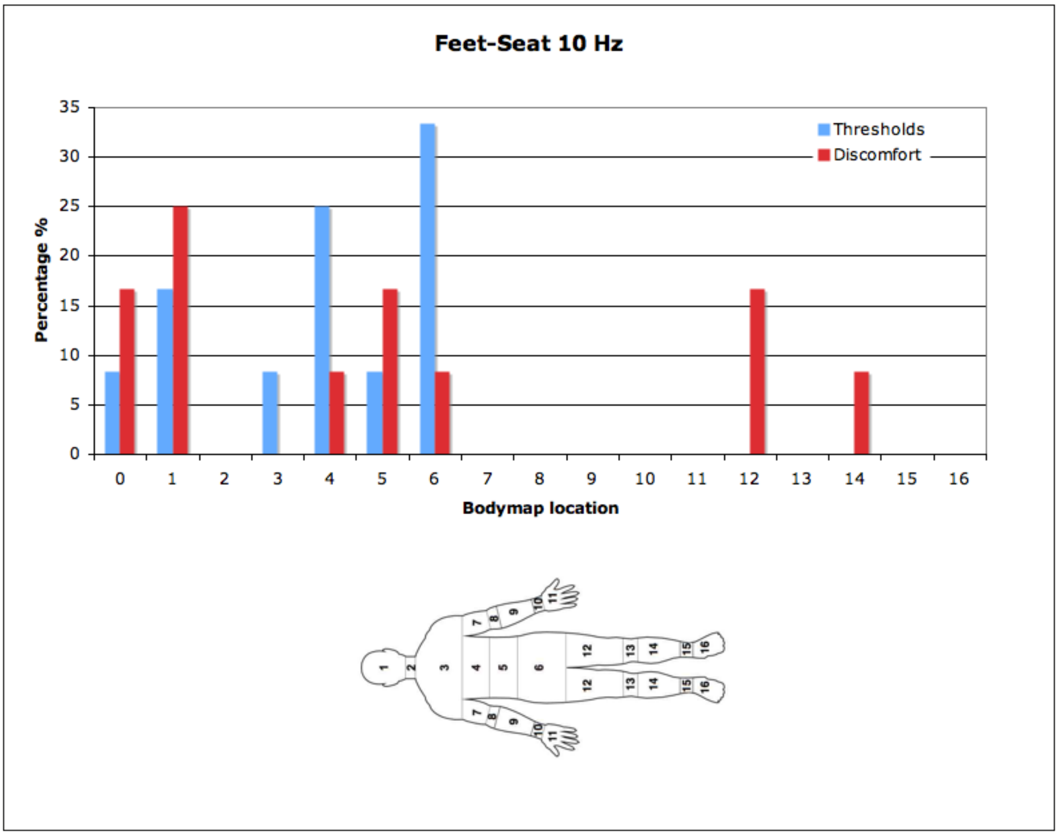


FIGURE C.32: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

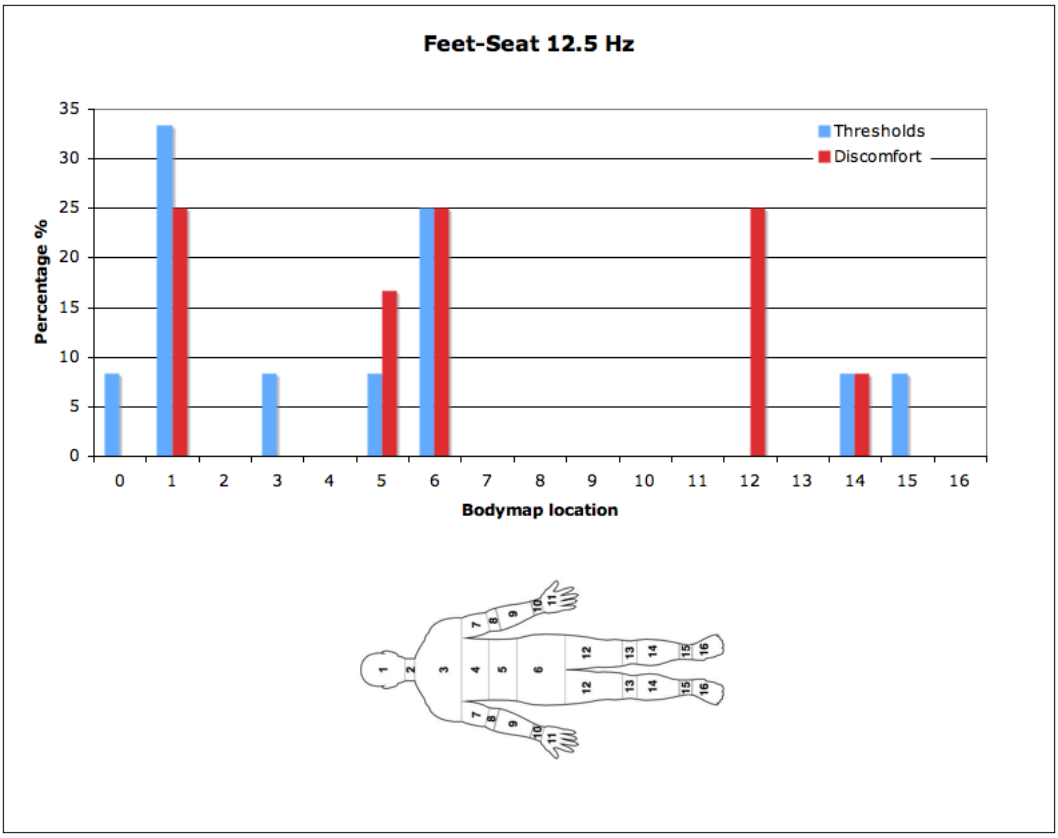


FIGURE C.33: Percentages of bodymap localisation for phase thresholds and phase discomfort, the bodymap indicates the numbers positioned on the body. Number 0 is express no sensation

TABLE C.55: Maximum and minimum phase thresholds values between hands and feet for all 12 subjects

Frequency	s1		s2		s3		s4		s5		s6		s7		s8		s9		s10		s11		s12	
Hands Feet	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min
2	120	75	75	45	180	165	165	150	105	45	180	180	60	30	120	30	120	75	60	30	120	45	90	45
2.5	135	90	150	60	180	180	180	180	120	105	180	180	90	45	180	75	120	45	90	45	150	135	105	60
3.15	135	60	180	180	180	180	150	135	180	180	180	180	105	75	120	105	150	90	120	60	150	105	120	105
4(1)	165	135	180	180	180	180	180	180	180	165	120	105	180	135	150	105	150	135	150	105	180	180	180	180
4(2)	120	60	180	180	180	180	150	135	180	180	150	135	135	75	120	105	120	105	120	75	180	165	150	135
4(3)	120	75	180	180	180	180	180	180	150	90	180	180	180	180	180	165	180	180	180	120	180	180	120	105
5	180	180	180	180	180	180	180	180	180	180	180	135	180	180	180	180	180	180	150	105	120	105	180	180
6.3	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180
8(1)	180	180	180	180	180	180	180	180	90	75	180	180	120	105	180	180	180	180	180	180	180	180	180	180
8(2)	180	180	180	180	180	180	180	180	180	180	180	180	150	75	180	180	180	180	180	180	180	180	180	180
8(3)	180	180	180	180	180	180	90	75	180	180	180	180	105	45	180	180	180	180	180	180	150	135	180	165
10	150	135	180	180	180	180	180	180	90	75	180	180	150	120	180	180	180	180	180	180	180	180	180	180
12.5	180	180	135	75	180	180	180	180	180	180	180	180	135	75	180	180	180	180	180	180	180	180	180	180

TABLE C.56: Maximum and minimum phase thresholds values between hands and seat for all 12 subjects

Frequency	s1		s2		s3		s4		s5		s6		s7		s8		s9		s10		s11			
Hands Seat	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min
4(1)	135	45	150	135	180	180	180	180	180	120	180	120	135	105	120	105	120	60	90	60	165	135	105	75
4(2)	180	75	90	75	150	105	180	180	120	60	180	180	165	90	165	135	180	135	135	75	180	180	150	105
4(3)	120	60	165	65	150	135	180	180	180	180	150	120	135	90	120	90	180	165	135	75	120	90	150	120
5	180	180	150	120	120	45	150	75	120	75	135	105	165	135	180	180	135	60	180	90	120	75	120	75
6.3	150	135	180	180	150	105	150	135	150	135	150	60	150	135	180	105	90	75	75	30	150	120	150	135
8(1)	180	180	180	180	150	120	180	180	150	120	150	120	165	135	150	120	180	180	150	120	180	180	165	135
8(2)	165	135	165	135	150	135	150	105	180	180	180	180	150	135	180	180	150	135	150	105	180	180	165	120
8(3)	150	105	165	105	180	180	150	105	150	135	150	135	180	105	180	180	180	180	150	90	180	165	150	75
10	180	105	180	180	150	105	180	180	150	105	150	135	135	90	150	135	180	180	150	120	150	105	150	105
12.5	150	135	180	180	150	90	150	135	150	120	75	30	150	135	150	120	150	105	150	120	120	75	150	135

TABLE C.57: Maximum and minimum phase thresholds values between feet and seat for all 12 subjects

Frequency	s1		s2		s3		s4		s5		s6		s7		s8		s9		s10		s11			
Feet Seat	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min
4(1)	60	15	180	180	165	75	150	75	180	180	180	180	135	105	180	135	120	30	180	135	165	75	180	180
4(2)	120	75	180	180	180	180	165	60	180	180	150	105	180	180	180	105	60	15	150	75	180	135	180	180
4(3)	120	75	180	180	135	45	180	180	180	180	180	180	165	105	180	165	105	30	150	90	150	135	180	180
5	120	45	180	180	135	90	150	105	180	180	150	75	180	180	150	135	180	180	150	90	90	75	180	105
6.3	150	120	150	135	150	135	150	135	150	120	150	105	150	135	150	105	180	180	150	75	150	135	180	180
8(1)	180	180	180	165	150	105	180	180	150	120	180	180	180	135	180	180	150	120	150	120	120	90	150	135
8(2)	165	105	180	180	180	180	180	180	120	90	180	180	150	105	150	120	180	180	135	105	180	180	180	180
8(3)	150	135	180	180	120	105	180	180	150	135	180	180	150	135	150	75	150	120	165	105	90	75	150	75
10	150	135	150	135	150	120	180	180	150	75	180	180	180	180	150	120	180	180	120	105	180	165	150	135
12.5	150	135	150	135	150	135	180	180	150	120	120	75	165	135	150	105	150	135	150	90	180	180	150	135