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The influence of whole-body vibration and postural support on activity interference in standing rail passengers

By

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ABSTRACT

Travel time has generally been regarded as an unproductive period, representing a 'means-to-an-end' in order to engage in activities at specific destinations. Rapid developments in mobile technology have provided people with innovative ways to multi-task and engage in meaningful activities while travelling. Rail transportation specifically, offers passengers advantages over other means of transportation as there is no need to focus on driving tasks. Due to the increase in passenger numbers and limited seating availability in train carriages, over one third of rail passengers are required to stand while travelling (DfT, 2013). The vibration to which rail passengers are exposed has been shown to interfere with the performance of activities and for standing passengers, it is often necessary to use postural supports such as holding on to grab rails or leaning on walls in order to maintain stability.

The overall aim of the research is to evaluate the influence of whole-body vibration (WBV) exposure and standing posture on the performance of manual control tasks and the associated subjective workloads experienced by rail passengers. The use of supports, such as a backrest in seated postures, has been found to influence the response of the human body to WBV exposure, yet no reported studies have investigated the effects of postural supports on the response of the body in standing postures. Understanding how the body is affected in these conditions would increase the current state of knowledge on the biomechanical responses of the human body to vibration exposure and provide improved representation of standing postures within vibration standards (for example, ISO2631-4 (2001)) and guidelines for device interface design. A field study, using direct observation, was conducted to assess the behaviour of standing rail passengers and determine the characteristics of typical vibration exposures. This information provided the basis for the design of four subsequent laboratory studies. The main investigations of the laboratory studies were the influence of WBV exposure on objective performance measures, such as task completion time and error rate, and subjective workloads (for example, NASA TLX) for a range of manual control tasks. One of these laboratory studies evaluated the influence of various postural supports (for example, backrests) on the biomechanical responses of standing individuals.

Measurements obtained during the field investigation indicated that the vibration exposures did not exceed the EU Physical Agents Exposure Action Value (EAV) and therefore posed little risk of injury. Vibration magnitudes in the horizontal directions (x- and y-axes) were higher than in the vertical direction (z-axis) and it was necessary for standing passengers to alter behaviours and use supports in order to maintain stability while travelling. The results of the laboratory studies indicated that in conditions where decrements in task performance occurred, the extent to which performance was degraded increased progressively with increases in vibration magnitude. There were conditions (for example, in the continuous control task and the ‘Overhead Handle’ supported posture in the serial control task) where vibration exposure showed no significant influence on performance measures. This suggested that individuals were able to adapt and compensate for the added stress of vibration exposure in order to maintain performance levels however, this occurred at the expense of mental workload. The workload experienced by the participants increased with corresponding increases in magnitude. Vibration frequency-dependent effects in performance and workload were found to match the biomechanical responses (apparent mass and transmissibility) of the human body and resemble the frequency weightings described in the standards (ISO2631-1 (1997)). During the serial control task, the postures which demonstrated the greatest decrements to performance (for example, ‘Lean Shoulder’ and ‘Lean Back’) corresponded to the same postures that showed the greatest influence on the biomechanical responses of the body. It was concluded therefore, that measurements of the biomechanical responses to WBV could be used to offer predictions for the likelihood of activity interference. Consideration should however, be given to the applicability of this research before these results can be generalised to wider contexts. Further validation is recommended for future work to include different conditions in order to substantiate the findings of this research.

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CHAPTER 1

GENERAL INTRODUCTION

During day-to-day activities, interactions between humans and the environment usually involve exposure to a number of different sources of vibration. Due to the variety of contexts in which individuals may be exposed to vibration, a broad distinction has traditionally been employed between whole-body and local vibration. Local vibration, often termed 'hand-arm vibration' or 'hand-transmitted vibration', occurs when a vibrating device is held in the hands and the effect of interest is local to that source of contact (for example, pneumatic drills).

Whole-body vibration (WBV) however, occurs when the whole environment undergoes motion and the vibration affects body parts remote from the site of exposure (Griffin, 1990 and Mansfield, 2005). Such examples of WBV include but are not limited to: people commuting to and from work in a car, bus or train; workers operating industrial vehicles and military personnel travelling in ships or aircraft (Mansfield, 2005). Whole-body vibration (WBV) exerts a substantial influence on the human body in numerous work environments and despite considerable research, the effects of vibration exposure still remain a key ergonomic issue (Conway *et al.*, 2007) and the consequences of such exposures are often variable, complex and not easily predictable. Whether the vibration causes annoyance, discomfort, interference with activities, impaired health or motion sickness depends on a number of factors; including the characteristics of the vibration and the exposed person, the type of activities being performed and environmental context (Griffin, 1990). In many situations these effects of vibration occur simultaneously (for example, a motion may cause discomfort, interfere with a task as well as being a potential source of injury).

Based on questionnaire data, Palmer *et al*. (2000) estimated that approximately 54.6% and 17.2% (males and females respectively) of the working population in the UK were exposed to occupational whole-body vibration each week. The principal environments in which whole-body vibration occurred were generally associated with the transport industry, in particular land transportation. Although these estimates reflect only occupationally related vibration exposures, those associated with non-occupational activities must also be considered. In order to account for such leisure time exposures, Palmer *et al.* (2000) examined the relative contribution from common non-occupational exposures and found that 66% and 92% of respondents (males and females respectively) were estimated to incur greater exposures outside of the working environment than in an occupational context.

In a culture that exhibits an increasing expectation of continuous availability and responsiveness; many people tend to utilise travel time to engage in both work-related and leisure activities (Lyons and Urry, 2005). In this regard, rail transportation systems offer distinct advantages over other land transport systems as there is no need to focus on driving tasks. People travelling by rail therefore, have a greater opportunity to multi-task and engage in meaningful activities (Tillema *et al.*, 2009). With recent developments in mobile technologies, the range of tasks that can be performed while travelling has increased and consequently, both operator and passenger activities could be at greater risk to detrimental effects associated with WBV exposure (Mansfield, 2005).

By investigating the influence of whole-body vibration (WBV) exposure on task performance during rail travel, the representation of activity interference in vibration standards (for example, ISO 2631-1 (1997)) could be improved. Historically, studies designed to investigate the influence of WBV on task performance have focused on seated postures. There are however, many environments (such as, on trains) where individuals are exposed to WBV in standing postures. Only a limited number of studies have investigated WBV exposure in different standing postures; and of those which have, none considered the performance of manual control tasks or the influence of postural supports on the biomechanical response of the standing human body.

This introduction chapter outlines the main aims of the thesis and provides an overview of the thesis structure.

1.1 SCOPE AND AIMS OF THE THESIS

The research presented in this thesis is principally concerned with a human factors or ergonomics viewpoint, and addresses issues associated with task performance in a moving environment. The fundamental objective of the thesis is to enhance the knowledge of two key topic areas relating to the human response to whole-body vibration (WBV) that have not previously been investigated. These areas are: i) the vibration-induced activity interference in manual control tasks experienced by standing individuals, and ii) the influence of postural supports on the biomechanical response of the standing human body to vibration.

A field measurement phase will allow a sample of rail transport systems to be measured in order to establish current typical vibration exposures. A concurrent field observation phase of rail passengers will provide useful insight into the behaviour of standing passengers and the range of tasks that these passengers engage in while travelling. Using this information to inform the experimental design, a series of four laboratory studies is proposed to investigate the objective performance effects and subjective workload during WBV exposure.

The specific aims of the thesis are to:

- Classify the behaviour of standing rail passengers, relating to the:
    i) use of technology and mobile communication devices,
    ii) types of support strategies used to maintain stability while travelling,
    iii) standing postures adopted by standing passengers.
- Quantify the physical exposures typically experienced by passengers in public rail transportation systems, in a variety of postures and performing a variety of tasks.
- Evaluate the influence of WBV vibration exposure (with specific consideration to the magnitude, direction and frequency of exposure) on the objective performance of manual control tasks and the associated subjective workloads.
- Quantify the biomechanical responses of the human body to WBV in a variety of standing postures.
- Evaluate the use of biomechanical responses to WBV as a predictive method for activity interference in manual control tasks and judgments of subjective workload.

1.2 STRUCTURE OF THE THESIS

The thesis is organised into 10 chapters (Figure 1.1), comprising an introduction and literature review, equipment and analysis chapter, one field study and four laboratory studies, each of which address particular issues relevant to the influence of whole-body vibration exposure on manual control performance. An overview chapter then synthesises the results and knowledge in two chapters: general discussion and conclusions, thereby enabling the aims of the thesis to be accomplished. Within this thesis, there is a progression from the investigation of general issues (Chapter 4) through to more specific concerns (Chapters 5 – 8). Further information is provided in a brief chapter-by-chapter summary (Section 1.3).

THE INFLUENCE OF WHOLE-BODY VIBRATION (WBV) AND POSTURAL SUPPORT OF ACTIVITY INTERFERENCE IN STANDING RAIL PASSENGERS

Chapter 1:	**General Introduction**
Chapter 2:	**Literature Review** Environmental Context | Human Response to WBV | WBV-Induced Activity Interference
Chapter 3:	**Equipment and Analysis** Equipment Design | Ethics | Participants | Vibration Measurement Systems | Statistical Analysis
Chapter 4:	**Field Observations and Measurement** IV: Train | DV: Vibration, Tasks, Postures and Supports
Chapter 5:	**Influence of WBV and Stance Orientation (Posture) on Manual Control Performance** IV: Vibration (magnitude, direction) and Posture (stance) | DV: Manual Control Performance (discrete and continuous) and Workload (semantic and magnitude estimation)
Chapter 6:	**Influence of WBV and Posture (Seated and Standing) on Manual Control Performance** IV: Vibration (magnitude, direction and frequency) and Posture (full body) | DV: Manual Control Performance (serial) and Workload (semantic)
Chapter 7:	**Influence of Postural Supports on the Biomechanical Response of the Standing Human Body** IV: Vibration (magnitude and direction) and Posture (supports) | DV: Apparent Mass and Transmissibility
Chapter 8:	**Influence of WBV and Postural Supports on Manual Control Performance** IV: Vibration (magnitude) and Posture (supports) | DV: Manual Control Performance (serial) and Workload (NASA-TLX)
Chapter 9:	**General Discussion**
Chapter 10:	**General Conclusions**

Where: IV = Independent Variable(s) and DV = Dependent Variable(s)

Figure 1.1 Structure of the thesis

1.3 CHAPTER-BY-CHAPTER SUMMARY

The first part of this research was a general review of the human factors and ergonomics knowledge on vibration-induced activity interference (Chapter 2). It was evident from this review that a substantial amount of research had been conducted to address a many of the wide ranging issues that exist in this topic area. Despite this previous research, a number of fundamental issues were identified for which relatively little or no work has been published. These issues included: the influence of WBV on manual control performance in standing postures and the effect of postural supports on the biomechanical responses of the standing human body. Chapter 3 outlines the experimental design, general equipment and analysis techniques that were used in this research.

The first study involved a field investigation conducted on underground trains (Chapter 4). Covert observations of standing rail passengers were used to provide a description of the contextual interactions between standing passengers and the environment. In particular the use of travel time was observed as well as the types of support strategies used to maintain stability while travelling. Measurements of vibration were taken to quantify the vibration to which passengers are exposed on different underground trains. The results of this study were used to help inform the design of the subsequent four laboratory studies.

Based on the observations presented in Chapter 4, the majority of standing rail passengers adopted one of two stance orientations – one foot in front of the other (Anterio-Posterior) and feet side-by-side (Lateral). Furthermore, the greatest magnitudes of vibration on underground trains were found to occur in the horizontal (x- and y-axis) directions. It was proposed that the selection of stance orientation in relation to the direction of movement would influence task performance (based on the base-of-support provided in the direction of motion). Chapter 5 outlines two laboratory studies designed to investigate the extent to which variations in stance orientation and horizontal exposure to whole-body vibration (WBV) influenced the performance of two types of manual control tasks. The first study investigated performance of a discrete manual control task, while the second study assessed continuous manual control. These types of manual control tasks have been investigated in previous studies and each represents a fundamental component of many ‘real-world’ manual control tasks. Generic (non-specific) tasks were used I this study to minimise any personal bias that might be introduced with ‘real-world’ devices as a result of individual preferences for a particular product, make or model. The results showed that task performance and workload were not widely affected by stance orientation and vibration direction. Increasing vibration magnitudes however, showed progressive degradations in discrete manual control performance but not in continuous control performance. Workload increased with vibration magnitude for both types of manual control task. These results show that although individuals may adapt to vibration exposure and maintain a level of performance, this usually occurs at the expense of workload. The results from this study supported previous findings reported within the literature. Such comparisons are made with caution however, as the majority of the published studies have only considered seated postures. There are no reported investigations that have provided a direct comparison of task performance in seated and standing postures.

In order to address this issue and gain a better understanding of the influence of body posture on task performance and workload during WBV exposure, the study presented in Chapter 6 considered both seated and standing postures. Additionally, the vibration frequency was included as an independent variable to identify any frequency-dependent responses associated with manual control performance and workload. Sinusoidal vibration was used in this study as it enabled single frequencies of motion to be considered separated with little noise in the signal. A serial manual control task was used to assess performance as this provided an improved representation of the typical hand-held devices used by rail passengers (Chapter 4). The results showed that the participants were able to adapt to the vibration exposure and maintain response time (supporting the findings in Chapter 5) however; performance accuracy and workload clearly demonstrated a frequency-dependent response. In general, performance and workload responses showed little variation between the seated and standing postures. In this study, the absence of postural supports (such as, a backrest) for the participants was identified as a probable factor contributing the limited influence of posture on performance and workload. In reality, individuals would typically use a range postural supports while travelling (Chapter 4).

Chapter 7 aimed to assess the influence of various postural supports on the biomechanical response of standing individuals exposed to vibration. An understanding of these biomechanical responses can provide valuable insight into the mechanisms that ultimately lead to decrements in performance. The most commonly used measures of biomechanical response are: i) apparent mass, which describes the response of the human body at the driving-point of vibration (for example, the floor in the case of standing individuals); and ii) transmissibility functions which characterise the vibration transmitted through the body (for example, from the floor to the hand). The results from this study showed that supports with the greatest contact area between the vibrating structure and the body corresponded to the greatest influence in biomechanical response. Additionally, rigid supports influenced the biomechanical response of the body to a greater extent than non-rigid supports (for example, a loose handle support). Based on these findings and the frequency-dependent performance and workload results from Chapter 6; it was proposed that the greatest decrements to manual control performance would be associated with postures that exhibited the most substantial influence on the biomechanical responses of the body.

The study presented in Chapter 8 was designed to build from the studies presented in Chapters 4 – 7. This study aimed to assess the extent to WBV exposure influenced serial manual control performance and workload measures in supported standing postures (similar to the postures used in Chapter 7). During the previous studies (Chapter 5 and 6), workload was evaluated using semantic rating scales and magnitude estimation techniques. These methods were not difficult for participants to learn, not particularly time consuming (an important consideration when there are many experimental conditions) and have been validated in previous studies within the literature. The approaches were however, rather simplistic and provided little insight into the individual components that form the overall measure of workload. For these reasons, a more detailed method (NASA-Task Load Index) was used for the study presented in Chapter 8. The results indicated that the supported postures in which performance was degraded due to vibration corresponded to the conditions where the biomechanical responses were significantly influenced by the postural supports in Chapter 7.

Chapter 9 discusses the combined results obtained from the various studies and literature review (Chapter 2). Within this chapter the limitations of the research presented in this thesis and probable future issues for investigation are also considered. The conclusions of the thesis are summarised in Chapter 10. This chapter highlights the contributions of the thesis to research knowledge by referring back to the original aims of the research and discusses the wider implications of this work to other topic areas (such as, human-machine interactions).

CHAPTER 2

LITERATURE REVIEW

This chapter describes the literature relating to the context surrounding the proposed research (Section 2.1). It further explains the response of the human body to whole-body vibration (WBV) exposure (Section 2.2), specifically the biomechanical response relating to apparent mass (Section 2.2.1) and transmissibility (Section 2.2.2). Following this the factors relating to activity interference as a consequence of exposure to WBV are discussed in Section 2.3.

2.1 ENVIRONMENTAL CONTEXT

2.1.1 Rail Transportation

Although rail transportation represents a relatively small proportion (approximately 3%) of the occupational exposures to WBV, the high passenger numbers associated with this mode of travel suggest a substantial number of people would experience vibration from non-occupational exposures. Consider that since the privatisation of the rail industry in 1997, passenger numbers in Great Britain have increased by 69% to over 1.39 billion annual passenger journeys and this figure has been forecast to double over the next 25 years (ATOC, 2007).

2.1.2 Postures Adopted by Standing Passengers

The majority of exposures to WBV occur in seated postures however, there are many environments where individuals experience vibration while standing (Mansfield, 2005). As a result, many previous studies have focused on the effects of vibration on seated individuals with limited attention given to alternative postures. On rail transport systems many passengers, adopt standing postures, either through personal choice or due to overcrowding and a lack of available seating (especially during peak travel times).

In order to gain a better understanding of the factors which influence passenger behaviour, the Rail Safety and Standards Board, UK (RSSB, 2009) investigated the typical postures adopted by standing passengers while travelling (Figure 2.1).

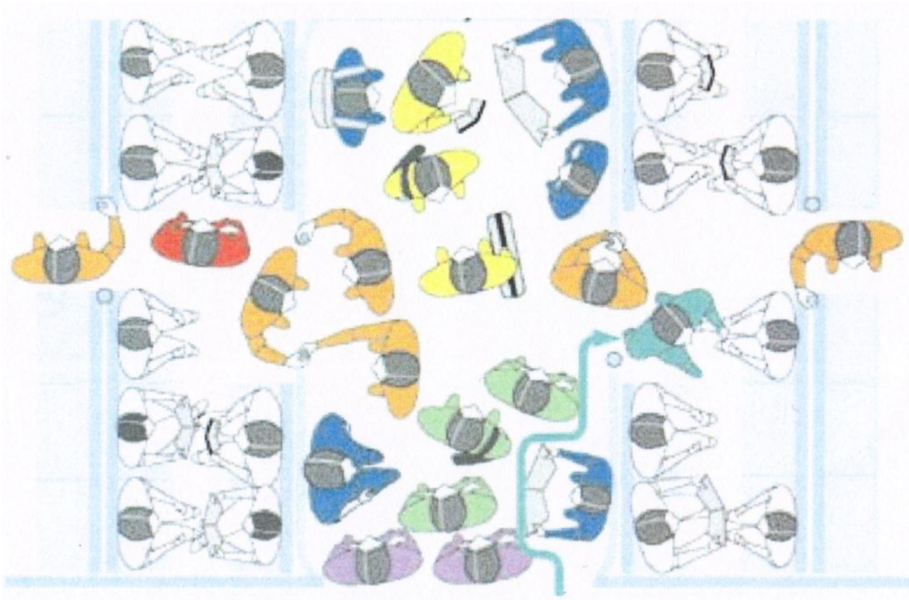


Figure 2.1 Typical standing postures adopted by rail passengers - see Figure 2.2 for colour coding (RSSB, 2009)

These patterns have been termed ‘characters’ and are described in Table 2.1, which details the location of the passengers, the type of supports used by passengers (* in some cases no information was provided) and various influencing factors relating to a specific ‘character’ or behaviour. The study aimed to provide recommendations that could be used to introduce operational and design-based measures to support the requirements of standing passengers. This information could further be used to inform studies investigating the effects of vibration in various postures on factors such as comfort, activity interference as well as standing stability. The study reported that passengers adopting ‘Sentinel’ and ‘Blocker’ positions typically used the walls and screens as leaning supports or held onto grab rails to maintain stability. In many positions however, no information was provided regarding the supports used by standing passengers. Overall, the study provided useful information about the positions of different passengers, but more detailed information is required to accurately describe the body postures adopted during standing travel. Particularly in the ‘Midfielder’ and ‘Hostage’ positions where the choice of position was largely dependent on the behaviour of other passengers and access to supports was limited, passengers may adopt alternative strategies to maintain balance. For example, Griffin (1990) proposed that increasing the base-of-support (BOS) at the feet could improve standing stability during exposure to lateral motions.

Table 2.1 'Character' descriptions for standing rail passengers (adapted from RSSB, 2009)

Sentinels 	**Location:** standing passengers positioned in the corners of the vestibule. **Supports:** leaning against a wall or draught screen. **Influencing factors:** need to be close to the door, short journey duration.
Blockers 	**Location:** standing passengers often block access to the aisle. **Supports:** usually hold or lean onto grab rails. **Influencing factors:** lack of suitable holding points further along the aisle.
Midfielders 	**Location:** standing passengers positioned in the middle of the vestibule. **Supports:** unknown * **Influencing factors:** limited space (unable to reach either the Sentinel or Blocker positions), short journey duration.
Hostages 	**Location:** standing passengers within a crowded vestibule area (limited options due to lack of space). **Supports:** unknown * **Influencing factors:** limited options due to other passenger behaviours and positions.
Seat Snatchers 	**Location:** passengers that stand in the best position to occupy a recently vacated seat. **Supports:** unknown * **Influencing factors:** importance of finding a seat, journey duration, extra space from other passengers.
Heroes 	**Location:** passengers that move through a crowded vestibule to the aisle space or an available seat. **Supports:** unknown * **Influencing factors:** long journey duration, importance of finding a seat or more space to stand.
Opportunists 	**Location:** passengers boarding a crowded vestibule area, typically near the doors. **Supports:** unknown * **Influencing factors:** time restrictions – not waiting for the next train.

2.1.2.1 Postural Assessment Methods

Posture assessment tools have been extensively employed in human factors and ergonomics assessments. These methods may include video-based or computer-aided analysis, direct measurements (for example, using goniometers) or pen and paper based observational techniques (Li and Buckle, 1999). Within the context of rail transportation, these pen and paper based approaches would be the most appropriate option. These methods are relatively inexpensive to carry out and the postural assessments can be made without causing disruptions to individuals. The main disadvantage of this approach is that the intermittent recording procedures may lack precision and consequently, the reliability of the systems has proved to be problematic (Burdorf *et al.*, 1992). Some of the most commonly adopted pen and paper based methods are summarsied in Table 2.2.

Table 2.2 Common pen-and-paper-based observational posture assessment methods (adapted from Li and Buckle, 1999)

Technique	Basic Features	Field of Applications
OWAS (Karhu *et al.*, 1977)	Categorised body postures in digital numbers	Whole-body posture analysis
RULA (McAtamney and Corlett, 1993)	Categorised body postures aas coded numbers	Upper limb assessment
PLIBEL (Kemmlert and Kilbom, 1987 and Kemmlert, 1995)	Checklist with questions for different body regions	Identification of risk factors
REBA (McAtamney and Hignett, 1995)	Score the body postures	Risk assessment of entire body for dynamics tasks
QEC (Li and Buckle, 1998)	Estimate exposure levels for body postures in different body regions	Assessing the change in exposure for static and dynamic tasks

The general approach of these methods for assessing body posture is fairly consistent (with the possible exception of the Quick Exposure Checklist (QEC) to some extent). The method consists of observation of the task, comparison of the posture observed with reference postures in tool documentation, combining the individual ratings and then comparing the overall score with risk levels and recommendations.

The QEC system (Quick Exposure Check) for work-related musculoskeletal risks was developed by Li and Buckle (1998). The method includes the assessment various body regions: the back, shoulder/upper arm, wrist/hand and neck. The approach considers the postures of these body parts and a wide range of additional information (for example, movements, task duration, maximum load handled, vibration, visual demand and subjective responses). The magnitude of each assessment item is classified into exposure levels which are then combined to represent the different risk factors for each body part.

Developed in response to the need to address problems associated with working postures in industry, the Ovako Working Posture System (OWAS) provided a method that broadly classified working postures and identified risk factors associated with these postures (Karhu *et al.,* 1977). The OWAS technique divides the body into four areas: the trunk, arms, lower body and head/neck. The system defines the movements of body segments around these areas as four types: bending, rotation, elevation and position. Fransson-Hall *et al.* (1995) noted that postural analysis techniques usually have two, often contradictory qualities of generality and sensitivity. While the OWAS procedure requires only a few seconds to record body postures, a possible shortcoming of the system is that the posture categories are too broad to provide accurate posture description (Li and Buckle, 1999).

PLIBEL represents a screening tool designed to identify ergonomics hazards in the workplace, through the use of a checklist (Kemmlert and Kilbom 1987). The checklist consists of questions regarding work posture, movements and workplace or tool design. These questions are answered based on five body regions, including: neck/shoulders and upper part of back, elbows/forearms and hands, feet/knees and hips and low back. Although the tool is useful for identifying risk factors associated with specific body regions, the methods requires the use of interviews and questioning approaches, which would not be feasible in a public context such as, travelling on train.

Proposed by McAtamney and Hignett (1995), REBA (Rapid Entire Body Assessment) was developed on the basis of the RULA (Rapid Upper Limb Assessment) system (McAtamney and Corlett, 1993), but it is appropriate for evaluating tasks where postures are dynamic, static or where gross changes in position take place. The classification system requires the observer to select a posture for assessment and then score the body alignment using the REBA diagrams (Appendix A1). The method uses well defined regions of the body and increases the sensitivity of the technique over other assessment tools.

2.1.3 Use of Travel Time

Generally, time spent travelling has been viewed as wasted time and transport policies have primary focused on the pursuit of quicker journey times (Lyons *et al.,* 2007). Accordingly, investment decisions in the transport sector have been justified on the basis that savings in travel time represented a conversion of unproductive time to economically valuable time (DETR, 2000). Lyons *et al.* (2007) proposed an alternative perspective stating that travel time was not merely a cost that should be reduced, but rather that it could be viewed as a positive utility.

Lyons *et al.* (2007) reported the results of a passenger survey conducted throughout rail stations in Great Britain in 2004, aimed at providing an evidence-based view of the use of travel time. The study which considered commuting, business and leisure journeys, reported that between 9 – 53% of passengers engaged in some kind of activity while travelling. Reading for leisure was the most commonly performed activity (53%), while 26% of passengers performed activities related to working or studying. In light of the widespread adoption and use of mobile technologies, a follow up study (Lyons *et al.,* 2011) was conducted in 2010 using the same* questionnaire as in the 2004 survey (* additional options were included to accommodate new technology). The principal results concerning how people used their journey time in 2004 and 2010 are presented in Table 2.3.

The findings revealed a consistency between 2004 and 2010 in terms of the overall proportions of passengers reading for leisure, window gazing, working or studying, talking with other passengers, eating and drinking and sleeping. Technology dependent activities (text messaging (personal and work related), listening to music, checking emails and internet browsing) showed an increase in the occurrence over the six year period. Lyons *et al.* (2011) noted that in 2010, passengers were 63% more likely to be texting or using a mobile phone for personal reasons and 83% more likely to do so for work.

Clearly, developments in mobile technology have provided passengers with greater opportunities for external communication, as well as facilitating a wider range of activities, both work-related and social. Furthermore, it was proposed that the use of mobile technologies has become socially more acceptable and travelers are increasingly able to personalise their environments (Lyons *et al.*, 2011). Overall, a greater proportion of passengers considered travel time to be very worthwhile in 2010 (30%), compared to 24% in 2004 and correspondingly, the proportion of passengers that judged travel time to be wasted, decreased by nearly a third; from 19% to 13% (2004 and 2010 respectively).

Table 2.3 Activities performed for some time of the journey by rail passengers in 2010 and (shown in brackets) in 2004 – only activities undertaken by at least 10% of the respondents are shown (adapted from Lyons *et al*., 2011)

Activity	**Journey Purpose**			
	All	Commute	Business	Leisure
Reading for leisure	54 (53)	63 (62)	43 (47)	48 (48)
Window gazing	53 (57)	47 (49)	46 (54)	64 (68)
Text messaging – personal	**30** (19)	**34** (20)	**26** (15)	**27** (19)
Working / studying	27 (26)	31 (27)	54 (52)	11 (13)
Listening to music	**20** (9)	**28** (12)	**14** (5)	**13** (7)
Checking emails*	**17**	**20**	**31**	**7**
Eating / drinking	17 (15)	13 (9)	23 (22)	20 (20)
Text messaging – work	**15** (8)	**17** (8)	**32** (21)	5 (3)
Talking to others	14 (15)	10 (11)	10 (13)	19 (22)
Internet browsing*	**10**	**13**	**11**	**6**
Sleeping	14 (15)	18 (18)	13 (13)	10 (11)

Where: * = new addition to 2010 questionnaire, **bold** = significant increase in 2010

The performance of such activities could be influenced by a range of environmental factors. Narayanamoorthy *et al*. (2008a) reported that 65% of rail passengers performing work-related activities rated vibration as the main source of disturbance to performance. It must be noted that these studies focused on seated passengers and there have been no published investigations concerning the use of travel time by standing passengers or the associated activity interference. In order to provide an environment for rail passengers that enables activity engagement with minimal interference, further investigation is required to gain a better understanding of the vibration experienced, types of activities performed and human response to such vibration in standing rail passengers.

2.1.3.1 *Whole-body Vibration Exposure on Trains*

Vibration measurements on trains in normal running conditions have only been reported in a few publications. The results from previous studies are shown in Table 2.4.

Table 2.4 Vibration emission values on passenger trains (reported in previous studies)

Reference	**Measurement**	**Type of Train**	**Vibration Magnitude (ms^{-2})** * axis specified in parenthesis
Suzuki (1998)	ISO weighted r.m.s.	Japanese standard trains	Peak: 0.65 (xyz) r.m.s.: 0.27 (xyz)
Birlik and Sezgin (2007)	ISO weighted r.m.s.	Turkish suburban trains	Peak: 1.34 (xyz) r.m.s.: 0.23 (xyz)
Narayanamoorthy *et al.* (2008a)	r.m.s. and Sperling Ride Index (Wz)	Swedish intercity trains	0.03 (x) 0.04 (y) 0.12 (z)
Narayanamoorthy *et al.* (2008b)	r.m.s. and mean comfort index	Indian intercity trains	Train 1: 0.69 (xyz) Train 2: 0.28 (xyz) Train 3: 0.66 (xyz) Train 4: 0.44 (xyz) Train 5: 0.61 (xyz)
Birlik (2009)	ISO weighted r.m.s. (A(8) and eVDV)	Turkish suburban trains	0.11 – 0.28 (x) 0.18 – 0.36 (y) 0.13 – 0.32 (z) 0.23 – 0.49 (xyz)

The dominant natural frequencies of train vibration have been found to occur between 1 – 3Hz on Swedish intercity trains (Sundström, 2006 and Narayanamoorthy *et al.*, 2008a). For all frequencies above 10z the vibration magnitudes decreased significantly. These frequencies correspond to the most critical frequency range of the human body, which shows resonant frequencies below 2Hz for horizontal motions and between 4 – 6Hz during vertical WBV exposure (Griffin, 1990).

It is clear from the studies presented in Table 2.4 that vibration exposure on trains is often variable between different types of railway systems and between different countries. The magnitudes presented in Table 2.4 are generally below the exposure limit value (ELV) of 1.15ms^{-2} A(8) as set by the Health and Safety Executive (HSE) in the United Kingdom (UK) and therefore present a low health risk to individuals. However, Narayanamoorthy *et al.* (2008a) found that even at low vibration magnitudes, issues relating to activity interference may still occur. None of the reported studies have investigated vibration exposures on trains within the UK. Not only does this lack of information limit the applicability of research findings to UK passengers, but variations in vibration exposures may have additional implications on factors such as comfort and activity performance.

2.1.4 Whole-body Vibration Standards and Guidelines

The risks associated with vibration exposure have been recognised, primarily in relation to the health effects and likelihood of injury (for example, low back pain). The EU physical agents (vibration) directive (PA(V)D) established exposure 'action' and 'limit' values for whole-body vibration (values are also provided for hand-transmitted vibration, although these are not within the scope of this thesis). The mandate detailed in the PA(V)D has been incorporated into the 'Control of Vibration at Work Act' (HMSO, 2005) and is enforced by HSE. An exposure action value (EAV) of 0.5ms^{-2} A(8) r.m.s. and an exposure limit value (ELV) of 1.15ms^{-2} A(8) r.m.s. in the worst axis is currently specified.

2.1.4.1 ISO2631-1 (1997) Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration: Part 1 – General requirements

ISO2631-1 (Part 1) is concerned with the measurement and evaluation of WBV exposures. The primary purpose of the standard is to define methods of quantifying WBV in relation to: i) human health and comfort, ii) the probability of vibration perception and iii) the incidence of motion sickness. Although ISO2631-1 (1997) recognises that *'whole-body vibration may.. influence human performance capability..'*, no guidance is provided for the potential effects of vibration on task performance. The explanation for its absence is that such information critically depends on ergonomic issues relating to the operator, the situation and the task design.

Measurement of WBV should be conducted according to a co-ordinate system originating from the point at which vibration is considered to enter the body (Figure 2.2). For vibration that does not contain large shocks the r.m.s. evaluation method is proposed and the frequency ranges considered within the standard are 0.5 – 80Hz for health, comfort and perception and 0.1 – 0.5Hz for motion sickness.

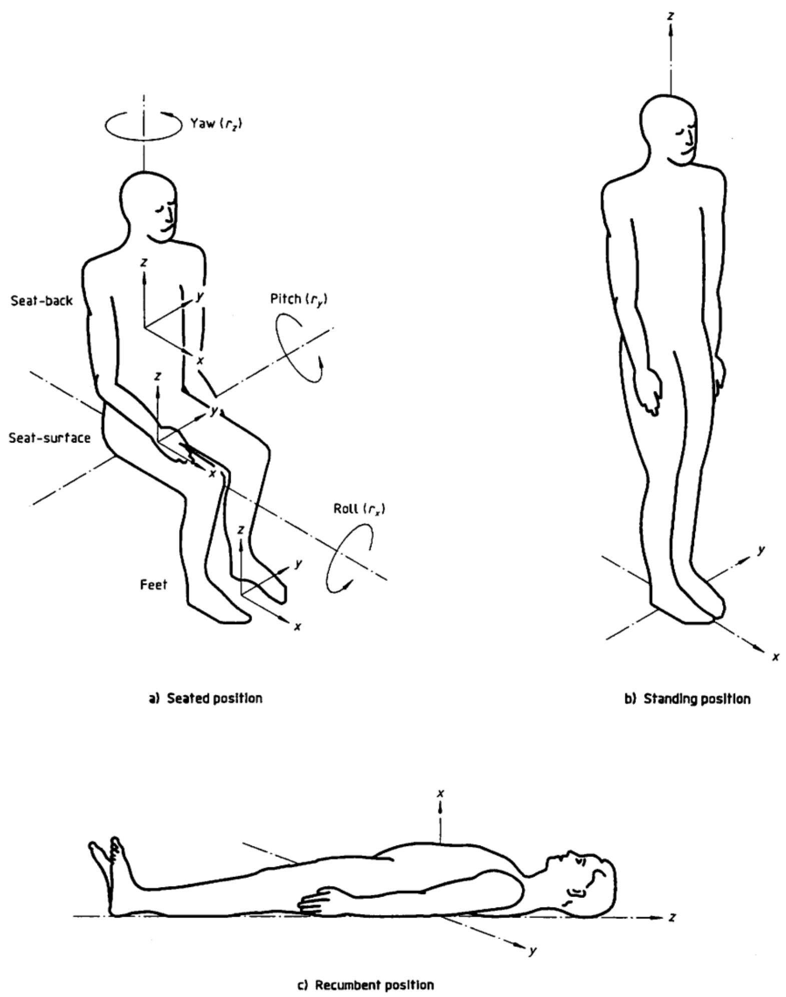


Figure 2.2 Basicentric axes of the human body (ISO2631-1 (1997))

Frequency weightings are used for each axis of vibration to account for the non-linear response of the human body to different frequencies of vibration (Griffin, 1990). Vibration that occurs near the resonant frequency of the body is assumed to have the greatest influence of health, comfort and performance effects.

Generally, the resonant frequency of a seated individual occurs at about 5Hz in the z-axis (vertically) and between 1 – 2Hz in the x- and y-axis (horizontally) (Paddan and Griffin, 1988; Fairly and Griffin, 1989; Kitazaki and Griffin, 1997; Matsumoto and

Griffin, 1998; Mansfield and Griffin, 2000). In standing individuals, resonance in apparent mass has been found at similar frequencies to seated individuals (Matsumoto and Griffin, 2000). Frequency weighting factors have been developed to account for such non-linearities in response. In the x- and y-axis W_d is applied, with W_k being used in the z-axis (Figure 2.3).

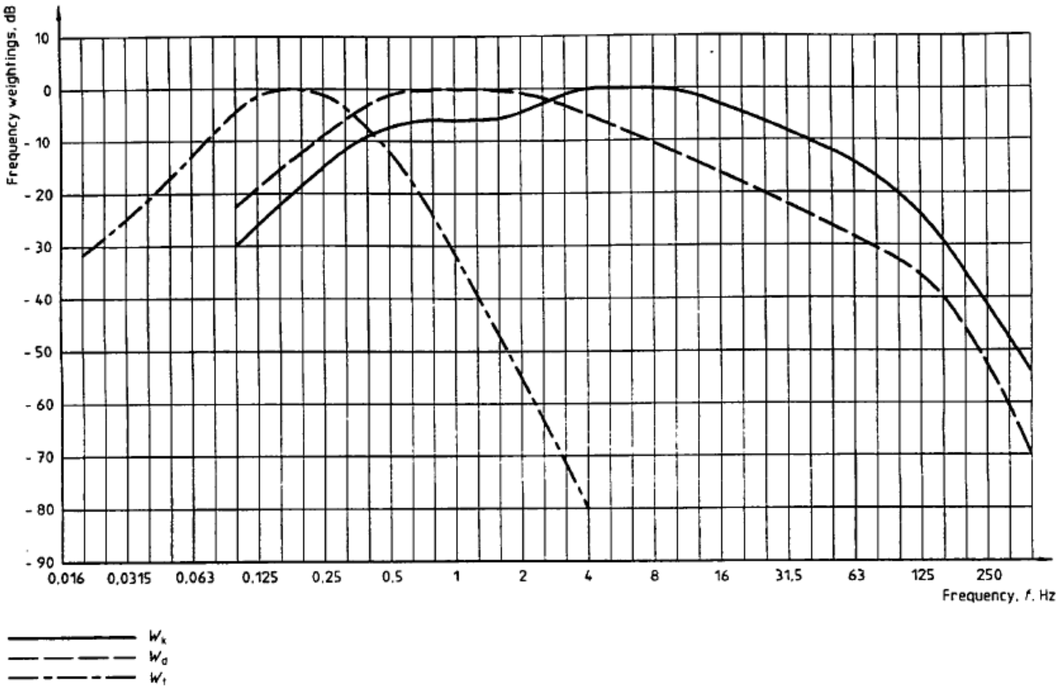


Figure 2.3 Frequency weighting curves for principal weightings (as specified in ISO2631-1 (1997))

2.1.4.2 ISO2631-4 (2001) Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration: Part 4 – Guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed guideway transport systems

The purpose of this part of ISO2631 is to aid in the design and evaluation of fixed guideway passenger systems, although the standard primarily focuses on the evaluation of passenger comfort. The vibration evaluation and measurement protocols stipulated in ISO2631-4 were therefore used to inform the development of an experimental design for the measurement of vibration on a public rail (fixed guideway) system. The standard proposes that special consideration should be given to lateral and longitudinal motions, particularly for passengers or crew in standing positions. The measurement location for standing individuals should be at the floor/feet interface, preferably in both empty and fully laden carriages and within the co-ordinate system provided in Figure 2.2

2.2 HUMAN RESPONSE TO WHOLE-BODY VIBRATION

The human response to whole-body vibration may be separated into five distinct effects (Griffin, 1990) involving: perception of low-magnitude vibration, motion sickness, degraded comfort, impaired health and activity interference (which is the focus of the research presented in this thesis). These effects are dependent on the method and extent to which vibration is transmitted to and through the human body (the biomechanical response of the human body).

Biomechanical data may also offer the possibility to predict the effects of whole-body vibration exposure (for example, Jex (1974)) however, this approach in practice can often be very complex as well as system- and situation-specific, thus limiting the applicability of such models (Lewis and Griffin, 1978). Consequently, Griffin (1990) cautioned that biomechanics should be used as a tool rather than an end-point objective of research. For example, knowledge of vibration at various locations on the body would be of little value without first understanding the relation between vibration exposure and the effect of interest (such as activity interference).

The majority of biomechanical literature relating to whole-body vibration has addressed four main categories (Mansfield, 2005). The first two categories describe transfer functions (Sections 2.2.1 and 2.2.2) using measurements of force and acceleration at the 'driving-point' (the contact site between the body and the loading force) and acceleration measurements at multiple sites remote from the driving-point (Mansfield, 2005). The third category of biomechanical research is that of developing models to describe and predict the human responses to vibration. Such models (Section 2.2.3) represent ideas or relationships and have frequently been designed to represent impedance or apparent mass and transmissibility data obtained in the first two categories of biomechanical research (Mansfield, 2005). The final category consists of other methods that have been reported but have not commonly been utilised. In many cases these methods were developed for a specific application (for example, the effects of WBV on bone density (Rubin *et al.*, 2004)).

2.2.1 Apparent Mass

2.2.1.1 Influence of Body Posture

The majority of biomechanical research has focused on seated exposures to vibration, particularly in the vertical direction. Measurements of the vertical apparent mass of the seated body have generally shown a resonance at around 5Hz (Fairley and Griffin, 1989). The apparent masses of 60 seated participants with no backrest (exposed to 1.0ms^{-2} r.m.s. random vertical vibration) are compared in Figure 2.4 (Fairley and Griffin, 1989).

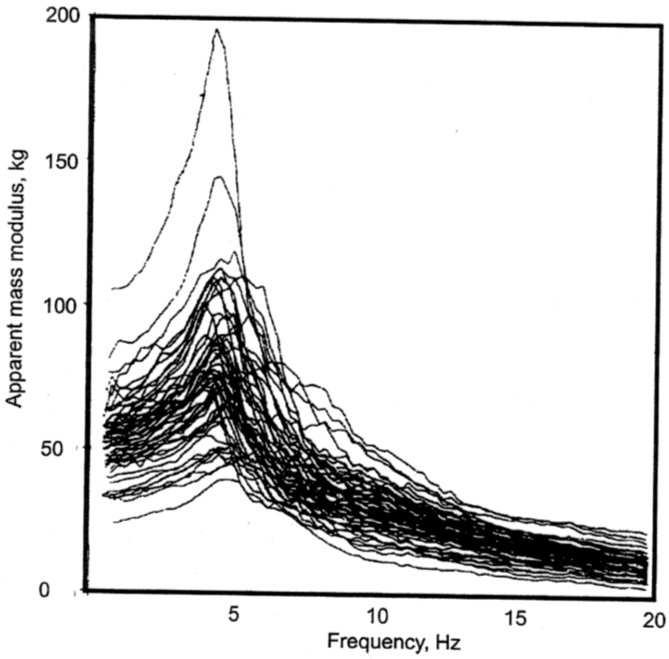


Figure 2.4 Apparent masses for 60 seated individuals exposed to vertical vibration (Fairley and Griffin, 1989)

At low frequencies the human body was effectively rigid and each apparent mass curve approaches the static mass of the participant supported on the seat. At the resonant frequency (around 5Hz) the response increased by 1.3 – 2.0 times greater than the static mass. In some cases a second peak was found in the region of 10Hz, although the frequency and magnitude of this second resonance varies considerably between subjects and was not always clear in the mean or median results.

Further investigation conducted by Fairley and Griffin (1990) considered the apparent masses of seated individuals exposed to horizontal (fore-and-aft and lateral) vibration. The results showed two peaks in apparent mass at about 0.7Hz and between 2 – 2.5Hz, during lateral and fore-and-aft motions respectively. More recently, Nawayseh and Griffin (2005) identified an additional peak between 3 – 5Hz during fore-and-aft vibration exposure. Despite the majority of research being conducted in seated postures, some studies have investigated the dynamic responses of standing individuals. Matsumoto and Griffin (2011) found that in a normal upright standing posture the lateral apparent mass peaked between 0.375 – 0.75Hz. During fore-and-aft vibration, no clear peak was observed in apparent mass however, apparent mass increased greatly as the frequency reduced from 1Hz to 0.125Hz. Based on these findings it was suggested that the peak in fore-and-aft apparent mass would occur at a frequency below 0.125Hz (Figure 2.5).

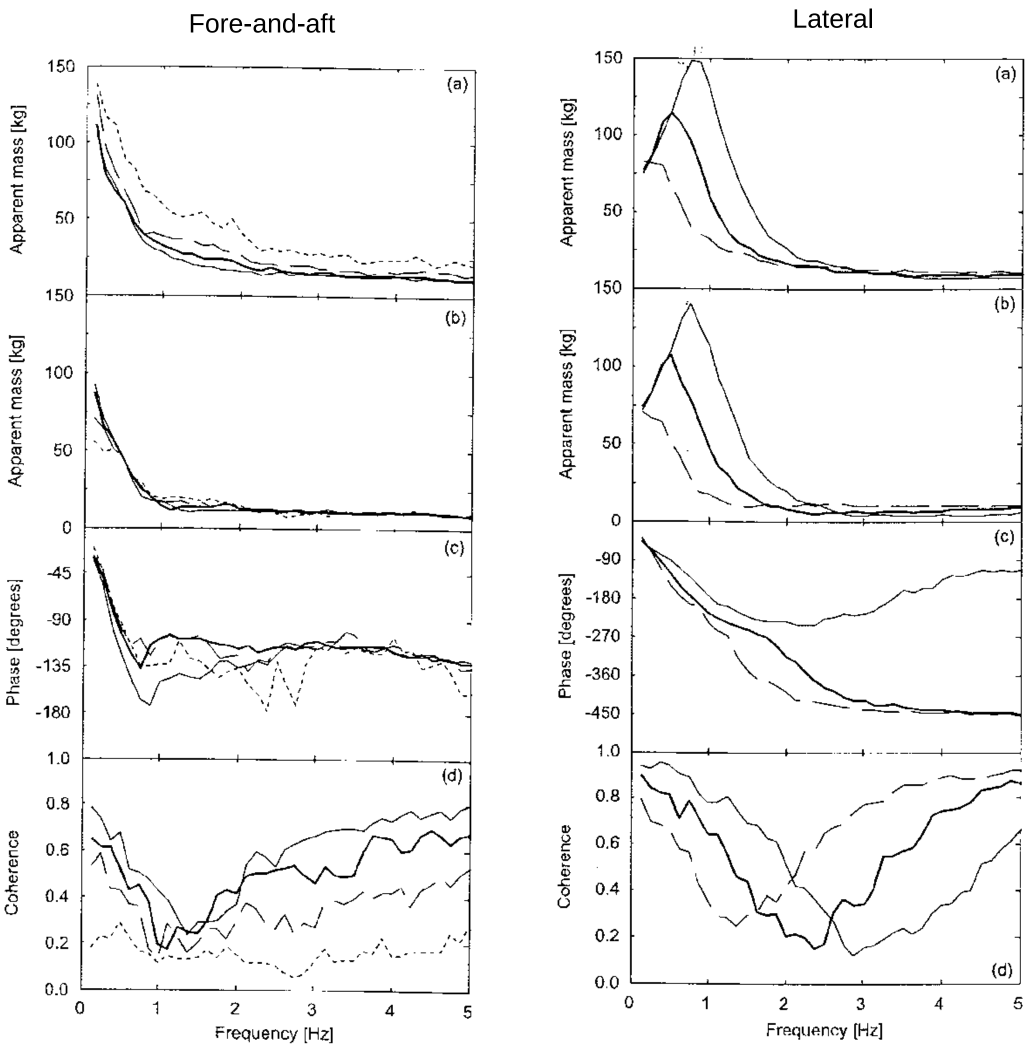


Figure 2.5 Median fore-and-aft and lateral apparent mass, phase and coherence for 12 standing subjects with three different separations of the feet at 0.063 ms^{-2} r.m.s.: (a) apparent mass (PSD method), (b) apparent mass (CSD method), (c) phases and (d) coherences (dashed lines = 0.15m; solid, bold lines = 0.3m; solid lines = 0.45m; Matsumoto and Griffin, 2011)

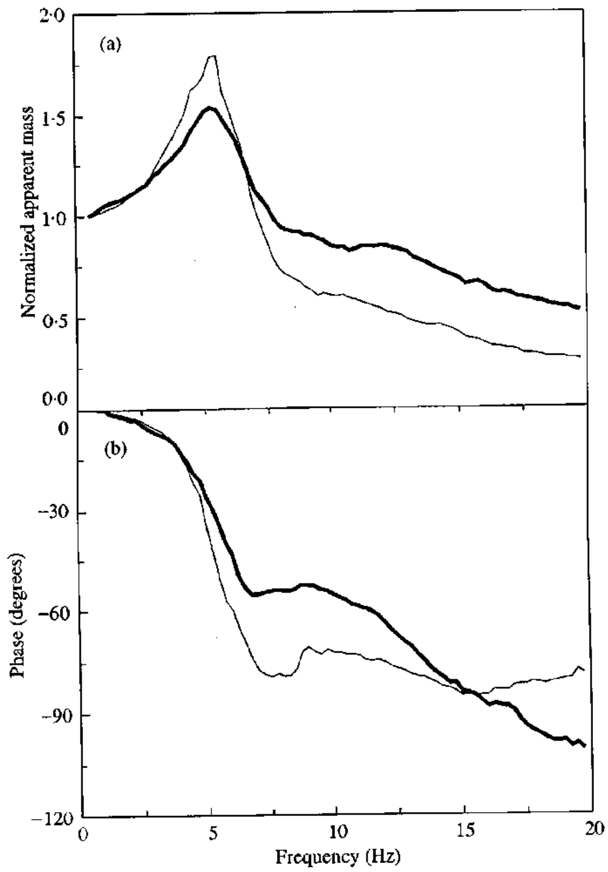


Figure 2.6 Median normalised (a) apparent mass and (b) phase in standing and sitting postures exposed to vertical vibration (solid, bold lines = standing; solid lines = sitting; Matsumoto and Griffin, 2000)

Comparing seated and standing postures during exposure to vertical vibration, Matsumoto and Griffin (2000) reported similar findings with the principal resonance apparent mass in both seated and standing postures occurring between 4 – 6Hz (Figure 2.6). In this case, the principal resonance was slightly higher for individuals in a standing posture than seated however; the difference was generally less than 1Hz. It was suggested that differences within seated postures and within standing postures would result in greater variations in the resonant frequency than comparisons between seated and standing postures.

When standing with both legs bent, the principal resonance frequency has been found to decrease to 2.75Hz (Matsumoto and Griffin, 1998). An investigation by Subashi *et al*. (2006) which included 'lordotic' and 'anterior lean', as well as 'legs bent' postures supported the findings of Matsumoto and Griffin (1998). This study showed resonant frequencies of 3.13Hz and 2.63Hz for the 'legs bent' and 'legs more bent' respectively. The remaining two postures ('lordotic' and 'anterior lean') however, revealed no systematic influence on the resonant frequency. It was concluded therefore, that variations in lower body postures imparted a greater influence on the resonance of apparent mass than changes to the upper body postures. With respect to the magnitude of apparent mass at the resonant frequency, the most significant postural influence was found in the 'lordotic' and 'anterior lean' postures (Subashi *et al*., 2006), where the magnitude of apparent mass decreased in comparison to the normal, upright posture. Altering the lower limb posture, such as bending the legs revealed no influence on the magnitude of apparent mass (Matsumoto and Griffin, 1998).

2.2.1.2 Influence of Postural Supports

An important consideration that has not been addressed in previous apparent mass studies is that very rarely do people stand freely while travelling. Standing individuals exposed to WBV often utilise postural supports such as grab rails or interior walls to aid in maintaining stability or to prevent muscle fatigue. Although the influence of standing posture on apparent mass has been investigated in a few studies, none have considered how the inclusion of postural supports would affect the dynamic responses of individuals exposed to vibration.

In seated postures, contact with a backrest has been found to increase the resonance frequency of apparent mass. Considering the influence of a backrest, Mansfield and Maeda (2007) identified peak resonant frequencies for seated individuals at 1.5 and 4.25Hz in a 'back-off' posture during y- and z-axis vibration respectively (no data was provide for the x-axis as the primary resonance could have been affected by the band limiting of the vibration signal). In the 'back-on' posture, resonant frequencies were found at 3.25, 1.5 and 5Hz during x-, y- and z-axis vibration respectively. The influence of a backrest support on the primary resonant frequency was clearly evident during x-axis vibration, yet in the y-axis there was no influence on the resonant frequency. These differences could possibly be due to the location of the back support in relation to the direction of motion.

Additionally, Toward and Griffin (2010) identified an increase in resonance frequency from 4.8Hz to 6.7Hz when seated participants were in contact with a backrest (Figure 2.7). Furthermore, when holding onto a steering wheel (providing support for the upper limbs) there was no evidence that the resonant frequency was influenced. However, the magnitude of apparent mass at resonance decreased which was attributed to the steering wheel supporting some of the mass of the arms.

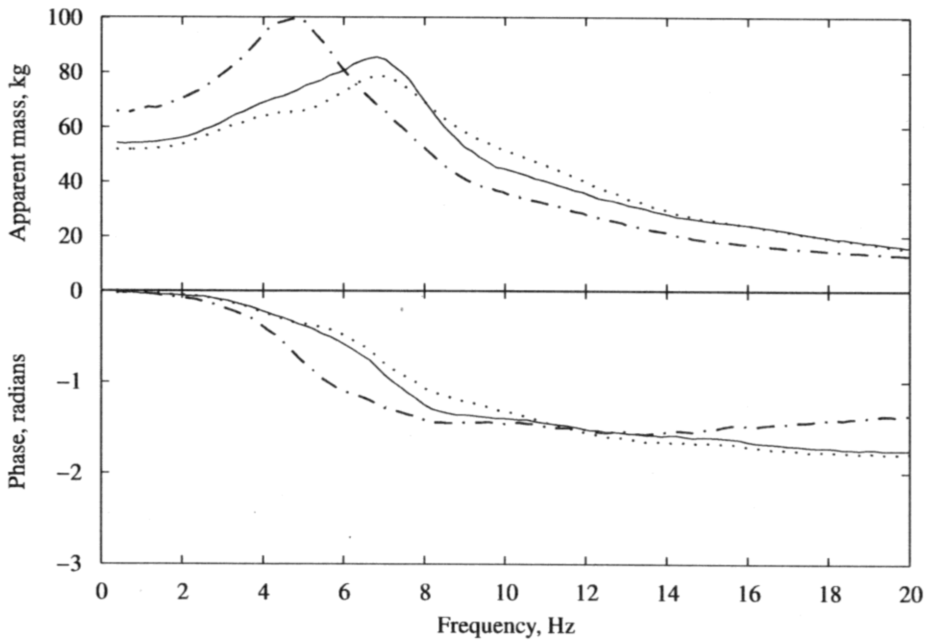


Figure 2.7 Effect of backrest and steering wheel contact on apparent mass (dashed lines = no backrest, hands in lap; dotted lines = backrest at 15°, hands in lap and solid lines = hands on steering wheel, backrest at 15°; Toward and Griffin, 2010)

2.2.2 Transmissibility

2.2.2.1 Influence of Body Posture

The propagation of vibration through the body depends on many variables, including: the characteristics of the vibration, the system (source of the vibration-human coupling) and the human body itself (Harazin and Grzesik, 1998). Body posture has been identified as a predominant factor in determining the biomechanical response to whole-body vibration (Griffin, 1990). Variations in posture may influence the surface of contact between the body and the vibrating structure, the position of the spine, tension within different muscle groups or the trunk and the extremities (Harazin and Grzesik, 1998).

Most of the relevant investigations of vibration transmission through the body have been concerned with vertical vibration. Considering standing individuals, Matsumoto and Griffin (1998) investigated the transmission of vertical vibration to the lower spine (L4) in 'normal', 'legs-bent' and 'one-leg' standing postures. The results showed similar resonant frequencies to those identified during measurements of apparent mass. In the 'normal' posture, transmissibility to the spine showed a peak resonance at about 5.9Hz, which was reduced to 2.75 and 3.75Hz in the 'legs-bent' and 'one-leg' postures respectively.

Additionally, Paddan and Griffin (1993) proposed that there remained many uninvestigated variables that could influence the transmission of vibration particularly during horizontal motions. Such factors included: the separation of the feet and the effect of holding onto a handrail. Consequently, a study was designed to assess the transmission of floor vibration in the x-, y- and z-axes to the heads of standing participants (Figures 2.8; 2.9 and 2.10). During horizontal vibration exposure (x- and y-axis), the greatest transmission of vibration to the head was found at frequencies below 3Hz (resonant frequencies for fore-and-aft and lateral transmissibility were found at about 1.5Hz in both directions).

In the fore-and-aft (x-axis) direction, participants held onto a handrail with both hands with either a rigid or light grip. The transmissibilities illustrated in Figure 2.8 show that head motions due to vibration transmission occurred predominantly in the fore-and-aft, vertical and pitch axes. In the fore-and-aft direction there was significantly greater head motion at frequencies above 1Hz when standing holding onto the handrail with a rigid grip, as compared to a light grip (Figure 2.8).

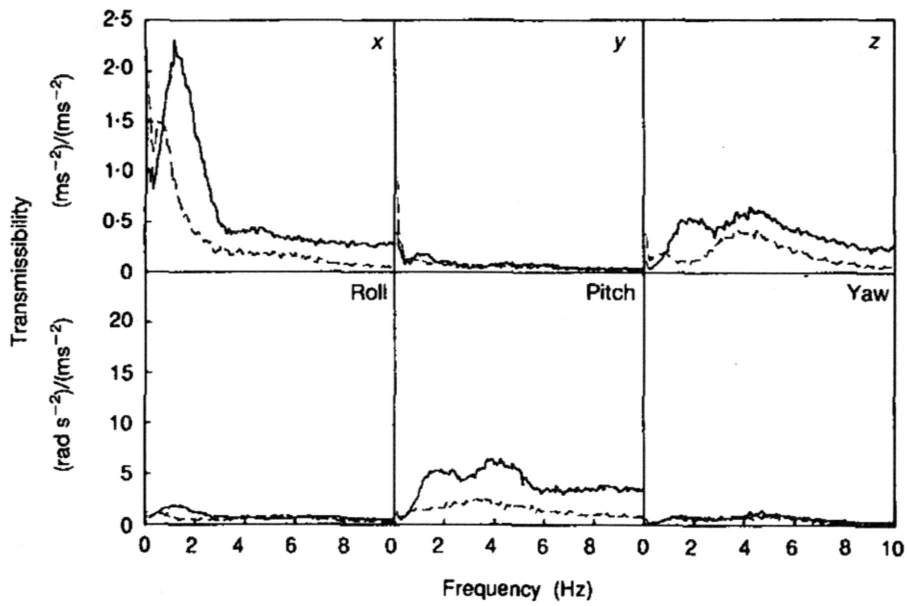


Figure 2.8 Median transmissibilities to the head with fore-and-aft floor vibration for 12 participants standing in two body postures (solid lines = rigid grip; dashed lines = light grip; Paddan and Griffin, 1993)

During exposure to lateral (y-axis) vibration, the participants stood freely with three different feet separations: feet together, feet separated by 30cm and 60cm (Figure 2.9). As expected, motions of the head occurred mainly in the lateral direction. The transmissibilities presented in Figure 2.9 show a tendency for the transmission of lateral vibration at resonance to increase with increasing separation of the feet. Transmission of vertical vibration showed a peak at about 5Hz in the x- y- and z-axes (other peaks were also observed, particularly in the z-axis). Similar results were found for the 'legs locked' and 'legs unlocked' postures however, the transmissilities were slightly lower in the unlocked condition (Paddan and Griffin, 1993). The most notable difference in transmissibility during vertical vibration occurred in the 'legs bent' posture where the resonant frequency reduced to about 3Hz (Figure 2.10).

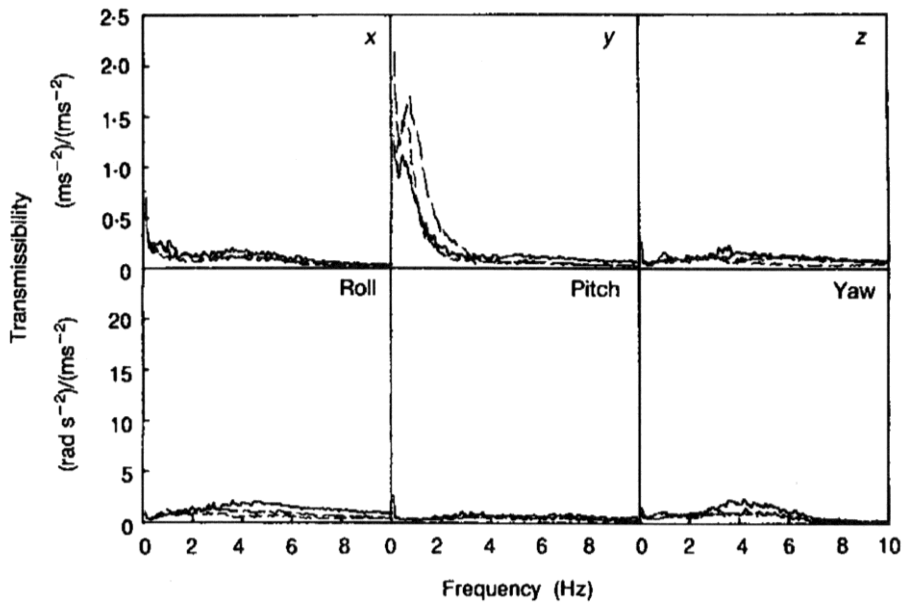


Figure 2.9 Median transmissibilities to the head with lateral floor vibration for 12 participants standing in three body postures (solid lines = feet together; dotted lines = 30cm separation and dashed lines = 60cm separation; Paddan and Griffin, 1993)

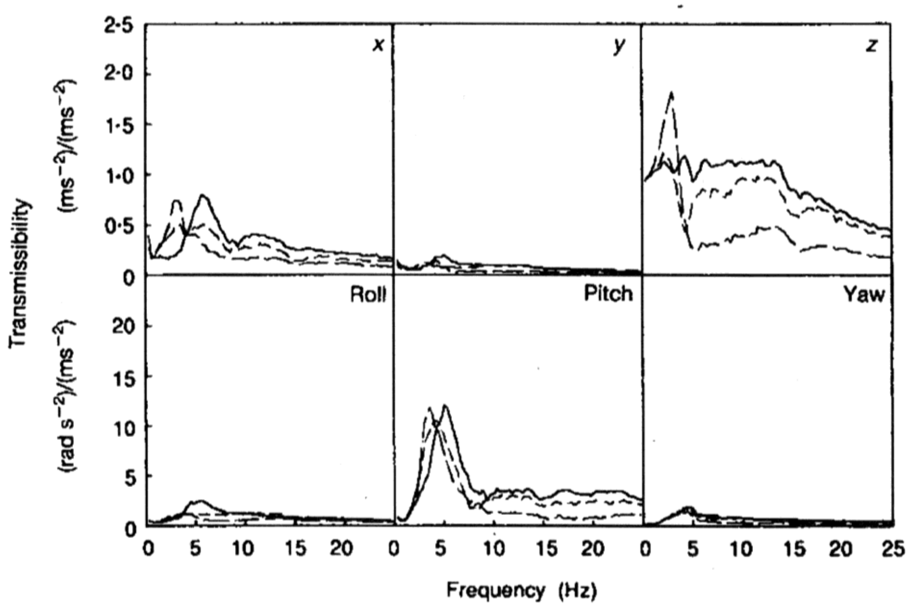


Figure 2.10 Median transmissibilities to the head with vertical floor vibration for 12 participants standing in three body postures (solid lines = legs locked; dotted lines = legs unlocked and dashed lines = legs bent; Paddan and Griffin, 1993)

2.2.2.2 Influence of Supports

It is clear that posture exerts a substantial influence on the transmission of vibration to various locations on the body, such as the spine and the head (Matsumoto and Griffin, 1998 and Paddan and Griffin, 1993). When considering the effects of vibration exposures (for example, manual control performance) the transmission of vibration to locations such as the operating limb or hand must also be considered. A series of investigations were designed to assess transmission of vibration to the hand of seated individuals exposed to: fore-and-aft (Paddan, 1994), lateral (Paddan, 1995) and vertical (Paddan and Griffin, 1995) vibration (Figures 2.11; 2.12 and 2.13).

These studies considered the influence of body supports (backrests) and the location of the hand in relation to the body on vibration transmission. During exposure to x-axis vibration, the fore-and-aft transmissibility to the hand showed a peak at about 1Hz in the ‘back-off’ condition. Contact with the backrest resulted in an increase in the resonant frequency to between 4 – 5Hz (Paddan, 1994). Furthermore, in the ‘back-off’ posture motions at the hand were closely matched and showed similar resonant frequencies in the fore-and-aft direction for both arm positions (elbow held at 90° and 180°). Slight variations were found during the ‘back-on’ posture however, the main differences were found in the lateral and vertical directions. Peak transmissibilities were found between 4 – 6Hz with the arm held at 90° (lateral direction) and with the arm extended at 180° in the vertical direction (Figure 2.11). These results suggest that when the hand is held freely, vibration transmission in the direction of motion remains fairly consistent irrespective of the position of the hand in relation to the body.

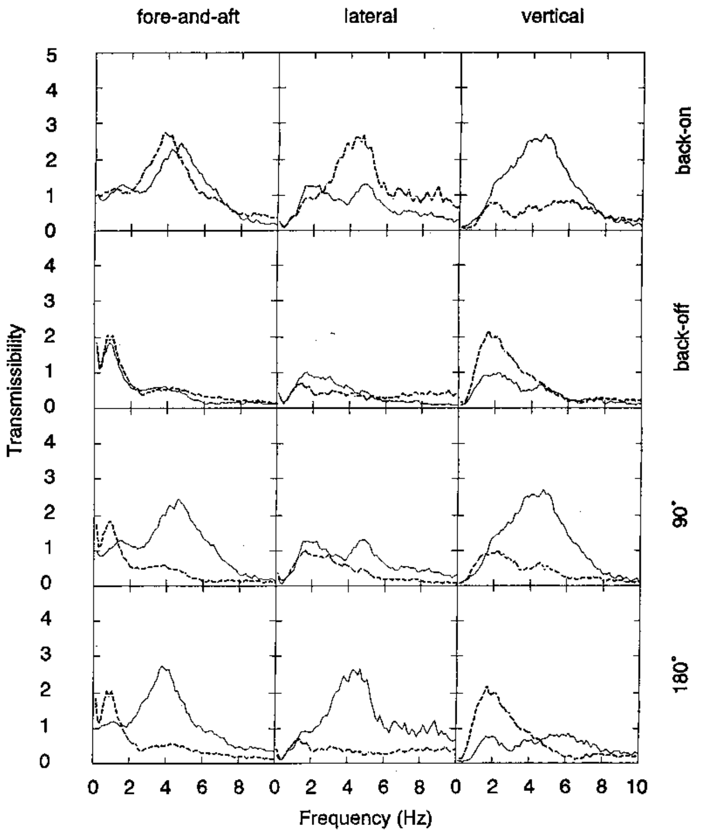


Figure 2.11 Median transmissibilities between fore-and-aft seat vibration and the translational axes of motion at the hands of seated subjects, 0.126Hz resolution (rows 1 and 2: solid lines = 90°, dashed lines = 180°; rows 3 and 4: solid lines = 'back-on', dashed lines = 'back-off'; Paddan, 1994)

In the lateral direction (Figure 2.12), transmissibility showed similar results to the fore-and-aft transmissibility, with a peak between 1.5 – 2Hz in the 'back-off' condition. In the 'back-on' condition, the presence of a backrest showed little influence on the frequency of resonance (Paddan, 1995). In both directions (x- and y-axis), the presence of a backrest resulted in higher magnitudes of the transmissibility at the frequency of resonance. Finally, considering vertical transmissibilities (Figure 2.13), Paddan and Griffin (1995) found two clear peaks in transmission of vibration to the hand in a 'back-on' posture: the first at about 2Hz and the second around 5Hz (with the arms held at 90° and 180° at the elbow)

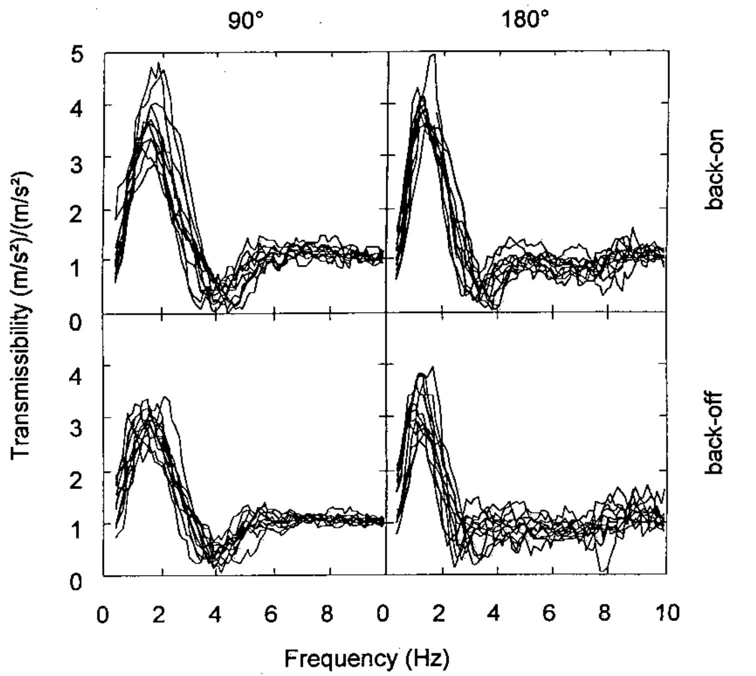


Figure 2.12 Relative transmissibilities between lateral seat acceleration and lateral acceleration at the hands of seated subjects with two body postures (‘back-on’ and ‘back-off’) and two arm postures (90° and 180°) (0.126Hz resolution; Paddan, 1995)

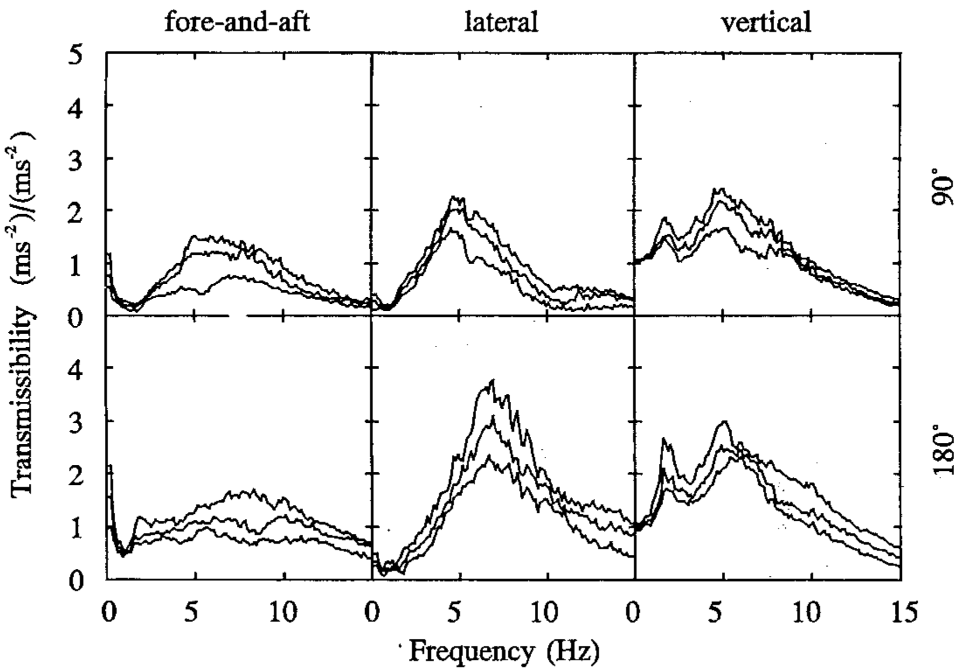


Figure 2.13 Median and interquartile transmissibilities between vertical seat acceleration and lateral acceleration at the hands of seated subjects in a ‘back-on’ posture with two arm postures (90° and 180°) (0.126Hz resolution; Paddan and Griffin, 1995)

2.2.3 Biomechanical Modeling

Numerous types of biomechanical models have been developed (Table 2.5) and it is important to remember that any given model will only show specific aspects of the overall system. The range of applicability and validity of a model must therefore be taken into account to ensure the model provides a trustworthy representation of the response of the body to motion (Griffin, 2001).

Griffin (2001) reviewed the validation of different types of biomechanical models. These models were organised into three categories however, it should be noted that the classifications were not designed to be mutually exclusive (Table 2.5). For example, a mechanistic model may involve partial aspects of a quantitative or effect model. Generally, simplicity has been highlighted as the most useful approach to providing sufficiently accurate predictions of the response of interest. Due to the complex nature of the human response to vibration, complex models have been developed to represent complex hypotheses – these however, are unlikely to be fully tested and verified. Nevertheless, possible applications for models include: enhancing the understanding of the nature of body movements, providing predictions of movements caused by certain motions or offering information for the optimisation of systems coupled to the body.

Biomechanical models may provide: i) an understanding of how the human body moves (mechanistic models), ii) a summary of the biomechanical responses to vibration from apparent mass and transmissibility measurements (quantitative models) and iii) predictions of health effects, comfort and performance (effects models).

Table 2.5 Classification of biomechanical models (adapted from Griffin, 2001)

Type	Description	Form of Model	Examples
Mechanistic Models			
1 (a)	Explain how the body moves. Models assume the laws of physics are sufficient to predict human response.	Qualitative description of how the body moves	Phrases referring to body response
1 (b)		Mechanical system representing a characteristic giving rise to the output	Model predicting effects of characteristics (posture, mass)
1 (c)		Human cadavers	Specific types of cadaver
Quantitative models			
2 (a)	Most biomechanical models fall into this category. Represent input-output relationships without claiming to show the mechanism that relates the two. Should provide predictions of one or more responses of the body to movement.	Table of numerical responses to input	Tabular values of measured transmissibilities
2 (b)		Equation representing numerical values in 2(a)	Equation with specified form and parameters
2 (c)		Idealised mechanical system with responses similar to 2 (a)	Single and multiple degrees of freedom models, continuum models
2 (d)		Mechanical dummy	Anthropometric dummy (seat testing)
Effects models			
3 (a)	Models the effects of motion on the body may be qualitative and partly mechanistic. Purpose is to predict effects and prevent the consequences (such as injury).	Numerical values indicating specific response	____________
3 (b)		Equations to values specified in 3 (a)	Mathematical models of crash-test dummies
3 (c)		Idealised mechanical system with responses similar to 3 (a)	Crash-test dummies

2.2.3.1 Mechanistic Models

These models provide explanations of how the human body moves and reflect the mechanisms involved in the biomechanical response of the human body to vibration. If a mechanism can be correctly identified and understood, these types of models may be used to predict a response that has not been measured.

Kitazaki (1994) used two-dimensional finite-element models to represent the mode shapes of the body in the mid-sagittal plane. The initial material properties in these models were based on data from cadavers; the models were then optimised using measurements of impedance. From this experimental analysis, the principal resonance in the apparent mass of the body was concluded to be caused by deformation of the tissue beneath the pelvis in phase with vertical motion of the viscera. A secondary mode occurring at about 10Hz was found to be due to rotation of the pelvis (Kitazaki, 1994). While these models may provide a useful understanding of the motions of the body, in practice a purely mechanistic model cannot yet be defined due to the limited understanding of the mechanisms associated with most biomechanical responses (Griffin, 2001). Particularly considering the variability that exists in biomechanical responses due to factors such as posture and vibration input spectra (Toward, 2010).

2.2.3.2 Quantitative Models

Currently most biomechanical models fall into this category. These models describe input-output relationships without representing the mechanisms that relate the two (Griffin, 2001). These models have no predictive power, however by conducting a range of measurements that encompass a variety of conditions the model may indicate what will likely happen with inputs other than those on which it is based (for example, other vibration magnitudes or frequencies).

Many of these models have been developed using simple combinations of masses *(m)*, springs *(K)* and dampers *(C)* to represent the human body (Figure 2.14). Some models provide useful approximations of the relationships between selected inputs and outputs, however the majority have been formed without considering how the body moves (Griffin, 2001). Consequently, the model parameters have simply been adjusted until the relation between the input and output variables match a measured transfer function (for example, apparent mass).

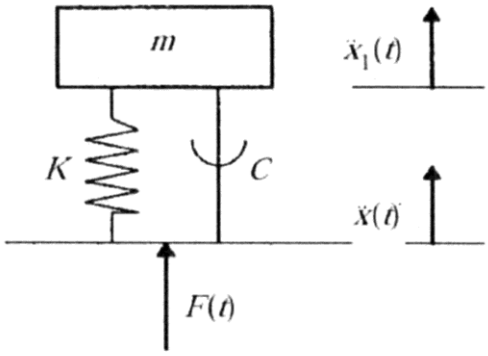


Figure 2.14 Example of a lumped parameter (quantitative) model (Wei and Griffin, 1998)

2.2.3.3 Effects Models

These models describe cause and effect relationships due to vibration exposure and may be quantitative as well as partly mechanistic. Quantitative models are limited by the difficulty of measuring relevant inputs and identifying and measuring the associated outputs (Griffin, 2001). Effects models therefore, attempt to relate inputs (such as vibration magnitude and frequency) with resulting outputs (such as health effects (injury), discomfort or performance degradation).

These models are based on three requirements: i) evidence that the effect is caused by the motion (a causal relationship), ii) knowledge of the type of motion that is causing the effect (a means of quantifying the cause) and iii) knowledge of the effect (a means of quantifying the effect). Where other moderating factors that may influence the cause and effect relationship exist (such as, body posture), these must also be taken into consideration. The responses of the human body to vibration are unlikely to be accurately predicted by a biomechanical model if the relevant factors are not included. For example, many standing rail passengers choose to engage in activities on mobile devices while travelling. Due to the vibration experienced in such environments, the majority of these standing passengers will use supports to maintain stability (Chapter 4). If an accurate description of task performance during vibration exposure is to be made, the influence of posture variations and support strategies should be included. Biomechanical models have been developed to describe the influence of vibration on manual control performance and examples are provided in Section 2.3.4.

2.3 WHOLE-BODY VIBRATION INDUCED ACTIVITY INTERFERENCE

Vibration poses a particular threat to performance as it influences several aspects of human performance (Conway *et al.*, 2007). Using a theoretical framework, Hancock and Warm (1989) distinguished three facets of stress (known as 'the trinity of stress') to explain the relationship between stress and performance (Figure 2.15). The first is the 'input', which described the composition of the surrounding environment which included physical aspects such as vibration and noise, as well as temperature. Hancock and Warm (1989) expressed these inputs as a 'stress signature' because 'real-world' environments consist of many forms of these various inputs. The second facet of stress was 'adaptation', which encompassed both psychological appraisal mechanisms as well as physiological capacity. The psychological appraisals identified explicit performance goals in comparison with the cognitive state and physiological capacities of the individual. Based on these assessments a response would be initiated in order to achieve these goals. These processes enable individuals to compensate for, and adapt to environmental inputs and additional stress in order to maintain performance. The final component to the trinity of stress was the 'output', which reflected how an individual behaved in respect of set performance goals (Hancock and Warm, 1989). In the 'trinity' the output focuses on the actions of an individual, the input focuses on the stressors that must be overcome (such as vibration) in order to achieve the goals, and the adaptation describes the spectrum of behaviours that mediate between the input and the output (Hancock and Szalma, 2008).

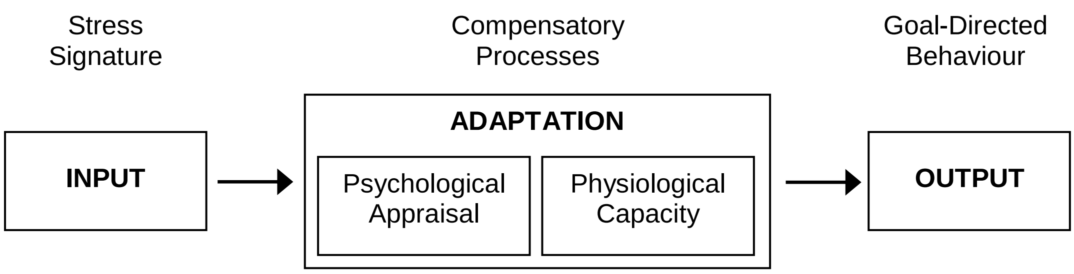


Figure 2.16 The 'trinity of stress' (Hancock and Warm, 1989). A descriptive framework for the environmental origin of stress (input), its representation as a direct pattern of adaptive, regulatory responses (adaptation) and its manifestation in disturbance to on-going performance capacity (output)

The extent to which vibration exposure influences manual control performance depends largely on two specific groups of moderating factors, namely: the characteristics of the vibration itself and the characteristics of the human-task system (Conway *et al.*, 2007, Mansfield, 2005). Due to the wide variety of possible conditions and the range of task variables, rarely will there be two situations which are the same, and therefore the influence of vibration on manual control performance could also vary. Consequently, Griffin (1990) proposed that the mechanisms responsible for such disturbances should be considered as well as the extent to which vibration interferes with performance. The mechanisms identified by Griffin (1990) are described in Section 2.3.4.3 however, these are not fully understood and there remain aspects of vibration exposure and performance that have not been investigated (for example, standing exposures to WBV and the influence of stability supports). Providing a better understanding of these factors could potentially lead to improved performance modeling, as well as form useful additions to current vibration standards.

2.3.1 Vibration Characteristics

2.3.1.1 Effect of Frequency

Frequencies most often associated with WBV occur between 1 – 20Hz, within which a resonance zone exists where the effects on a system will be maximised dependent upon the stimulus it receives (Mansfield, 2005). Lewis and Griffin (1978) reported that for WBV exposures below 20Hz, there was reasonable agreement that performance decrements were related to the transmission of vibration through the body. Much of this previous research has focused on the effects of vibration on seated subjects. Performance decrements due to vertical (z-axis) vibration were positively correlated with transmission to the upper body and controlling limbs with the greatest decrements (for tracking tasks) occurring at frequencies of 4 – 5Hz (Buckhout, 1964) and between 3 – 8Hz (McLeod and Griffin, 1989). Considering writing tasks, Corbridge and Griffin (1991) demonstrated that writing was most difficult (representing decreased performance) between 5 – 6.3Hz. In the same study, a task involving an unsupported limb (holding a cup of liquid) showed difference frequency dependencies. In this instance, the probability of spillage (representing reduced performance) was greatest between 3 – 5Hz. The differences found between the tasks could be as a consequence of different levels of vibration being transmitted through the body as there are different points of contact with the vibrating surface.

Considering horizontal (x- and y-axis) vibration, Hornick (1962) and Shoenberger (1970) found the largest effect on continuous control performance to occur between 1 – 3Hz. Lewis and Griffin (1980) showed that reading performances were degraded at frequencies between 5.6 – 11Hz for fore-and-aft (x-axis) vibration as well as a slight degradation at 5.6Hz for lateral (y-axis) vibration. The effects were only present however, when a seat with a backrest was used and it was concluded that vibration transmitted to the head was responsible for the reduced performances. In a later study, Griffin and Hayward (1994) showed significantly lower reading performances during horizontal vibration exposure between 1.25 – 6.3Hz, with the largest effect occurring at 4Hz for both x- and y-axis vibration (Figure 2.16). The variation in the frequency dependence between these studies was attributed to differences in task characteristics.

Griffin and Hayward (1994) required subjects to read characters from a hand-held clipboard whereas in the earlier study by Lewis and Griffin (1980) the subjects read from a fixed display. In these conditions, the motion of the reading material would vary depending on the capabilities for the body (in the case of the hand-held clipboard) and the fixed display to attenuate vibration transmission.

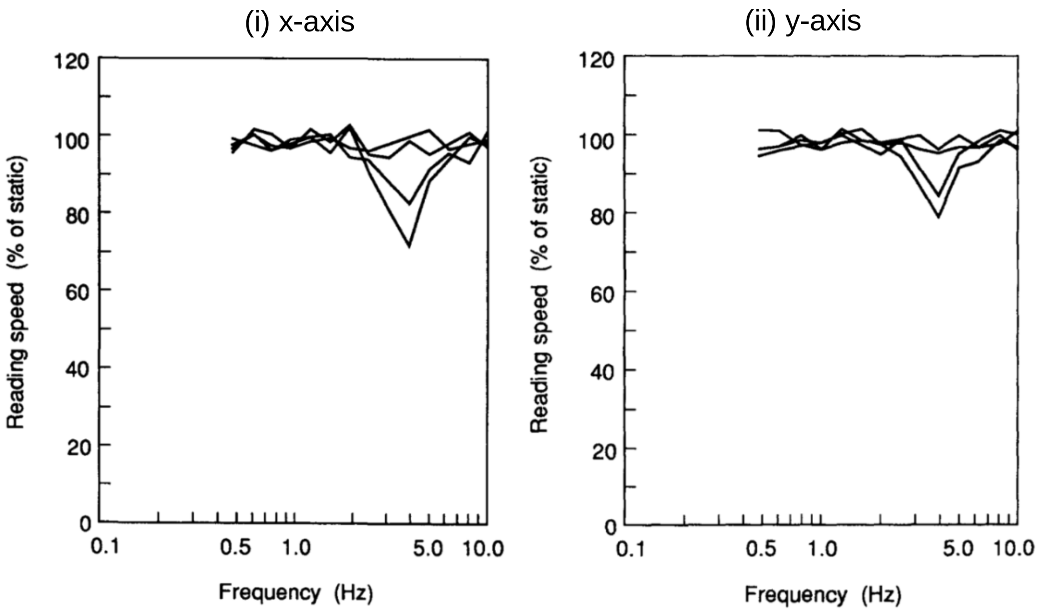


Figure 2.16 Measured reading speed (percentage of static reading speed) during i) x-axis and ii) y-axis vibration at 0.6, 0.8, 1.0 and 1.25ms^{-2} (Griffin and Hayward, 1994)

Overall, the frequency effects of vibration on manual control performance have been found at relatively low frequencies (below 10Hz) and these effects can be expected to correlate with vibration transmission to the head and controlling limbs. This might also apply for standing individuals. However, variations in standing posture (for example, bending at the knees) have been shown to influence transmissibility (Paddan and Griffin, 1993). As a result of such changes in biomechanics of the human body, decrements to performance may occur at different frequencies in standing postures, compared to seated postures.

2.3.1.2 Effect of Magnitude

Generally the magnitudes of interest with whole-body vibration are in the range from 0.01 – 10.0ms^{-2} r.m.s. Vibrations at the upper limit of this range may reasonably be assumed to be hazardous (Griffin, 1990). At low magnitudes issues of refinement and perception of vibration are important while at slightly higher magnitudes, vibration may cause discomfort and activity interference (Mansfield, 2005). Typical vibration magnitudes encountered within everyday life (road and rail transportation) may vary between 0.2 – 1.0ms^{-2} r.m.s. and in extreme cases, up to 2.0ms^{-2} r.m.s (Griffin, 1990).

From numerous studies, there is good agreement that, for a given vibration spectrum, performance is progressively degraded as the magnitude of vibration is increased, above a certain threshold of effect. This has been demonstrated by many researchers for x-, y- and z-axis vibrations (Lewis and Griffin, 1978), based on which it seems reasonable to draw the general conclusion that increases in vibration magnitude, above some threshold of effect, will result in progressive degradation of performance. Some research has been the exception to this rule, for example Newell and Mansfield (2008) found only moderate performance decrements with increasing vibration magnitudes. A notable finding was that the workload experienced by the subjects in this study increased significantly, possibly in an attempt to maintain the level of performance.

Corbridge and Griffin (1991) assessed the effect of vertical vibration on task performance by measuring the level of magnitude at which liquid is spilt from a cup held in an unsupported hand. Random motion at 0.63ms^{-2} r.m.s. did not cause any spillage (impaired task performance) but the subjects did spill some liquid at 2.5ms^{-2} r.m.s. In terms of horizontal vibration Griffin and Hayward (1994) showed that a reduction in reading performance occurred for vibration magnitudes of 1.0 ms^{-2}

r.m.s. and greater. Both studies used similar vibration frequencies, between 1 – 10Hz and in each case the tasks involved objects held in unsupported limbs. The results suggest that the lower limit of vibration magnitude to result in performance interference is variable, supporting earlier statements by Griffin (1990).

More recently, Mansfield *et al*. (2007) considered the use of computer input devices during tri-axial vibration exposure in seated postures. Subjects were required to accurately place the monitor cursor over a specified area. The results identified no significant differences between 'zero' and 'low' (0.508 ms^{-2} r.s.s.) vibration magnitude conditions but differences were found between these and the 'high' (0.878ms^{-2} r.s.s.) condition. The absence of a significant difference between zero and low vibration conditions indicated that low levels of vibration did not adversely affect performance when using these computer devices. At these magnitudes of vibration, subjects were able to adapt and maintain task performance, however, at higher magnitudes no further adaptation was possible and performance decreased. Additional results from this study revealed that the subjective workload experienced by the subjects increased with vibration magnitude. Vibration exposure therefore affects individuals even at low magnitudes, however these effects may only manifest into objective performance decrements once the individual's ability to adapt with such stress has been exceeded.

2.3.1.3 Effect of Direction

There is a substantial lack of information that directly compares the effects of x-, y- and z-axis vibration on task performance. Tracking tasks have been used in the majority of studies to determine the effect of vibration direction on task performance. Fraser *et al*. (1961) found that horizontal tracking performance was affected more by y-axis vibration than by z-axis vibration at the same displacement. Vertical tracking was affected more by z-axis vibration than by y-axis vibration. Vibration in the x-axis had no effect on either horizontal or vertical tracking. These findings would be expected when the nature of the task is considered. Performance of tracking tasks requires accurate movements to be made by the subject in either the horizontal or vertical directions while the controlling limb is in contact with the vibrating control. Unwanted movements of the controlling limb that occurs in the same direction as the tracking task would therefore produce greater decrements in performance than movements that occur in other directions. These types of tasks have, in essence, a performance bias that is dependent on the interaction between direction of tracking and the direction of vibration.

It is important to assess the effects of vibration direction on performance of tasks that have no directional bias. Griffin and Hayward (1994) compared the effects of x- and y-axis vibration on reading performance. The results from this study showed that x-axis vibrations, rather than y-axis vibrations, produced greater reductions in reading speed. The magnitude of this effect however, appeared to be dependent on the presence of a seat backrest that could contribute to increased transmissibility of x-axis vibrations through the body as compared to y-axis vibration transmission.

Single-axis vibration is, in reality, an extremely rare occurrence and usually people are exposed to multiple axis vibration environments. Proposals to the International Organisation for Standardisation (ISO) suggest that the effect of multiple axis motion may be similar to the effect of a single-axis motion at a level corresponding to the root square sum (r.s.s.) of the levels in each axis (Lewis and Griffin, 1978). Generally, the largest decrements in tracking performance can be expected to be caused by vibration in the same direction as the sensitive axes of the control and display (Lewis and Griffin, 1978). In standing persons the 'sensitive axes' of the individual might be considered in terms of stability. Continual disturbances and slight loss of balance while performing a task would affect performance.

2.3.1.4 Effect of Duration

The ISO2631-1 (1997) suggests that the effects of vibration on performance may show a time-dependency and that the tolerable level of vibration magnitude decreases with time. The degree to which exposure duration affects task performance therefore depends on vibration magnitude and task characteristics (Griffin, 1990). Using a range of various simple tasks to test performance during a three-hour exposure to vertical vibration (1.2ms^{-2} r.m.s. and 5Hz), Gray *et al.* (1976) found a clear decrease in performance for an audio vigilance task with time, an improvement on a visual search task with time, no real change in a tracking task and a degradation of writing ability with time. The interesting aspect about the results, however, is that the trends were the same without vibration present as they were in the presence of vibration. Therefore, the effect of duration on performance of these tasks appeared to be independent of any WBV present. For short term duration exposures of a few minutes there does not appear to be any time-dependency effect. Overall, there seems to be no evidence given to indicate any reduction in performance ability with time under vibration which is not already present in the absence of the vibration (Clarke, 1979). A review by McLeod and Griffin (1989) revealed similar results and a lack of conclusive experimental evidence regarding the duration effects of vibration duration on performance, could be the influence of additional factors such as motivation and arousal levels.

2.3.2 System Characteristics

2.3.2.1 Type of Task

Considering manual control tasks, Schmidt (1975) detailed a system for classifying different tasks based on the way movement was organised. Although the categories have been described separately, the classifications are not mutually exclusive but rather form a continuum of manual control tasks. Tasks that could be characterized as having a defined beginning and end point are termed discrete tasks and are generally short in duration, for example pushing a button. The second classification refers to serial tasks which consist of numerous discrete components that are performed in sequence. These tasks differ from discrete tasks in that the performance of serial tasks usually requires a longer duration, yet each element in the series retains a discrete beginning and end (for example, typing on a keyboard). Finally, tasks with no definable beginning or end are classified as continuous tasks. These tasks are generally repetitive or rhythmic and may take several minutes to complete (for example, playing a racing game using a mobile device, where the device is tilted to move the position of the object on the screen).

Historically, the majority of investigations designed to assess the influence of vibration exposure on task performance have focused on continuous (tracking) tasks (for example, Lewis and Griffin, 1978). With the increasing availability and usage of mobile technologies, more recent studies have considered activities that involve greater discrete and serial task components, such as typing on laptop computers (Nakagawa and Suzuki, 2005; Mansfield *et al.*, 2007; Bhiwapurkar *et al.*, 2010 and Lin *et al.*, 2010). Differences in device preferences between participants should be taken into consideration when using ‘real-world’ devices as these could introduce a personal bias into the assessment of performance depending on the make or model of a particular device. Traditionally, mobile technologies have predominantly been placed on table tops or rested on the legs of seated individuals. However, many devices (for example, smartphones) can be operated in a hand-held position and still provide a similar level of functionality. Consequently, the method by which vibration exposure could result in performance disruptions would differ from tasks that have direct contact with the vibrating structure.

2.3.2.2 Device Location and Supports

Paddan and Griffin (1995) proposed that the effect of vibration on task performance depended on the relative displacement between controlling limb/hand and the operating device. A smaller relative displacement could therefore lower the likelihood of errors in performance. Two principal methods have been used to reduce the relative displacement between the controlling limb/hand and the device: firstly, by reducing the mechanical coupling between the device and the vibrating structure (for example, holding the device in the hand). Secondly, by providing additional support to the controlling limb/hand the device and the limb/hand would experience similar vibration exposures, therefore reducing the relative movement between the limb/hand and the device. This case has been shown by Newell and Mansfield (2008) in a study investigating reaction time performance with and without arm rest support. By providing arm rests, participants were able to maintain a greater level of reaction time performance during vibration exposure than without arm supports (Figure 2.17).

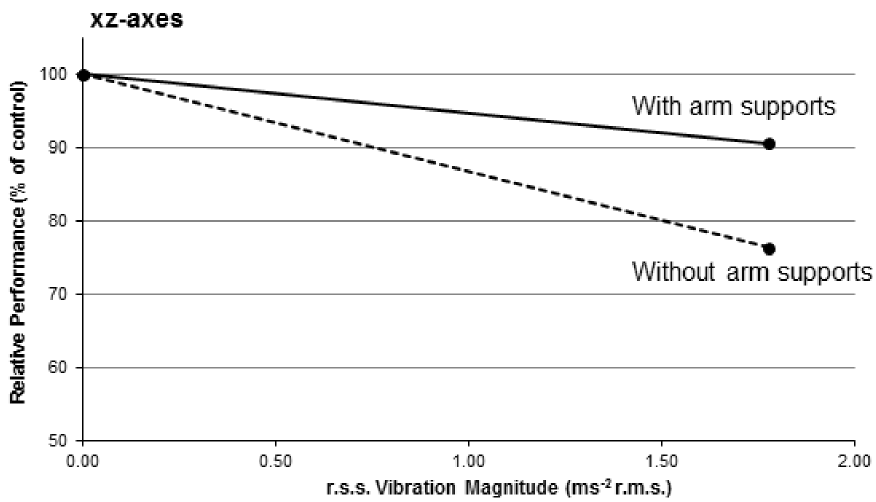


Figure 2.17 Influence of arm supports on reaction time performance during exposure to whole-body vibration (Newell and Mansfield, 2008)

2.3.2.3 Perceived Workload and Task Difficulty

Several authors have suggested that the effects of vibration exposure on task performance may depend on the workload imposed on the individual performing the task. McLeod and Griffin (1989) provided the examples of studies conducted by Besco (1961) and Weisz *et al.* (1965) during which the required response frequency of a continuous tracking task was varied. Both studies found that increasing the response frequency (higher task demands) resulted in greater errors in performance without vibration. As the task became more difficult, the effects of vibration were more pronounced.

In an additional experiment, Weisz *et al.* (1965) varied the workload experienced by the participants by introducing a secondary task. This additional task could serve to make the continuous control task more realistic, or as suggested by Poulton (1965), it could also increase the difficulty of the primary task (and the workload on the participants). Decrements in performance of the continuous control task during 5Hz vibration exposure were disproportionately greater when participants performed a secondary task than when only the primary task was performed. It was suggested that the secondary task increased the workload experienced by the participants, which interacted with the additional stress of vibration and lead to a degraded level of performance. Overall, the influence of vibration may depend on the difficulty of the task being performed (more difficult tasks being more affected) and the associated perceived workload experienced by the individual.

2.3.3 Adaptability

Hockey (1997) stated that humans are 'active agents in their world and are capable of adapting to environments when motivated to do so'. This adaptation ability has further been recognised in the maximum adaptability model proposed by Hancock and Warm (1989). A central feature to the model is that under most environmental conditions individuals adapt effectively to an 'input' disturbance and maintain performance capacity. A second feature is that adaptation occurs at multiple levels, which can be represented using the extended-U hypothesis (Figure 2.18).

These levels include subjective (workload), behavioural (performance) and physiological classifications. As the stress on the individual increases, due to greater intensity, duration or both of input disturbances (such as vibration), the adaptation progressively fails (Conway *et al.*, 2007). The first failure of adaptation to such disturbances occurs in the subjective state, as demonstrated by an increase in perceived workload in order to maintain the current level of performance. With additional disturbances a behavioural failure would follow, resulting in decreased performance. Factors associated with this level of adaptation could include adjustments to the technique used by individuals to perform the task or alternatively a re-assessment of the performance goals. Changes in postures or non-work related movements may also be used to minimise the effects of stress on performance outcomes (Conway *et al.*, 2008). Finally, the last failure of adaptation occurs at a physiological level, where an individual would be physically unable to complete the required task and task performance is ceased. The maximum adaptability model (Figure 2.18) suggests there is an optimum level of stress that is necessary to provide adequate motivation and arousal to optimally complete the task.

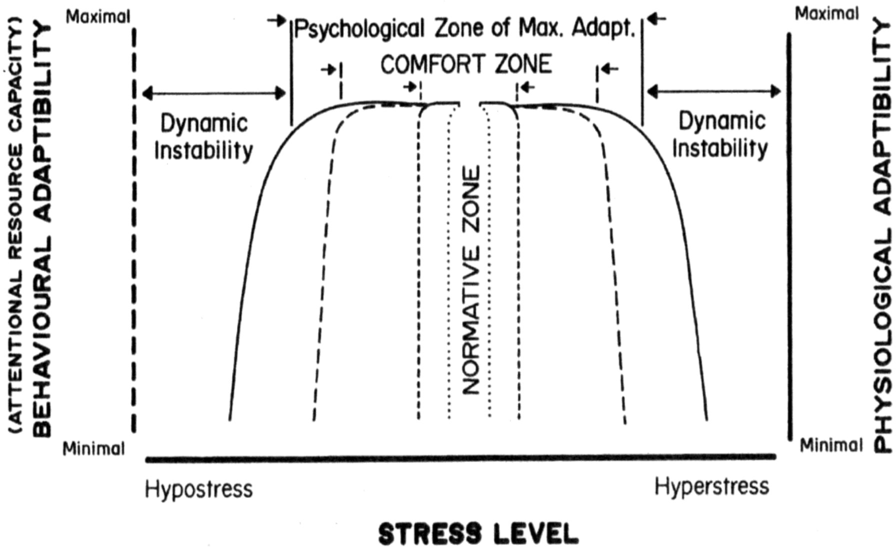


Figure 2.18 The extended-U relationship between stress level and response capacity (Conway *et al.,* 2007)

By managing the effort required to perform a task, Hockey (1997) proposed that individuals would be able to control the effectiveness of task behaviour in relation to concurrent goals (for example, performing a secondary task) and changing demands (such as, exposure to vibration). The adoption of a 'performance protection' strategy (Hockey, 1997) to regulate the effort required to maintain an acceptable level of performance can be expressed in the compensatory control model (Figure 2.19).

In this model, routine performance corrections are conducted automatically (Loop A), without additional effort, and therefore at no appreciable cost to the individual (no increase in workload). The second level of control (Loop B) is used to regulate effort when the discrepancy due to external disturbances exceeds the ability for low-level corrections to maintain acceptable levels of performance (Hockey, 1997). In this upper-level of regulation (Loop B), the effort monitor is used to identify increasing control demands in Loop A (for example, a failure to resolve performance discrepancies). No automatic response occurs at this point, but rather the perception of a change in task demands causes control to shift to a higher level, the supervisory controller (Figure 2.19). At this level, performance regulation may take different modes. Firstly, there may be an increase in the effort (workload) expended by the individuals in order to maintain current performance criteria or alternatively, the task goals could be adjusted so that performance levels remain within acceptable tolerance criteria. These stages could be related to the subjective and behavioural levels described in the maximum adaptability model (Hancock and Warm, 1989).

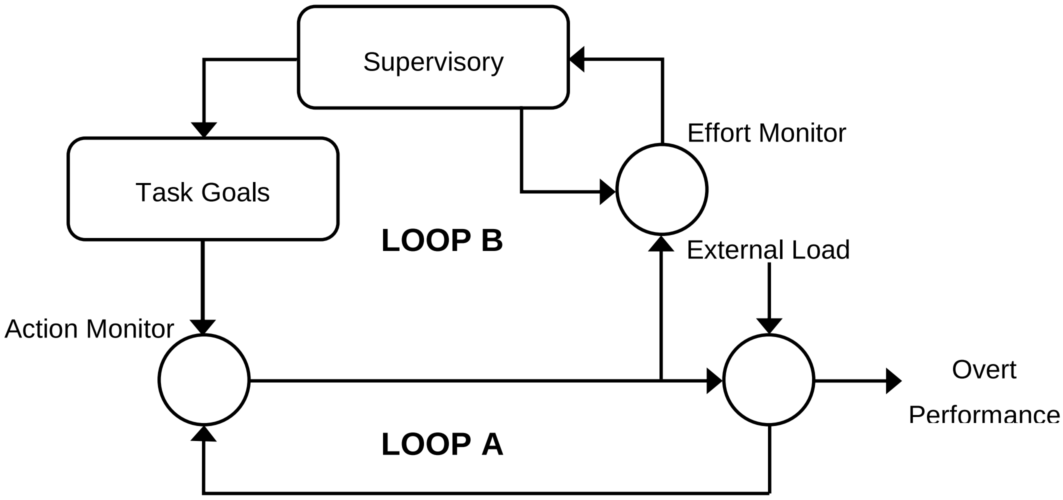


Figure 2.19 The compensatory control model of performance regulation. Loop A represents routine regulatory activity and Loop B represents effort-based control (Hockey, 1997)

An important consideration of the two stage compensatory control model is that the system requires two separate levels of effort, both lower and upper set-points. The lower set-point is based on the demands and characteristics of the task and the skill level of the individual. Increases in demands below this level are not effortful (no additional workload) and control of performance appears automatic (Hockey, 1997). The upper set-point is determined by the capacity of the individual to meet the additional demands associated with stressful environments.

2.3.4 Modeling the Effects of Vibration on Activity Interference

This section describes three examples of different approaches to modeling the effects of vibration on manual control performance. These approaches differ in the aims, the form of the models and the generality of application for each model.

2.3.4.1 Taxonomic Descriptive Model

The taxonomic model illustrated in Figure 2.20 was proposed by Lewis and Griffin (1976) to describe the processes which contribute to performance in a vibration environment. The prinicpal behind the model was that if the effects of vibration on isolated component processes could be determined; then the gross effects of vibration on a particular task could be predicted by determining the contributions of the component processes to the performance of the task.

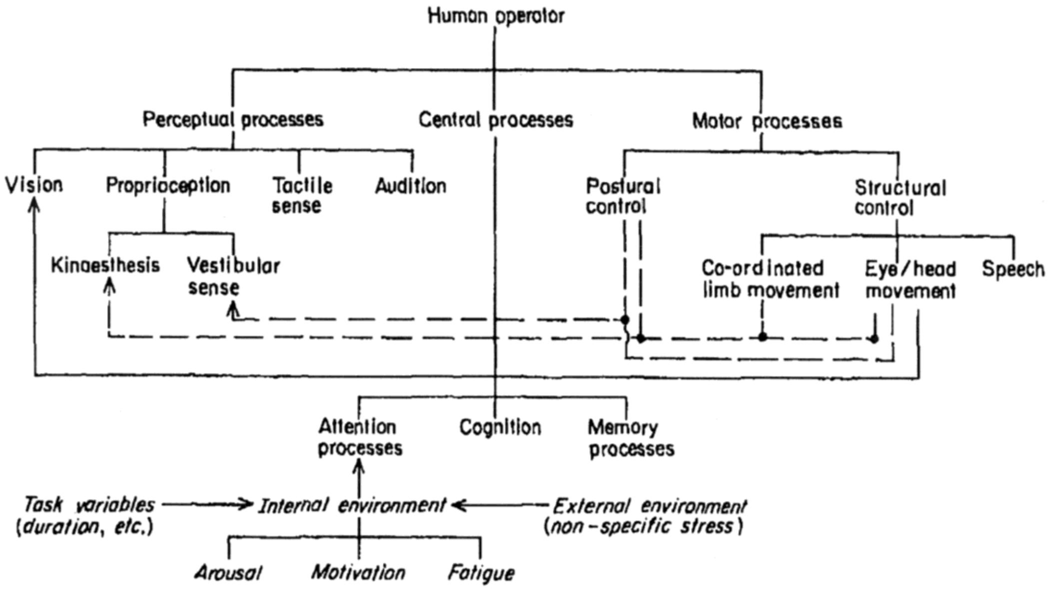


Figure 2.20 A taxonomic model of human operator processes contributing to performance with vibration (dashed lines = fundamental feedback pathways and solid lines = interactive effects; Lewis and Griffin, 1976)

Various shortcomings associated with this model meant it has not be used as a rigorous predictor of control performance in a quantitative sense. Firstly, the relationships between the diffierent processes within the model are not well understood and there is not a clear distinction between perceptual and central processes. Additionally, there is little indication of the manner in which the effects of vibration on component processes might combine to affect overall task performance (Lewis and Griffin, 1976). The model does however, serve to identify specific areas in which knowledge needs to be improved, as well as providing direction for future research (Lewis and Griffin, 1978).

2.3.4.2 Biomechanical Approach Model

Biomechanical models of individual parts of the human-machine system have been used to investigate the effects of vibration on manual control and develop further understanding on the mechanisms associated with these effects. These models have commonly taken the form of mathematic or mechanical representations and may be relatively simple (for example, Figure 2.14) or more complex in design (such as, Figure 2.21). The model illustrated in Figure 2.21 uses combinations of masses, springs and dampers to represent different components of the human-machine interaction (HMI), which would ideally perform similarly to the actual processes of the human operator (Lewis and Griffin, 1978). Masses are used to represent the segments of the body, while springs and dampers represent the biomechanical response (apparent mass) of the human body to vibration exposure (Subashi *et al.,* 2008).

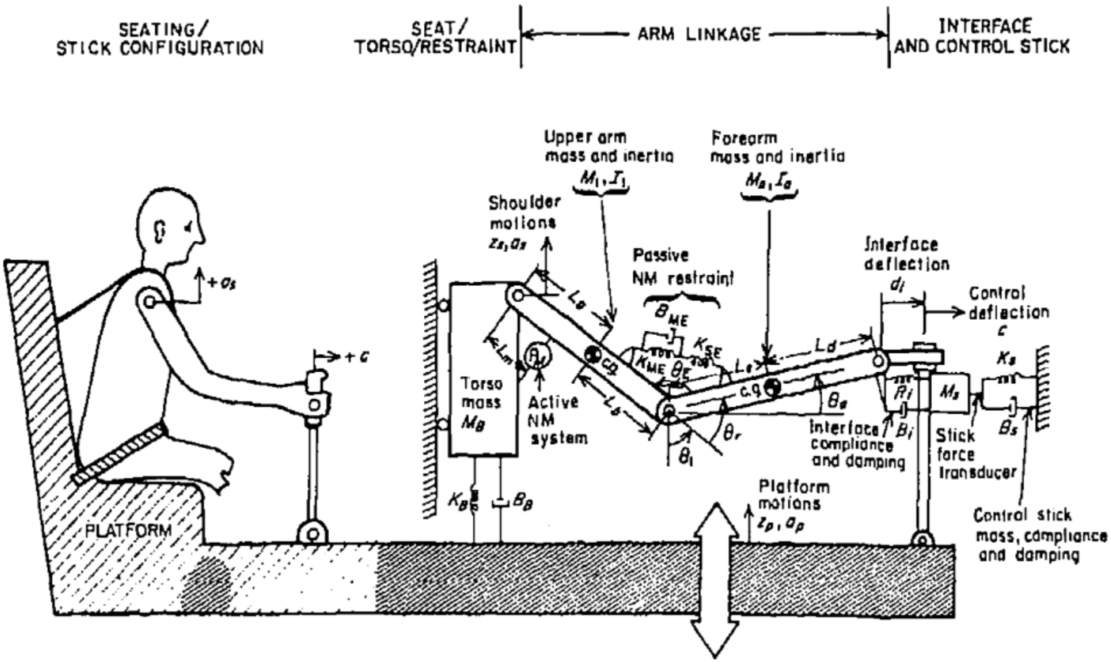


Figure 2.21 Biomechanical model of the torso, arm and stick linkage, illustrating the effects of vertical vibration on pitch control (Lewis and Griffin, 1978)

These models are extremely detailed in the description of both active and passive mechanisms affecting the relative motion between the body and the immediate environment (such as, displays and control devices). Such detail can be useful in identifying the location of vibration effects and describing mechanisms such as, vibration breakthrough, which occurs at the linkage (mechanical coupling) between the operator and the control device (Lewis and Griffin, 1978). The high level of detail however, also represents one of the limitations of biomechanical models. In order to evaluate even a relatively simple system, substantial quantitative data must first be obtained for numerous different parameters. Furthermore, many of these models tend to be very situation-specific as the complexity of the model tends to be proportional to the generality of its application.

Nonetheless, these factors should not detract from the contributions made by these biomechanical models - the models are complex because the nature of the system and the effects of vibration on the human body are complex (Lewis and Griffin, 1978). In order to improve the application of such models, further understanding must be gained on the mechanisms by which vibration interferes with task performance and the methods used by humans to adapt to such disturbances.

2.3.4.3 Behavioural Model

McLeod and Griffin (1989) proposed a ‘behavioural model’ to firstly, describe the processes involved in manual control performance and secondly, to emphasize the principal mechanisms by which vibration could result in performance interference (Figure 2.22). The three stages of information processing presented in the behavioural model show a similarity to those described in the ‘trinity of stress’ by Hancock and Warm (1989). There is an input (visual processing) stage, during which the individual obtains information from the surrounding environment. There is also a sensory role for the vestibular (inner ear) system which is sensitive to movements of the head. The second phase is a cognitive processing stage, during which time the individual uses the perceived information to select appropriate response based on the instantaneous state of the system and the performance strategy adopted. The strategy will depend on the task performance criteria and the cognitive state of the individual (for example, motivation). The final process is the output (muscular activation) stage, responsible for the movements of the body and the controlling hand in order to perform the required task (McLeod and Griffin, 1989).

Vibration has been assumed to interact directly with the behavioural model at two points: it could produce motions at the head or, it could result in movements of the controlling hand (McLeod and Griffin, 1989). The transmission of vibration through the body will determine the extent of direct interference at the head or the hand. Additional factors such as vibration frequency and direction, as well as the posture adopted and the use of supports will also contribute to the effects of vibration on manual control performance. .

Based on the three stages of information processing outlined in the behavioural model and the trinity of stress (Hancock and Warm, 1989), the four principal mechanisms described by McLeod and Griffin (1989) in the behavioural model are illustrated in Figure 2.22.

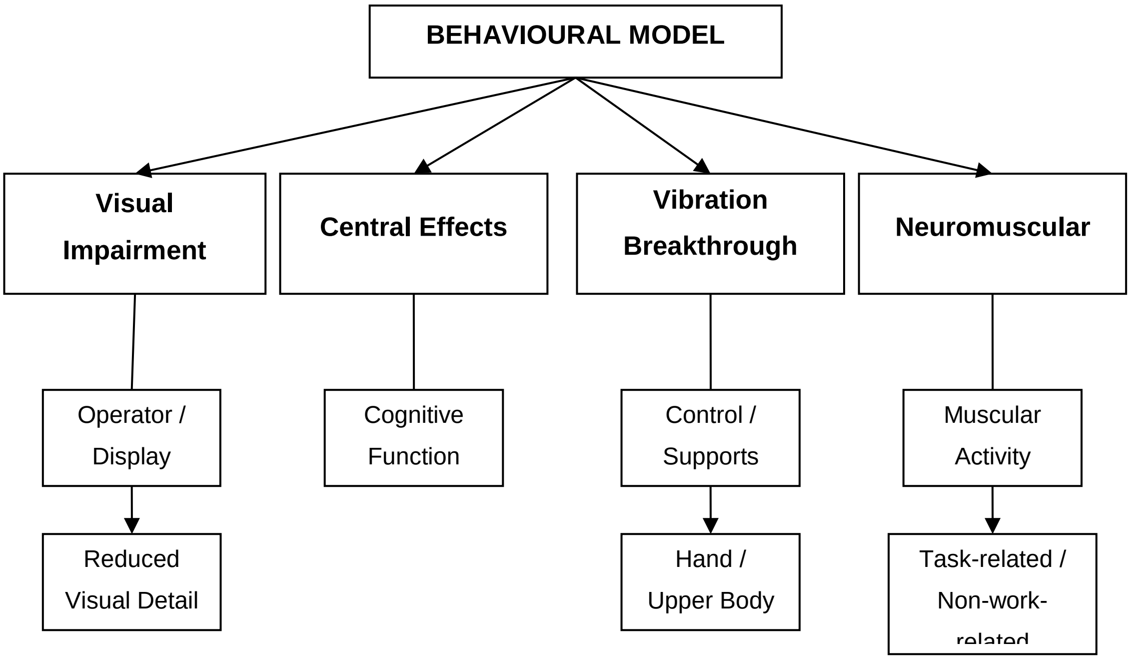


Figure 2.22 Mechanisms associated with vibration-induced activity interference (based on the 'Behavioural Model', McLeod and Griffin, 1989)

2.3.4.3.1 Visual Impairment

Vibration-induced movement (either from vibration transmitted to the head of the operator or vibration of the display) between the eyes and the display can cause the image of the display elements to move over the retina and thereby impair the ability to resolve visual detail. The displacement of an image on the retina is inversely proportional to the viewing distance (McLeod, 1986). When operating mobile devices, Holleis *et al.* (2007) found that individuals tended to shift visual focus between the device and the surroundings. For manual control tasks that require a target area to be selected on a control device (for example, selecting buttons on a keypad device) while attending to cues from the environment (for example, a train), variations in viewing distance when shifting focus could further influence with performance. Such visual impairment could however, be reduced by compensatory eye movements at frequencies up to 10Hz (Wells, 1983). This could explain some of the differences found between reading and writing tasks (Corbridge and Griffin, 1991 and Griffin and Hayward, 1994).

2.3.4.3.2 Central Effects

It has been suggested that vibration could directly interfere with cognitive processes affecting levels of arousal and motivation (McLeod and Griffin, 1989). Changes to these central factors could lead to changes in performance in a number of ways, for example: individuals may increase or decrease the effort (workload) that is exerted in performing a task. Individuals may choose to alter the performance strategy adopted and lower the criteria for acceptable performance, or vibration could act as a distraction, drawing attention away from the primary task (for example, the need to maintain stability in a moving environment would require additional cognitive effort). Limited experimental evidence has meant the precise effects of these central processes have been difficult to define (McLeod, 1986). In some cases changes in arousal could produce improvements in performance during vibration exposure, particularly at low magnitudes of exposure. Comparing the reaction times during a lane change task (LCT) in static and vibration conditions, Appan (2009) reported no significant influence on reaction times when participants were exposed to vibration. Based on the maximum adaptability model (Section 2.3.3) this could suggest that vibration exposure provided an optimum level of cognitive arousal to maintain task performance. Further increases in magnitude however, would likely result in a decrease in performance as the capacity for adaptation progressively failed.

2.3.4.3.3 Vibration Breakthrough

When there is mechanical coupling between the control and the vibrating structure, vibration could be transmitted through the body from the vibrating structure (for example, the floor or seats) leading to vibration-induced motion at the hand. For continuous, tracking tasks, vibration at the control may produce movements on the display (errors in performance) at the frequency of vibration. This has been termed ‘vibration breakthrough’ (McLeod and Griffin, 1989). The magnitude of vibration breakthrough on the display depends on the sensitivity of the control and the system dynamics at the vibration frequency.

For tasks where there is no mechanical coupling between the device and the hand (for example, discrete control tasks), vibrations of the device would not be transmitted to the hand. The separate movements of the hand and the devices however, would increase the relative motion of the hand and directly influence performance, as the ability to accurately select the target area (for example, selecting a specific button) would be compromised. This becomes increasingly important for modern devices, such as smartphones, when the reduced size and increasing number of targets is considered.

2.3.4.3.4 Neuromuscular Interference

Exposure to vibration could interfere with the neuro-muscular processes in the body by reducing the signal-to-noise ratio between intentional activity (which is required to perform the task) and random, non-work related activity (such as, motions of the hand caused by vibration breakthrough). This could lead to perceptual confusion about the forces being generated in the controlling limb. Generally, these effects have been associated with frequencies above 10Hz (Ribot *et al.*, 1986) however McLeod and Griffin (1989) attributed increased control activity during vibration exposure at frequencies of 0.5 and 4Hz, to an increase in neuro-muscular 'noise'. This type of interference would affect both continuous and discrete/serial manual control tasks as each requires precise muscular activity to perform.

2.4 SUMMARY

The majority of whole-body vibration (WBV) exposures occur in seated postures however, there are a number of environments (for example, travelling on trains) where individuals may experience vibration while standing. The vibration to which passengers are exposed has been identified as a source of physical stress and a main contributing factor to activity interference for rail passengers (Narayanamoorthy *et al.,* 2008a).

Within the current standards concerned with the measurement and assessment of whole-body vibration (ISO2631-1 (1997)), no consideration is given to activity interference in standing postures. The standards provide guidance on the biomechanical response (apparent mass and transmissibility) of the standing human body during WBV exposure; however, the majority of these are free-standing postures. In reality, standing individuals exposed to vibration would use supports such as grab rails or walls, to main postural stability. Further research is required to improve the current state of knowledge regarding the influencing factors on the response of standing individuals to vibration.

The majority of studies that have investigated activity interference during vibration exposure have historically assessed discrete or continuous manual control tasks. With rapid technological developments, serial control tasks performed on hand held devices are likely to emerge. Relatively few studies have assessed task performance using hand held devices and none of these considered standing exposure to vibration. Through studies with seated postures, it has been well established that increases in WBV magnitude typically result in degraded task performance and increased subjective workloads. The extent of this activity interference often depends on the characteristics of the vibration, the type of task being performed and the characteristics of the individual. Decrements to performance tend to occur at frequencies that correspond to those at which the body is most sensitive and where the biomechanical response is therefore greatest.

CHAPTER 3

EQUIPMENT AND ANALYSIS

3.1 INTRODUCTION

One field study and four laboratory studies were conducted for this thesis, the results and analysis of which are reported in five chapters. This chapter provides an outline of the experimental design, the principal equipment used, test configurations, calibration and analysis methods. Figure 3.1 provides an introduction to the studies included in this thesis. Further details relating to equipment and analysis techniques specific to each study are provided in the relevant experimental chapters.

3.2 EXPERIMENTAL DESIGN

The studies were designed so that, where possible, the results and conclusions from one study would inform the design of the next. All experimental studies were conducted in the UK, apart from the study presented in Chapter 6, which was conducted in Tokyo, Japan.

The passenger behaviours observed in the field study (Chapter 4) were used to identify postural conditions for laboratory studies in Chapters 5, 7 and 8. In Chapter 6 the experimental conditions included seated postures. These were included to investigate full-body postural variations during vibration exposure and enabled a direct comparison to be made between seated and standing postures. The magnitudes and frequency ranges of vibration exposure obtained during the field study were used to determine the exposure levels in the laboratory studies. In Chapter 5, the vibration conditions included magnitudes which included the peak values recorded in the field study. Based on the performance and stability results obtained in Chapter 5, it was decided to delimit the magnitude of vibration exposure (below 1.5ms^{-2}r.m.s.). This allowed additional postural conditions to be included within Chapters 7 and 8 without increasing the duration of exposure for the participants.

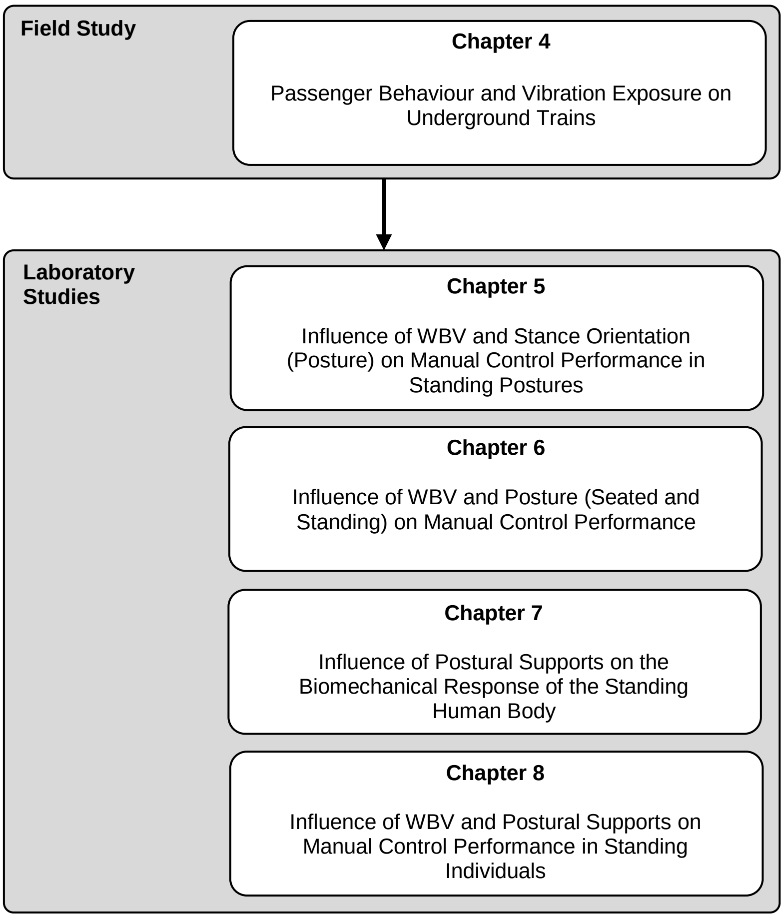


Figure 3.1 Outline of the of experimental studies presented within this thesis

3.3 ETHICAL APPROVAL

Ethical approval for the experimental conditions was obtained from the Loughborough University Ethical Advisory Committee prior to commencing each study. The field study adhered to generic protocols G02-P1 (Quantification of vibration exposure of vehicle occupants) and G07-P3 (Discrete observation of members of the general public whilst in public spaces in order to identify real design needs); while the laboratory studies followed generic protocols G05-P1 (Use of a multi-axis vibration simulator) and G04-P3 (Subjective and objective measures of human response to whole-body vibration). Additional ethical clearance was granted by the Research and Ethics Committee of the National Institute of Industrial Health (National Institute of Occupational Safety and Health, Japan). The experimental procedures conformed to the guidelines in ISO13090-1 (1998).

3.4 PARTICIPANTS

General participant information (such as, age and gender) was collected on commencement of each study, as well as additional anthropometric data including stature (m) and mass (kg). Stature was measured using a free standing stadiometer and mass using an electronic scale (Mettler Toledo KCC150). This allowed body mass index (BMI) to be calculated using the standard formula, presented in Equation 3.1.

$$BMI = \frac{M}{H^2} \qquad \text{Equation 3.1}$$

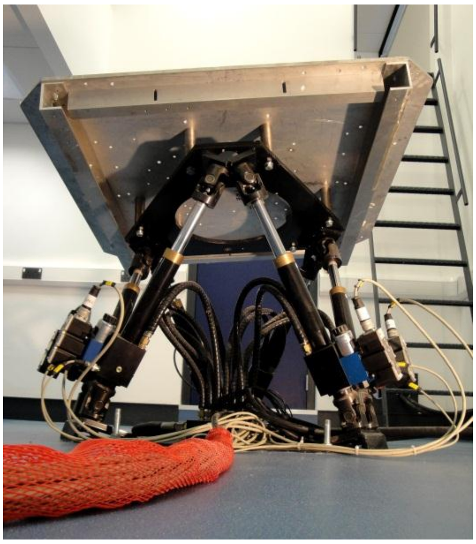
Where *M*, is the mass of the individual (kg) and *H*, is the height (m)

3.5 VIBRATION MEASUREMENT SYSTEMS

3.5.1 Multi-Axis Vibration Simulators

The primary system used to generate vibration (Chapters 5, 7 and 8) was a Rexroth Hydraudyne B. V. Micro Motion six-axis vibration simulator (600-6-DOF-200-MK5), situated in the Environmental Ergonomics Research Centre, Loughborough University (Figure 3.2). The system was capable of producing motion in the frequency range of 1 – 25Hz, driven by six hydraulic rams mounted in a 'Stewart Platform' configuration and had a maximum payload of 600kg (including the mass of the simulator platform). Peak- to-peak displacement in the fore-and-aft (x-axis) and lateral (y-axis) is ±0.15m and ±0.09m in the vertical direction (z-axis). The peak-to-peak angle for pitch and roll motions is ±17° and for yaw motion is ±27°. During single-axis sinusoidal motion, the distortion was specified at less than 10% displacement and cross talk between axes was also less than 10%.

The second motion system, shown in Figure 3.2, was an IMV multi-axis simulator (IMV Corp. Ltd.) used in Chapter 6. The system was based in the Human Engineering and Risk Management Research Group laboratory at the National Institute of Occupational Safety and Health, Japan (JNIOSH). Driven by seven electrodynamic rams (one in the fore-and-aft direction, two in the lateral direction and four in the vertical direction) the system was capable of producing motion within the frequency range 0.13 – 50Hz, with a maximum acceleration of 3.5ms^{-2}(peak). The simulator had low cross-talk between axes (less than 5%). The working platform surface measured 1.5m × 1.0m and had a mass of 500kg. An additional maximum payload of 200kg could be supported by the system.



Multi-Axis Vibration Simulator (Loughborough University, UK)

IMV Multi-Axis Vibration Simulator (JNIOSH, Japan)

Figure 3.2 The vibration simulator systems used at Loughborough University (UK) and JNIOSH (Japan)

3.5.1.1 Safety and Normal Operating Procedures

Experiments conducted on the vibration simulator were in accordance with ISO13090-1 (1998) 'Mechanical Vibration and Shock – Guidance on safety aspects of tests and experiments with people'. Safety barriers were set around the simulator to avoid any possible contact by personnel with the motion base or any parts fixed to the motion platform. Emergency stop buttons were clearly visible and within reach of the researcher at all times. A mechanical end-stop system has been built into the actuators to avoid end-stop shocks. In the event of a power failure, additional accumulators added to hydraulic system dampen motion during depressurisation.

In the case of non-emergency situations, the system would be brought to a 'settled' position without the use of the emergency button.

Normal operating procedures included:

- Participant fitted with safety harness, shown standing position on simulator platform and harness secured to support frame.
- The area around platform was closed to personnel with safety barrier.
- Simulator system was pressurised using the dedicated laboratory computer.
- Platform set to a 'neutral' position (0.15m above 'settled' position).
- System engaged – vibration magnitude monitored during vibration exposure on computer (Shake 1).

- Simulator platform set to ‘settled’ position and depressurised.
- Participant then allowed to dismount from the platform.

3.5.2 Accelerometers and Force Platform

Acceleration was measured using a tri-axial S2-10G-MF (Biometrics Ltd, UK) piezo-resistive accelerometer. The specifications for this type of accelerometer are provided in Table 3.1.

Table 3.1 Manufacturer specifications for S2-10G-MF accelerometers (Biometrics, UK).

Parameter	**Specification**
Maximum Range	±10g (98.1ms^{-2}
Sensitivity	±1V/ms^{-2}
Cross-Axis Sensitivity	Less than 5%
Cross Talk	5%
Accuracy	±2% full scale
Operating Environment	0ºC - 70ºC

By means of gravitation forces acting on a seismic mass fitted inside the accelerometer casing; the output for a vertically aligned accelerometer provides a measure of +1g (9.81ms^{-2}) acceleration, and an inverted accelerometer provides a measure of -1g (-9.81ms^{-2}) acceleration (Mansfield, 2005). Using gravity as a known acceleration source, the accelerometer was calibrated prior to and after the experiment using this ‘inversion’ procedure.

Force at the floor (used for calculations of biomechanical response) was measured using a Kistler 9286AA force plate. For the apparent mass calculations, the influence of the mass of the force plate was removed using a mass cancellation technique.

3.5.2.1 Validation of Equipment

In order to ensure there was agreement between the accelerometers used to record vibration, a validation study was carried out by performing an ‘inversion’ test. The accelerometers were fixed together in the same alignment and inclined vertically on a horizontal surface. The accelerometers were turned through 180° after 10s, and then returned to the original orientation after a further 10s. A recorded time history from both accelerometers has been shown in Figure 3.3.

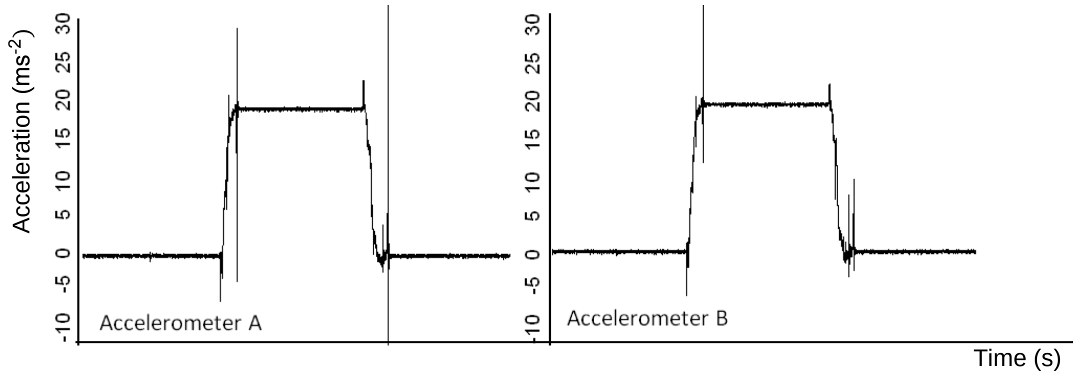


Figure 3.3 Examples of calibration time histories for two accelerometers mounted together and inverted through 180°

The accelerometers were secured to the vibrating surfaces using bees wax as an adhesive. This method was validated in by comparing the vibration outputs obtained from two accelerometers attached to the vibration simulator platform (Figure 3.4).

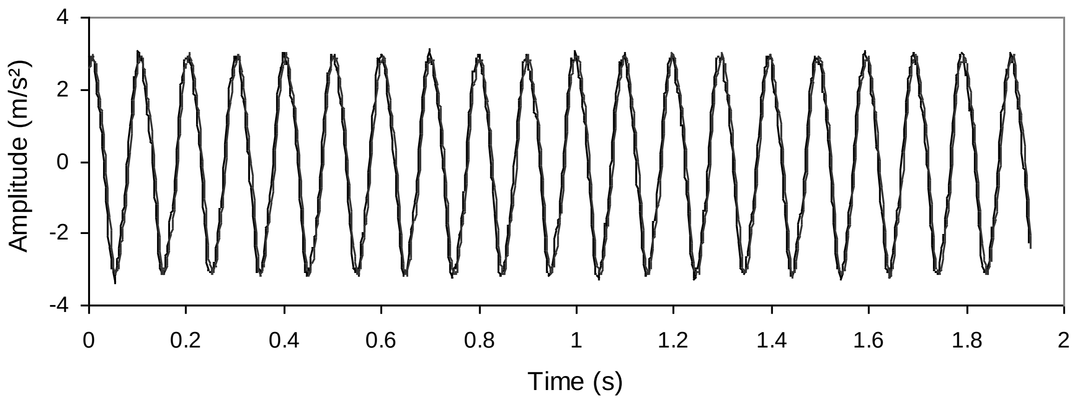


Figure 3.4 Example outputs from two accelerometers mounted on a shaker with an excitation of 10Hz

3.5.3 Data Acquisition

In the Environmental Ergonomics Research Centre (Loughborough University, UK) vibration data was acquired using a multi-channel data acquisition system. The simulator is operated by a dedicated computer with no network access or additional software. Eight additional accelerometers mounted on the simulator platform, provided acceleration data that was monitored using in-house LabView software on a separate laboratory computer (Shake 1); another computer (Shake 2) was used to acquire additional force and acceleration data (Chapter 7). Additional programs necessary to operate the driving simulator software (Chapter 5) and LabVIEW software used to acquire numerical input signals (Chapters 6 and 8) were run on a personal laptop computer.

At JNIOSH (Kawasaki, Japan) the vibration input was controlled by a trained researcher using a multi-channel data acquisition system (Pulse Version 8).

During the field measurements, a data acquisition system in the form of a stand-alone data logger (DataLOG, P3X8 v2.11, Biometrics Ltd, UK) enabled discrete waveforms (obtained from the accelerometer) to be stored for subsequent analysis on a laboratory computer (Figure 3.5).

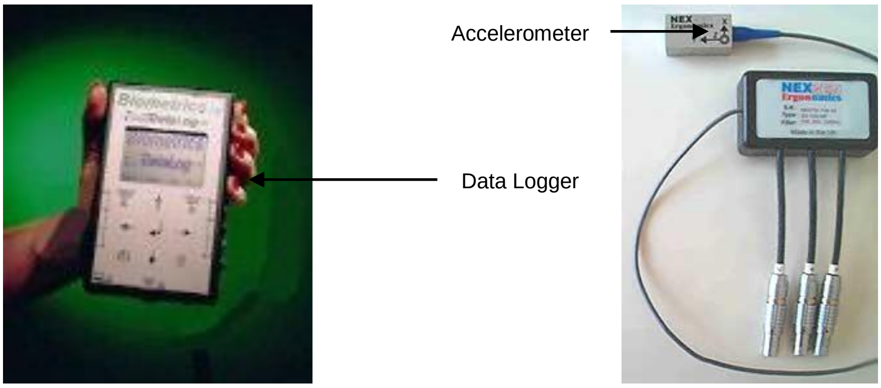


Figure 3.5 Data logger and accelerometer used for vibration measurement in the field

The system was fitted with low-pass, 'anti-aliasing' filters set at 100Hz and a sample rate of 1000Hz was selected to ensure the characteristics of the signal were retained. The sample rate would ideally be 1024Hz, as this would provide a convenient resolution to be selected when analysing the frequency domain, however, the Biometrics systems did not allow for selection of such a sampling rate.

3.5.4 Data Analysis

Signal processing was conducted using the Vibration Analysis ToolSet (VATS v7.5) software (NexGen Ergonomics, Canada), which is compliant with ISO8041 (2005). Frequency weightings were applied to the data in accordance with ISO2631-1 (1997). These weightings account for variations in the sensitivity of the body at different frequencies and provide a model of the response of the human body to vibration (Mansfield, 2005). The weighting factors used were: W_d (frequency range 0.5 – 80Hz) for horizontal directions (x- and y-axis) and W_k (frequency range (0.5 – 80Hz) for the vertical direction (z-axis). In some environments (such as rail vehicles), the W_b weighting factor could also be considered for vertical motions. Generally, the W_k weighting has been shown to produce higher values for the weighted acceleration than the W_b weighting due to deviations between the curves: below 3Hz (where W_k is higher than W_b) and above 12Hz (where W_k is lower than W_b). Based on the extensive use of the W_k weighting by ISO2631 (1997) and the EU

Physical Agents Directive (2002); the W_k weighting factor was accepted as an appropriate weighting factor.

The principal method used for evaluating exposure to WBV, prescribed by ISO2631 (1997), was the frequency-weighted root mean square (r.m.s.). No additional multiplication factors were applied to the acceleration data. The mathematical equation for r.m.s. is presented in Equation 3.1.

$$a_{w\,r.m.s.} = \sqrt{\frac{1}{T}\int_0^T a_w^2\,(t)dt} \qquad \text{Equation 3.2}$$

where $a_{w\,r.m.s}$. is the frequency-weighted r.m.s. acceleration, T is the measurement duration and $a_w(t)$ is the frequency-weighted acceleration at time, t.

3.5.5 Measurement of Biomechanical Response

Measures of the dynamic responses of a system are represented by transfer functions. A transfer function of a mechanical system is defined as the ratio of an input signal to an output signal as a function of frequency, where the input and output signals may be acceleration, velocity, displacement or force (Griffin, 1990). These input and output signals can either occur at the same location (the point of contact with the vibrating structure) or at different locations on the structure (remote from the point of contact).

Transfer functions over a given frequency range can be calculated using random excitation and transferring the input and output signals into the frequency domain using a Fourier transform (Fahy and Walker, 1998). The transfer function, *H(f)*, can then be given by (Equation3.3):

$$H(f) = \frac{\mathrm{Y(f)}}{\mathrm{X(f)}} \qquad \text{Equation 3.3}$$

where *f* is the frequency, and *X(f)* and *Y(f)* are the inputs and outputs, respectively. In practice, noise will be found on the input and output signals which results in some inaccuracy in the calculation of the transfer function according to Equation 3.3. The effect of this noise can be minimised by using alternative transfer functions based on the cross spectra and power spectra of the input and output.

The cross-spectral density (CSD) method calculates the transfer function as:

$$H(f) = \frac{S_{XY}(\mathrm{f})}{S_{XX}(\mathrm{f})}$$ Equation 3.4

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

$$H(f) = \frac{S_{YY}(\mathrm{f})}{S_{XX}(\mathrm{f})}$$ Equation 3.5

where $S_{YY}(f)$ is the power-spectral density of the output. The CSD method calculates the transfer function between the input and the part of the output that is linearly related to the output. The PSD method calculates the transfer function between the input and output including all 'noise' between the input and output. If there is no noise in the system then the two methods would yield identical transfer functions; however, when noise is present in the system the modulus of the transfer function calculated using the CSD method will be lower. An advantage of using the CSD method is that it ensures the two signals correlated to one another – this reduces the influence of noise (improved accuracy) and also generates the phase difference between the signals (Griffin, 1990).

3.5.5.1 Standing Apparent Mass

Apparent mass frequency response functions (i.e. the ratio of the force to the acceleration as a function of vibration frequency) have previously been used to represent the general dynamic response of the body at the driving-point of vibration (Matsumoto and Griffin, 2000). The apparent mass was calculated by dividing the cross-spectral density (CSD) function between the driving point acceleration at the floor and the resulting force at the driving point, by the power spectral density function of the driving-point acceleration (Equation 3.6). A resolution of 0.25Hz was used for the calculation of spectra.

$$M_m(f) = \frac{CSD_{Force-Acceleration}(\mathrm{f})}{PSD_{Aceleration}(\mathrm{f})}$$ Equation 3.6

where *Mm* is the measured apparent mass, *CSD(f)* is the cross-spectral density between the acceleration and the force and *PSD(f)* if the power-spectral density of the acceleration. The mass of the force plate and equipment should be removed from the calculated response to obtain the apparent mass for an individual. In order to do this, a 'mass cancellation' technique was used (Equation 3.7).

$$M(f) = M_m(\mathrm{f}) - M_e(\mathrm{f}) \qquad \text{Equation 3.7}$$

where the apparent mass of the equipment (measured without a participant), $M_e(f)$, was subtracted from the measured apparent mass with a participant, $M_m(f)$, to give the true apparent mass, $M(f)$:

3.5.5.2 Floor-to-Hand Transmissibility

Transmissibility represents the ratio between motions a point of contact with the vibrating structure (for example, the floor) and a remote location (for example, the hand). Simialr to the apparent mass calculations, transmissibility can be calculated using the CSD or PSD methods discussed in Section 3.7.3.1 and the CSD method was selected in order to minimise the effects of noise (Equation 3.8).

$$T(f) = \frac{CSD_{Floor-Hand}(\mathrm{f})}{PSD_{Floor}(\mathrm{f})} \qquad \text{Equation 3.8}$$

where $T(f)$ is the transmissibility, $CSD(f)$ is the cross-spectral density between the floor and hand acceleration and $PSD(f)$ is the power-spectral density of the floor acceleration.

3.6 STATISTICAL ANALYSIS

A variety of statistical methods were used to determine whether there were significant differences between conditions. An overview of the statistical methods used in the experiments is provided in Table 3.2. Parametric methods were used for analysis of objective performance and subjective workload and non-parametric methods were used for statistical analysis of apparent mass and floor-to-hand transmissibility.

Before the parametric tests were used the assumptions of normality were met. The statistical analyses were then used to test for any significant effects between control (no vibration) conditions and vibration exposure conditions, and between different postures. A repeated measures analysis of variance (ANOVA), followed by a Tukey *post-hoc* test, was used to determine the exact nature of the significance between the individual conditions. Statistical significance was accepted at the 5% confidence level ($p < 0.05$).

A Friedman test was used to evaluate differences between the posture conditions and follow-up pairwise comparisons were conducted using a Wilcoxon test (a Bonferroni correction was used to control for Type I errors). Non-parametric tests were used in Chapter 7 due to the use of median values as a measure of central tendency. Median values have typically been reported in previous studies that have investigated the biomechanical response of the body to vibration (for example, Matsumoto and Griffin, 2000).

Table 3.2 Parametric and non-parametric methods used for statistical analysis

Experiment (Chapter)	**Independent variables (factors)**	**Levels of Factors**	**Dependent variables**	**Statistical Method**
Study 1 (Chapter 5)	Vibration	1. Magnitude (2/3) 2. Direction (3)	1. Performance 2. Workload	Repeated measures analysis of variance (ANOVA)
	Posture	1. Foot orientation (2)		
Study 2 (Chapter 6)	Vibration	1. Magnitude (2) 2. Direction (3) 3. Frequency (4)	1. Performance 2. Workload	Repeated measures ANOVA
	Posture	1. Seated 2. Standing		
Study 3 (Chapter 7)	Vibration	1. Magnitude (1) 2. Direction (3)	1. Apparent mass 2. Transmissibility	Friedman
	Posture	1. Supports (6)		Wilcoxon
Study 4 (Chapter 8)	Vibration	1. Magnitude (2)	1. Performance 2. Workload	Repeated measures ANOVA
	Posture	1. Supports (7)		

CHAPTER 4

FIELD OBSERVATIONS OF PASSENGER BEHAVIOUR AND VIBRATION EXPOSURE ON PUBLIC TRANSPORT

This chapter presents a field based study conducted on underground trains. The study consisted of observations of standing passengers and measurements of vibration exposure at the floor surface. Anecdotal evidence suggests that a growing number of passengers stand while travelling by rail; therefore the aims of the field study were to describe contextual interactions between standing passengers and the environment. In particular the use of travel time was observed as well as the support strategies used to maintain stability. Furthermore, measurements were taken to quantify the vibration at the floor to which passengers would be exposed on various trains.

4.1 INTRODUCTION

Historically, travel time has generally been considered a wasteful period, often associated with negative valuations it has represented a ‘means-to-an-end’ in order to engage in activities at destinations. Savings in travel time during a working day have therefore been assumed to signify a conversion of unproductive time to economically valuable time (Ohmori and Harata, 2008). Despite the considerable amount of work conducted on travel statistics within the UK, urban short journeys in environments of extreme mobility (for example, underground trains in London), remain an area that has been particularly neglected.

Rather than uniformly trying to minimise travel time, it has been proposed that people would aim to find a balance between travel time and activities (Mokhtarian and Salomon, 2001), leading to the opinion that travel times could be viewed as a positive aspect (Lyons *et al.*, 2007). Rail transport in particular has been found to provide passengers with the opportunity to multi-task and engage in meaningful activities (Tillema *et al.*, 2009). Indeed, in a society that exhibits an increasing dependence on mobile technology coupled with the expectation of continuous availability and responsiveness, many rail passengers chose to utilise this travel time for work.

The combination of rapid technological development and miniaturisation of communication and electronic equipment, such as smart-phones, laptop and tablet computers, has provided people with the ability to work in innovative ways while travelling (Ohmori and Harata, 2008 and Lyons and Urry, 2005). These changes have facilitated a separation of activities away from specifically designed work spaces, presenting both users and ergonomists with a unique set of difficulties.

Results obtained through subject interviews during an exploratory study (Sarker and Wells, 2003), revealed a 'background context' existed, which influenced the use of mobile technology. Originally, this background context consisted of economic aspects that often determined the type of device available for an individual to use; as well as social factors that referred to the expectation of availability and the desire to remain engaged during free time. Factors that were not mentioned in the description of this background context related to the physical environment in which these devices were used. In addressing these factors, Constantiou (2009) referred to the physical environment as the 'local context'.

Considering rail transportation as the local context, issues such as vibration exposure and body posture could lead to activity interference and influence the adoption of mobile technology while travelling. Despite the extent to which technology has become part of daily life, manufacturers continue to produce mobile devices based on the conceptions of designers, as opposed to what a generalised user might need or desire (Sarker and Wells, 2003). Understanding the contextual issues that influence the use of mobile technologies while travelling, could provide human interface device (HID) professionals and designers with constructive information for future developments.

4.2 RESEARCH OBJECTIVES

This chapter presents a field study designed to provide context-specific, covert observations of standing rail passengers and practical measurements of vibration exposure during rail travel. Specifically, three categories were selected for inclusion in the observations of standing passengers, namely:

i) Type of devices used
ii) Type of support strategies adopted
iii) Stance orientation

4.3 METHODS

4.3.1 Context

Public underground rail transport systems were selected as the environment in which to conduct the study. This selection was based on two factors; firstly, the high number of passengers that utilise this means of transportation. In 2005/2006, underground rail systems accounted for approximately 44% of all train journeys made in the UK, representing an annual usage of over 1 billion passengers (DfT, 2006). Secondly, a study by Sarker and Wells (2003) suggested that individuals were more likely to utilise mobile technologies during relatively short journeys (less than 45mins) compared to passengers on longer journeys. The relatively short distances travelled on underground trains combined with the high passenger numbers therefore provided the greatest opportunity to conduct observations on passengers performing activities while standing.

4.3.2 Participants

Participants were not actively recruited for the study but were selected for inclusion based on pre-defined criteria; delimited to include standing passengers performing any manual control task utilising a mobile, hand-held device (for example, using a mobile phone), while travelling on public rail transport. Covert observations were conducted to ensure the participants remained unaware of the observations taking place. Haynes and Horn (1982) found that the behaviour of individuals may be affected in response to the presence of an observer and this has since been termed ‘reactivity’. When such reactivity occurs, the validity of a study would be weakened as the effects from reactivity would not have been separated from any environmental influences. Additionally, the extent to which the findings could be generalised to different populations and environments may also be compromised. In order to minimise such effects, participants remained unaware of the observations taking place.

4.3.3 Ethical Considerations

Ethical clearance for the study was granted by the Loughborough University Ethical Advisory Committee (Section 3.3 Ethical Approval).

4.3.4 Pilot Testing

To gain sufficient proficiency in conducting discrete observations, the researcher attended a training session and completed a video-based practice exercise prior to using the technique in a public setting. An observation worksheet was developed to record the specific body postures, support strategies and tasks adopted by passengers travelling on public rail transport (Appendix A).

Pilot tests were conducted on local trains and buses, as well as underground trains, which afforded the researcher an opportunity to practice covert observation techniques. These sessions also provided information concerning the types of activities performed by passengers and the availability of support strategies while travelling on public transport. This information was combined with previous research documenting the use of travel time by passengers (Lyons and Urry, 2005) and the influence of postural supports on passenger comfort (Thuong and Griffin, 2010) to form part of the overall observation worksheet. Furthermore, pilot testing was used to define the measurement protocols for the field assessment of vibration exposure.

4.3.5 *In Situ* Observation

The researcher worked individually so as not to attract attention and adopted a position within the train carriage that provided a view of the vestibule area where the majority of passengers were standing. Overcrowding during extremely busy travel periods made it difficult to accurately observe passengers and therefore, morning and evening peak travel times between 07h30 – 09h00 and 17h00 – 18h30 respectively were avoided. Observations were conducted between 09h00 – 17h00 in order to minimise overlap with these busy periods. The observations were taken once the train had reached a steady speed. This was to ensure consistency with the vibration measurements that were recorded at the same time.

4.3.6 Vibration Measurement

Measurements were conducted using a data logger system described in Section **Error! Reference source not found.**5.3. Seven different underground train lines within an urban environment were selected and for consistency, vibration measurements were taken in the same location within the carriage for each train.

4.3.7 Data Analysis

A minimum of twelve individual observations were taken on each of the seven train lines selected for the study. In total, eighty-seven (87) observations were completed and the data were categorised in a *Microsoft Excel®2007* spreadsheet. Frequency response graphs were compiled based on categories of results according to the type of task performed, the types of postural supports used and the postures (stance orientation) adopted by passengers.

Vibration measurement files were downloaded from the Biometrics Data Acquisition system and processed using Biometrics software (Section 3.5.4 Data Analysis). The beginning and end of each vibration signal file was cropped to remove any artifact effects caused by placement and removal of the accelerometer.

4.4 RESULTS

4.4.1 Type of Device

To accommodate the wide diversity of devices available for individual use, devices of a similar nature were grouped to represent four overall classifications (Table 4.1). Smart-phones were defined as 'a category of mobile phone that is able to perform many of the functions of a computer, typically having a relatively large screen and an operating system capable of running general-purpose applications' (Oxford Dictionaries, 2010). Feature phones have the capacity to perform basic functions such as access the internet and play music but lack the advanced functionality of smart-phones (Oxford Dictionaries, 2010). Other devices such as gaming consoles or music players were classified as 'Entertainment'. For all devices a certain degree of reading was required, however the 'Read/Write' classification was delimited to include only situations where reading or writing was the primary task performed.

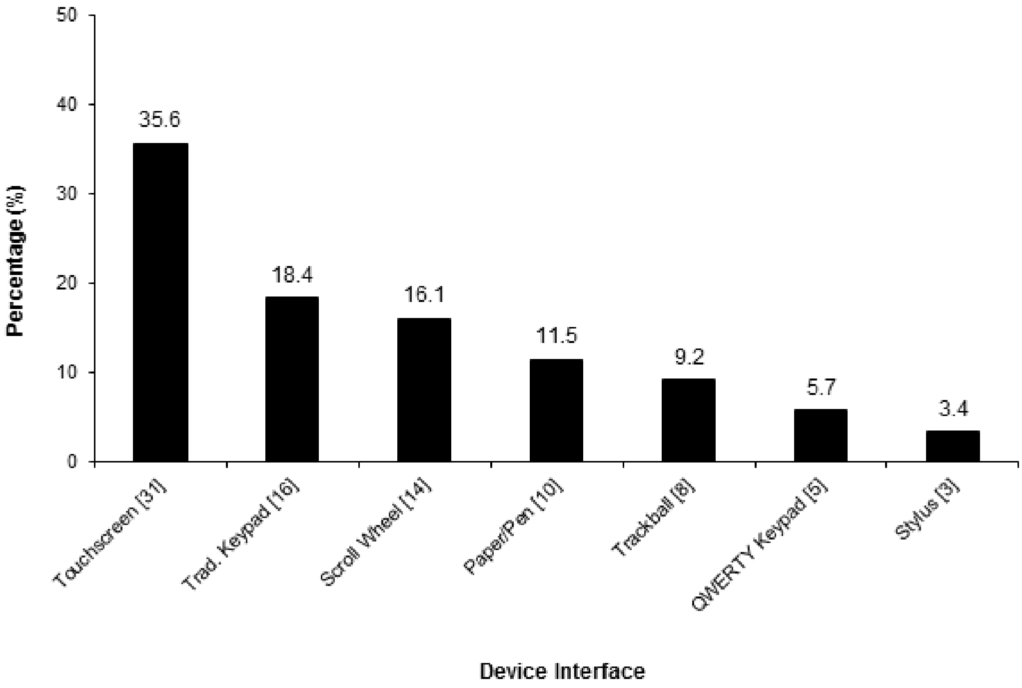
Table 4.1 Classification and prevalence of hand-held devices used by standing passengers travelling on underground trains in London

Classification	**Examples ***	**Prevalence (% observations)**
Smart-Phones	Blackberrys, iPhones, Windows phones and Android phones	**44.8** [39]
Feature Phones	Mobile phones other than 'smart-phones' (eg. Nokia C-series)	**23.0** [20]
Entertainment	iPods, mp3 players, PSPs, Nintendo DSs	**20.7** [18]
Read/Write	Writing, reading a book, newspaper or Kindle®	**11.5** [10]

Where: [ ] indicate the actual number of observations conducted
* = based on data collected in 2009

Figure 4.1 Examples of hand-held device interfaces used by standing passengers travelling on underground trains in London

The prevalence of mobile phone use was substantially higher than other types of devices (Table 4.1), accounting for 44.8% (smart-phones) and 23.0% (feature phones) of the observations. 'Entertainment' devices accounted for 20.7% of the observations of standing rail passengers, while the least commonly observed activities were reading and writing, corresponding to 11.5% of the observations.



Where: [ ] indicate the actual number of observations conducted

Figure 4.2 Type and prevalence of hand-held device interfaces used by standing passengers travelling on underground trains in London

The different types of device interfaces used by standing passengers are illustrated by the examples shown in Figure 4.1. Comparing the type of device interfaces used by standing passengers (Figure 4.2), touch-screens were the most commonly used (35.6%), followed by the traditional (alpha-numeric) keypad (18.4%) and the scroll wheel controls (16.1%). Other types of interface (such as, the 'Trackball', 'QWERTY Keypad' and 'Stylus') were considerably lower. The 'Scroll Wheel' represented the type of interface found on an 'iPod' (Figure 4.1ii), a circular scrolling pad with a central 'select' button (Figure 4.1iii). The 'Paper/Pen' interface represents the 'Read/Write' device classification as no electronic reading devices were used by standing passengers. The 'Trackball' control was used to describe the scrolling interface used on devices such as a Blackberry Pearl® (Figure 4.1iv), and the 'QWERTY Keypad' represented devices where the user interface was primarily a complete tactile keypad, such as a Blackberry Bold® (Figure 4.1v). It should be noted that due to technology developments and ever-changing market trends, the nature of these interfaces would be expected to change in the future. This information has been presented as it provides a contextual basis to the research presented in this thesis.

4.4.2 Support Strategies

Overall, six types of supports were found to be routinely used by passengers when standing (Figure 4.3). Three of these were considered to be 'Body' supports, providing support predominately through the shoulders and torso; while three were 'Hand' supports and provided support by holding onto a grasp rail. The body supports were classified as: i) 'Lean Back' (individual leant backwards against an interior wall on the train, with support from the buttocks to the shoulders), ii) 'Padded Back' (individual leant backwards with buttocks in contact with a padded support) and iii) 'Lean Shoulder' (individual leant sideways against an interior wall, with support on one shoulder). The hand supports were described as: i) 'Vertical Bar (Front)' (individual held onto a vertical rail with one hand and arm extended forwards), ii) 'Vertical Bar (Side)' (individual held onto a vertical rail with one hand and arm extended to the side) and iii) 'Overhead Bar' (individual held, with one hand, onto a horizontal rail positioned overhead).

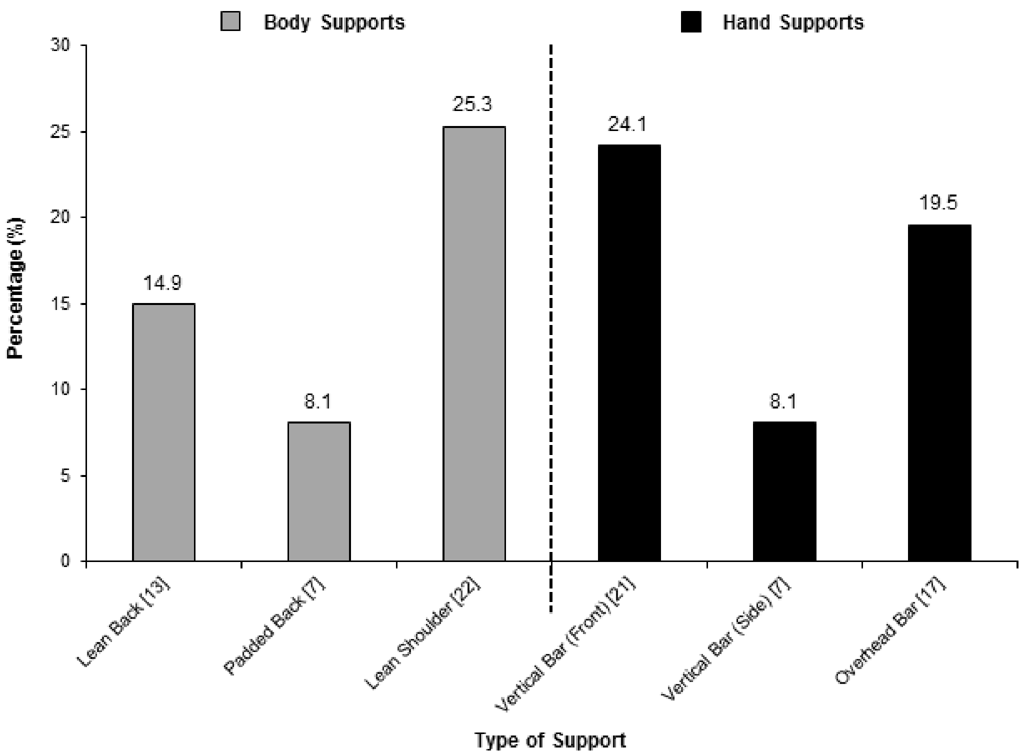


Figure 4.3 Types of support strategies used by standing passengers while travelling on underground trains in London (arranged in descending order based on contact area between support and individual)

The preferred supports were the 'Lean Shoulder' and the 'Vertical Bar (Front)', representing 25.3% and 24.1% of the observations respectively, followed by the 'Overhead Bar' (19.5%) and the 'Lean Back' (14.9%) supports. The least utilised supports were the 'Padded Back' and the 'Vertical Bar (Side)' supports.

4.4.3 Stance Orientation

Standing postures adopted by passengers were divided into two broad categories based on the orientation of individual foot positions, namely: Anterio-Posterior (A-P) orientation and Lateral (Lat) orientation. During pilot testing, variations from these postures were observed and consequently, these categories were divided further into six specific classifications (Figure 4.4): Anterio-Posterior (A-P), Lateral (Lat), Split, Resting (A-P), Resting (Lat) and Resting (Split).

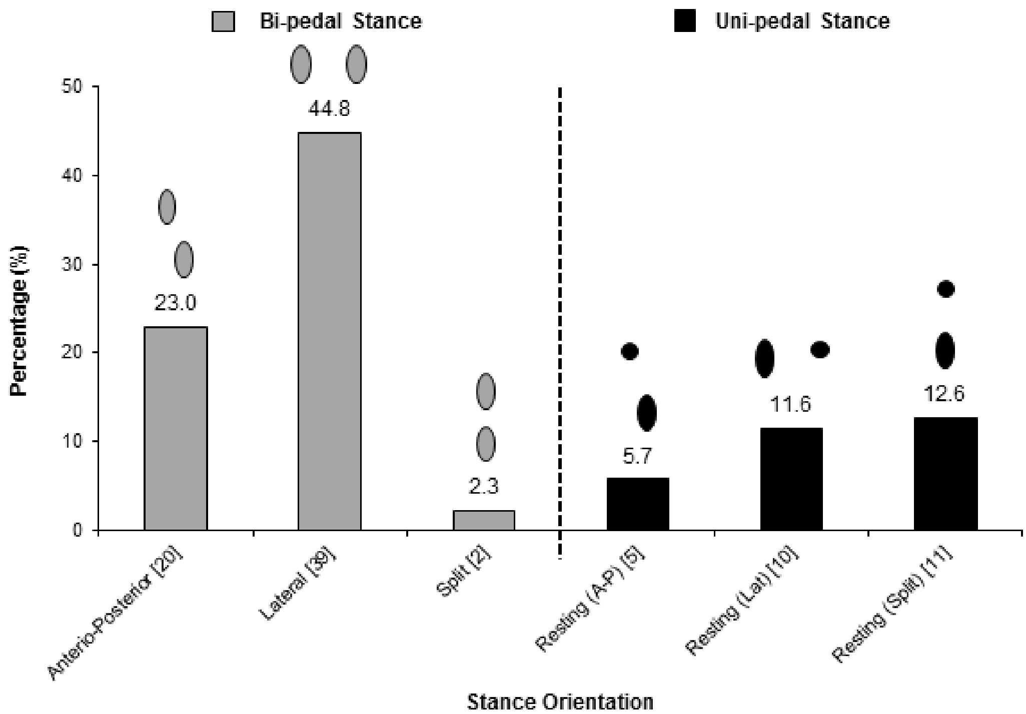


Figure 4.4 Foot orientations adopted by standing passengers on the London Underground (with diagrammatic representations of each posture)

The A-P standing posture was characterised by one foot being placed in front of the other (with a lateral separation between each foot). The Lat posture positioned the feet side-by-side (with minimal anterio-posterior separation) while the Split posture was similar to the A-P orientation however the feet were directly in-line with no lateral separation. These postures were classified as a bi-pedal stance as both feet provided weight-bearing support for the standing individual. The remaining three postures (Resting A-P, Resting Lat and Resting Split) were uni-pedal as weight-bearing as only one foot provided support for the individual while the other rested on the floor. Overall, 43.6% of the passengers observed were found to adopt an Anterior-Posterior stance orientation (Slipt stance included in this classification), while 56.4% chose a Lateral stance.

In standing individuals, the base-of-support (BOS) has been identified as a main contributing factor to maintaining stability (Nawayseh and Griffin, 2006) and instability would occur when the centre of mass (COM) of the individual moves outside the BOS. The majority of standing passengers adopted a bi-pedal stance (70.1%) with both feet providing support on the floor. This would be expected as the separation of the feet in a bi-pedal stance increased the BOS and consequently offered a greater contribution to standing stability than a uni-pedal posture.

4.4.4 Vibration Measurement

There are numerous means by which the vibration can be expressed but generally, acceleration (ms^{-2}) has been selected as the preferred measure for quantifying the severity of human vibration exposure.

Table 4.3 Frequency weighted vibration magnitudes, measured on underground trains in London

Train Line	Frequency Weighted Vibration Magnitudes (ms^{-2})						
	X-Axis		Y-Axis		Z-Axis		XYZ-Axes
	r.m.s.	Peak	r.m.s.	Peak	r.m.s.	Peak	r.s.s.
A	0.77	2.05	0.40	1.09	0.30	2.35	0.92
B	0.67	2.14	0.25	1.16	0.31	1.00	0.78
C	0.57	1.27	0.35	1.46	0.19	0.87	0.70
D	0.30	1.29	0.36	1.07	0.15	0.51	0.49
E	0.39	1.09	0.35	1.04	0.30	1.34	0.60
F	0.40	1.71	0.35	1.27	0.27	1.71	0.60
G	0.38	1.67	0.36	0.94	0.32	1.29	0.61
Mean	**0.50**	**1.60**	**0.35**	**1.15**	**0.26**	**1.30**	**0.67**

Where: r.m.s. = root mean square and r.s.s. = root sum of squares

With the single exception of Line D, the highest vibration magnitudes were found in the x-axis, followed by the y-axis and finally the lowest magnitudes in the z-axis (Table 4.3). In the context of these measurements, the x-axis was aligned in the direction the train was travelling; the y-axis was set at right-angles to this (perpendicular to the direction of travel) and the z-axis was aligned vertically through the floor of the train carriage. It could be suggested from these results that horizontal vibration (x- and y-axis) would be a greater contributing factor to control of postural stability and activity interference (in standing individuals) than vertical vibration. The results from the current study (0.50, 0.35 and 0.26ms^{-2} for x-, y- and z-axis vibration respectively), showed comparable vibration exposures to those obtained in other studies for rail transport (Table 2.4). Vibration magnitudes on Line A however, were significantly higher than the other lines, possibly due to variations in the quality of the track between different lines, the speed at which the trains travelled and driver behaviour.

In addition to the vibration magnitudes, spectral analysis was used to extrapolate the power spectra from the vibration data. The power spectral density (PSD) indicated how the energy of the vibration was distributed with response to frequency. The PSDs obtained during the field measurements in the x-, y- and z-axes are presented in Figure 4.5. The PSD curves showed that the vibration energy was generally found at frequencies below 5Hz, with peaks found at about 0.5Hz (x-axis), 1.25Hz (y-axis) and about 2.25Hz (z-axis).

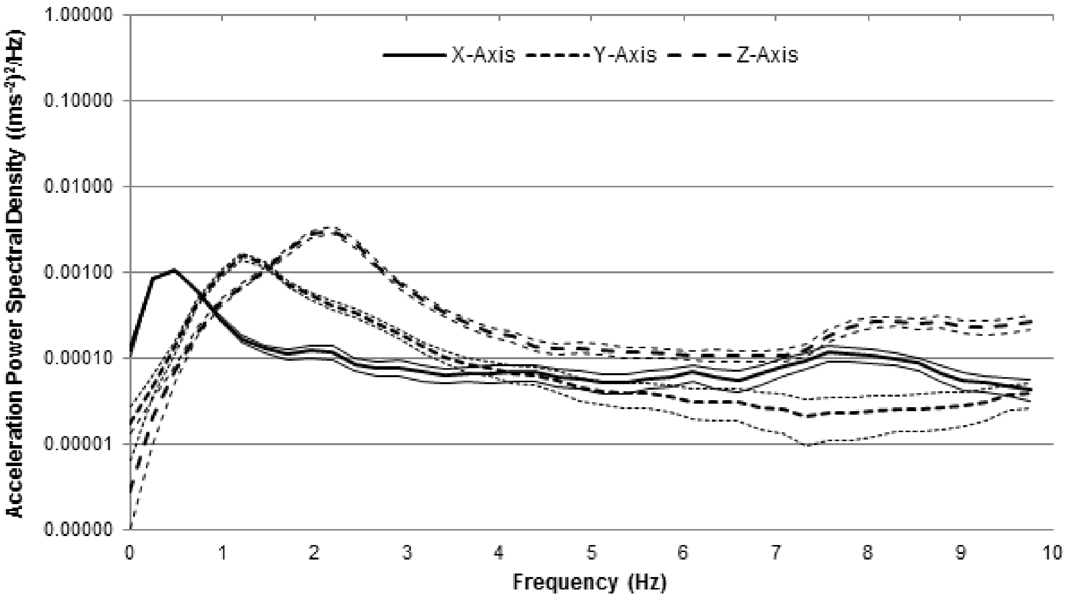


Figure 4.5 Power spectral densities (PSDs) for x-, y- and z-axes, obtained from measurements on underground trains in London

4.5 DISCUSSION

4.5.1 Use of Travel Time by Standing Rail Passengers

Due to the difficulty associated with accurately and covertly observing the actual task performed by passengers, observations were used to identify the type of device used by standing passengers rather than the specific task performed.

Considering market trends, differences in the prevalence of smart-phones (44.8%) compared to feature phones (23.0%) would be expected: in 2007 worldwide shipments of smart-phones increased by 53% from the previous year (Eskelsen *et al.,* 2009). Similar trends were also observed during 2010 where smart-phone sales increased by 48%, while feature phone sales decreased by 29% (IDC, 2011). The high popularity and demand for smart-phones coupled with increasing functionality could further contribute to the high prevalence observed on underground rail transportation.

The use of 'Entertainment' devices to occupy travel time would be expected in situations where the ability to use mobile phones would be limited (such as, underground with inconsistent network coverage). Such devices accounted for 20.7% of the observations of standing rail passengers. Many mobile phones however, have similar features and applications as the 'Entertainment' devices (for example, music player functions). The availability of these entertainment applications could have influenced the number of passengers engaged in these types of activities.

Reading activities represented the lowest prevalence of tasks performed by standing passengers (11.5%). Information obtained during a national survey in 2004, showed that approximately 53% of rail passengers engaged in reading activity for some time of the journey (Lyons *et al*., 2007). A follow up study conducted by Lyons *et al.* (2011) in 2010 showed no significant difference in the percentage of passengers that read while travelling (54%). Differences in the prevalence of reading tasks between the results presented in Table 4.1 and Figure 4.2 and those reported by Lyons *et al.* (2007 and 2011) could reflect possible issues faced by standing passengers. The majority of reading material (for example, newspapers, books or magazines) requires the use of two hands. This would restrict the options for postural support when standing and consequently, increase the risk of interference due to vibration. Other devices, such as mobile phones, were able to be operated using one hand, which meant the other could be used for additional postural support.

Considering the types of interfaces used by standing passengers, touch-screens accounted for 35.6% of the interfaces observed on underground trains. Global market trends have shown the prevalence of touch-screens has increased considerably: in 2007 approximately 13.9% of mobile phones had touch-screens, this increased to 37.3% by 2009 and is expected to reach 58% by 2013 (IDC, 2011). Despite such demand and popularity for touch-screen devices, anecdotal evidence suggests that users experience difficulty with the interface. Survey data revealed the top rated handsets used a traditional keypad interface rather than a touch-screen (Beaumont, 2009). Confounding factors could be due to a lack of experience with using touch-screens. A loss of tactile feedback associated with touch-screens compared to traditional keypads could be distracting to users and result in greater activity interference.

Device interfaces such as ‘QWERTY Keypads’ and the ‘Stylus’ were the least observed types of interface however, there could be some cross-over with other interfaces. For example, individuals may choose to use different keyboard settings on the mobile device (mobile phones may have both physical and touch keypads) or may simply refrain from using the stylus when operating the device.

4.5.2 Support Strategies used by Standing Passengers

Support strategies that provided the greatest contact area for the passengers were expected to provide improved stability in standing postures and would therefore be preferred by passengers engaging in activities. Despite the greatest contact area being provided by the ‘Lean Back’ support, alternative support strategies were preferred (Figure 4.3). A possible contributing factor could be the available space within the train carriage. For example, hand supports require less space compared to body supports, which would be an advantage in environments where space is limited. The influence of limited space within train carriages on the positions adopted by standing passengers has been identified by the Rail Safety and Standards Board, UK (RSSB, 2009) and illustrated in Figure 2.2 (Section 2.1.2 Postures Adopted by Standing Passengers). Additionally, the vibration transmitted through the support could lead to discomfort of standing passengers. During exposure to horizontal whole-body vibration, Thuong and Griffin (2010) found higher ratings of discomfort when individuals were supported by leaning backwards and leaning sideways on one shoulder, compared to when individuals were holding onto a bar with one hand.

The low prevalence of the ‘Padded Back’ support could be related to the limited availability of the support (generally there were only four padded supports in each carriage). The ‘Vertical Bar (Side)’ was usually observed in high-capacity carriages where there was limited space (often used by passengers adopting a ‘Blocker’ or ‘Hostage’ position (Figure 2.2, Section 2.1.2.1)). Given the opportunity to choose, the majority of passengers holding a vertical bar for support reached forward, rather than to the side. The selection of supports for standing passengers could depend on a compromise between the provision of stability, discomfort due to vibration and access to the support (related to space availability). Generally, there was little preference observed between body (48.3%) and hand (51.7%) supports (Figure 4.3).

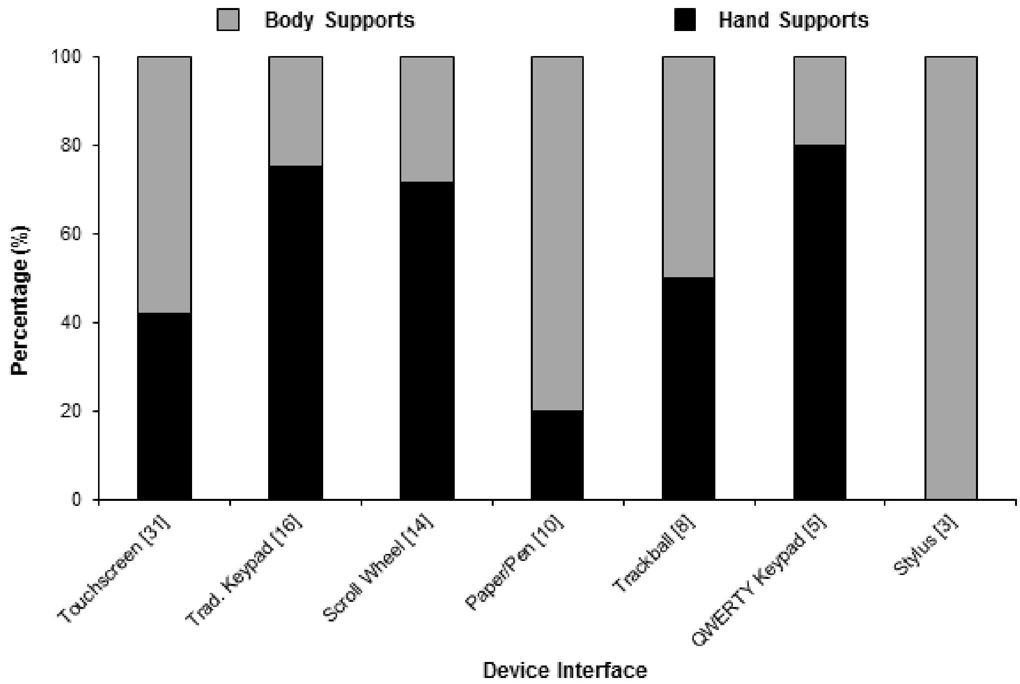


Figure 4.6 The use of hand supports and body supports by standing passengers travelling on underground trains in London, based on the device interface

Considering the interaction between the various support strategies types of device interfaces used to engage in activities, differences were found between the use of body supports and hand supports (Figure 4.6). Body supports enabled both hands to be available to operate hand-held devices. In particular, the ‘Stylus’ and ‘Pen/Paper’ interfaces were predominately operated with both hands and therefore the majority of individuals using these devices adopted body supports. For devices with ‘Touch-screen’ interfaces, approximately 60% of individuals used body supports while operating the devices, while no clear distinction could be made between body and hand supports for the ‘Trackball’ interface. Hand supports were predominantly used while operating devices with ‘Traditional Keypad’, ‘Scroll Wheel’ and ‘QWERTY Keypad’ interfaces (Figure 4.6).

A previous study conducted on Swedish inter-city trains reported that the choice of posture was strongly linked to the activity that was performed (Sundström and Khan, 2008). The observations from this field study suggest a similar link between activity performance and posture, such that: as the complexity of the task and interface sensitivity to vibration increased, the type of support adopted by individuals changed to accommodate the task demands (possibly the need for added stability or the use of both hands). For example, hand supports tended to be used for ‘Traditional Keypad’ interfaces however, for more challenging interfaces, such as the ‘Stylus’, individuals preferred body supports.

In order to fully understand the postures adopted by the passengers, the interactions between lower body stability (stance orientation) and upper body support strategies should be considered (Figure 4.7). The majority of standing passengers that used hand supports were found to adopt a bi-pedal stance, possibly to increase the lower body support in order to maintain stability. An exception to this trend was the ‘Lean Back’ support. In contrast, the ‘Padded Back’ and ‘Lean Shoulder’ supports were commonly used by passengers in a uni-pedal stance, suggesting that the additional support provided by the upper body support meant passengers were able to maintain stability with a reduced base of support (BOS) at the floor. It would appear that passengers manage the combination of lower body support (BOS at the floor) and upper body support strategies such that the threshold for a loss of stability is not exceeded. Additionally, the BOS for the upper and lower body were maximised in opposing directions. For example: the ‘Lean Back’ and ‘Padded Back’ supports increased the support for the upper body in the x-axis direction, while the majority of foot orientations were lateral and therefore maximised the BOS at the floor in the y-axis direction. Individuals using the ‘Lean Shoulder’ support (greater upper body support in the y-axis) tended to adopt foot orientations that maximised the BOS at the floor in the x-axis (Figure 4.7). By maximizing the support given to the upper and lower parts of the body in opposite directions, the overall base of support would be increased and therefore improve standing stability.

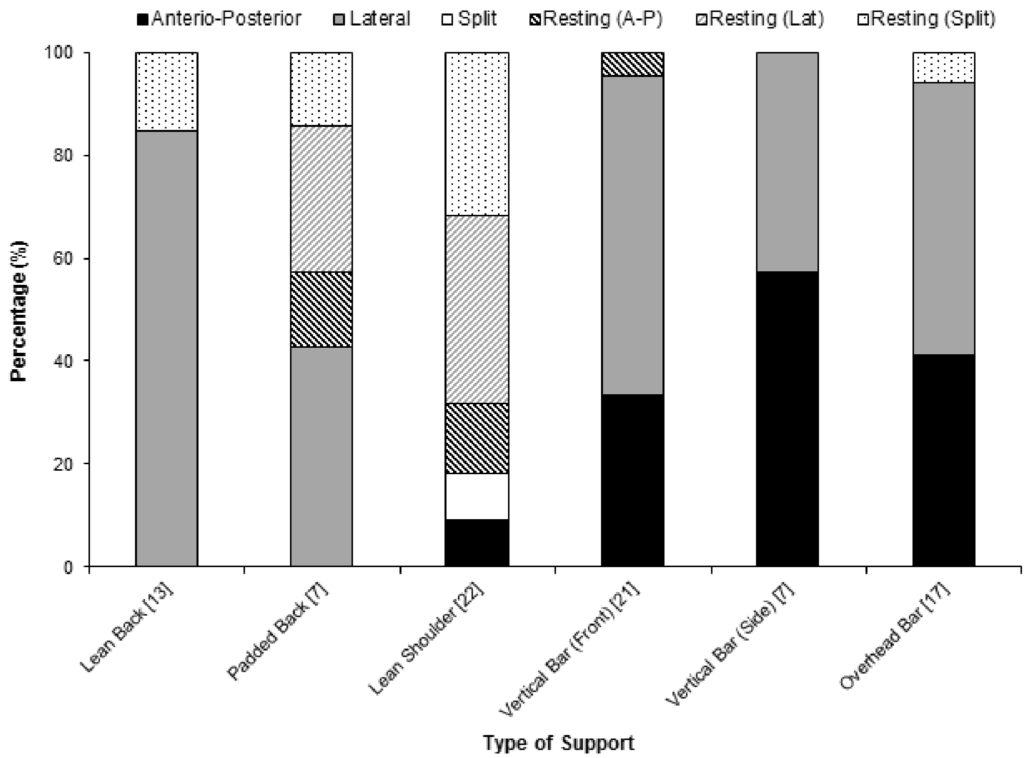
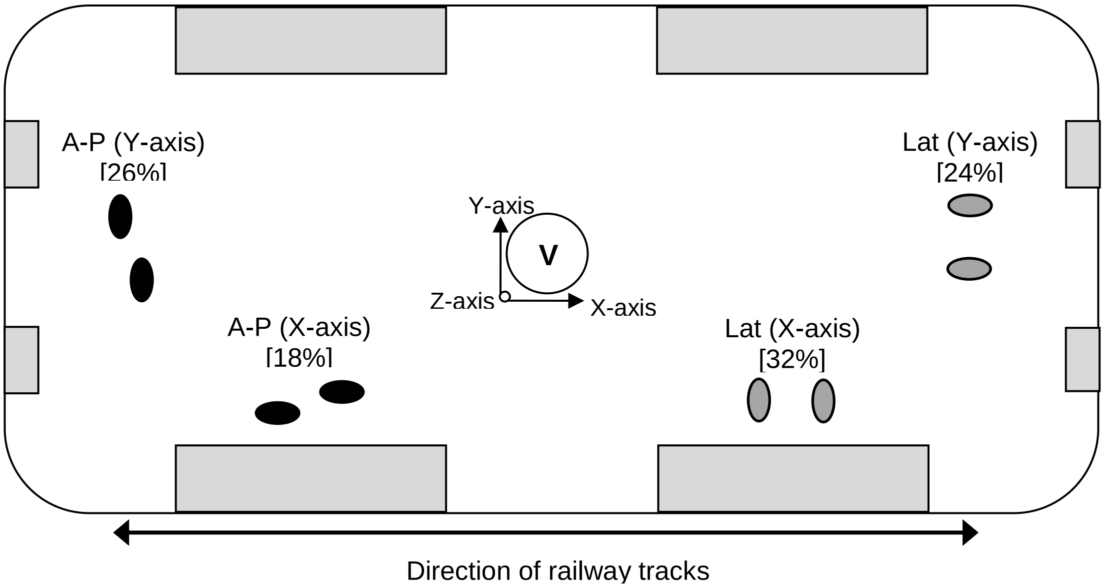


Figure 4.7 Standing foot positions adopted by standing rail passengers on the London Underground, based on type of support

In relation to the direction of vibration exposure, Griffin (1990) stated that by maximising the BOS in the direction of the most severe motion standing individuals could improve stability. For purposes of clarity the six stance orientations were considered as two broader categories based on the direction of maximum BOS, namely: Anterio-Posterior (A-P) and Lateral (Lat). By combining the two stance orientations (A-P and Lat) with the horizontal directions of motion (x-axis and y-axis), four postural alignments were determined (Figure 4.8). The alignments A-P (X-axis) and Lat (X-axis) were orientated such that the BOS was greatest in the x-axis, whereas, A-P (Y-axis) and Lat (Y-axis) had a maximum BOS in the y-axis.

It was proposed that the direction of postural alignment adopted by the majority of passengers would provide an indication of the most severe direction of movement, as determined subjectively by the passengers. Based on observation results presented in Figure 4.8, 50% of the passengers adopted an x-axis alignment and 50% a y-axis alignment. Consequently, these data provided little insight as to which direction of motion exerted the greatest influence on standing passengers. In order to gain a better understanding of the influence of vibration direction on standing passengers, objective measurements of vibration exposures were considered.



* Diagrams represent alignment only and not standing positions within the carriage

* Where: A-P (Y-axis) = Anterio-Posterior stance aligned in the Y-axis

A-P (X-axis) = Anterio-Posterior stance aligned in the X-axis

Lat (Y-axis) = Lateral stance aligned in the Y-axis

Lat (X-axis) = Lateral stance aligned in the X-axis

V = Site for vibration measurements

Figure 4.8 Schematic aerial view of a single carriage indicating stance orientations relative to the train body

4.5.3 Vibration Exposure on Trains

Objective measures of vibration at the floor of the trains revealed the highest magnitudes (ms^{-2} r.m.s.) occurred in the x-axis (Table 4.3). Based on these measurements, it would be expected that individuals adopting a postural alignment which provided minimal BOS in the x-axis would require additional upper body support, most likely selecting body supports over hand supports in order to improve stability. Observations of individuals in the A-P (Y-axis) and Lat (Y-axis) postural alignments (least BOS in the x-axis) showed the majority of passengers used body supports (62.8%) as opposed to hand supports (37.2%) (Figure 4.8). In comparison, individuals adopting a Lat (X-axis) or A-P (X-axis) alignment (largest BOS in the x-axis) predominantly utilised hand supports (65.9%) compared to body supports (34.1%).

Narayanamoorthy *et al.* (2008a) found that passengers usually adopted postures that would attenuate the intensity of vibrations in order to perform various activities. Results from observations presented in this chapter indicated there was an interaction between postural alignment at the feet and the support strategies used to stabilise standing passengers.

Previous studies have reported detrimental performance effects of WBV exposure (for example, Lewis and Griffin, 1978). A study by Mansfield *et al.* (2007) investigated the influence of WBV exposure on computer use with different pointing devices (mouse and touchpad controls) in seated postures. The results showed decrements in performance during exposure to multi-axis vibration in a 'high' magnitude condition (0.48, 0.53 and 0.51ms^{-2} in the x-, y- and z-axes respectively). The authors concluded that although it was possible to perform such computer work during vibration exposure, passengers should expect some activity interference at higher magnitudes. Comparing these results with the vibration measurements presented in this chapter, a degree of activity interference could be expected on the underground trains. Utilising mobile technology, many individuals could continue to engage in activities even while travelling in standing postures however, there are no published studies that have considered the performance of such devices for standing passengers.

4.6 CONCLUSIONS

The study presented in this chapter investigated the behaviour of standing rail passengers through context-specific covert observations and provided measurements of the vibration exposure to which these passengers were exposed during underground rail travel.

Devices associated with high functionality capabilities (such as smart-phones) showed the highest prevalence of use amongst standing passengers, with touch-screens and traditional physical keypads the most commonly used types of device interface. These results would be expected based on the market trends and sales estimations for mobile technologies at the time of the investigation.

Although the 'Lean Back' support offered the greatest contact area between the support and body, alternative support strategies were preferred by standing rail passengers. The 'Lean Shoulder', 'Vertical Bar (front)' and 'Overhead Bar' supports were more commonly used by passengers. A contributing factor could be the availability of supports within the carriage – hand rails/bars were more accessible than leaning on a wall.

A Lateral stance orientation (56.4%) was preferred to an Anterio-Posterior stance (44.6%) and furthermore, the majority of standing passengers adopted a bi-pedal stance (70.1%) rather than a uni-pedal stance. This was most likely due to a greater contribution to stability obtained when both feet provided weight-bearing support at the floor. Interactions were found between the stance orientation and the type of support strategy adopted. Typically, passengers in a bi-pedal stance chose to use hand supports were, while passengers in a uni-pedal stance predominantly selected body.

The vibration magnitudes found on the underground trains were similar to measurements reported in the literature from a variety of different rail transport systems. The greatest magnitudes were found in the x-axis ($0.50\,ms^{-2}$), and, followed by the y-axis ($0.35\,ms^{-2}$), with the lowest magnitudes in the z-axis ($0.26\,ms^{-2}$). Based on previous investigations reported in the literature, activity interference would be expected during exposure to the vibration experienced on underground trains.

The outcomes from the field study presented in this chapter were used to inform the design of the subsequent four laboratory studies presented in Chapters 5 – 8. Postural conditions and the support strategies used in the laboratory studies were based on the covert observations reported in this chapter. In order to improve the context validity of the laboratory studies, vibration stimuli were selected to represent the vibration characteristics obtained during field measurements on the underground trains.

CHAPTER 5

INFLUENCE OF WHOLE-BODY VIBRATION AND STANCE ORIENTATION ON MANUAL CONTROL PERFORMANCE

Based on information obtained during the covert observation study presented in Chapter 4, it was clear that the majority of standing rail passengers adopted one of two stance orientations – Anterio-Posterior (A-P) and Lateral (Lat). It was suggested that the selection of stance orientation could be related to the direction of motion and the need for standing passengers to maintain stability while travelling. Such interruptions could have further implications on the performance of activities that require manual control (for example, operating a mobile device).

The chapter presented here outlines two laboratory studies designed to investigate the extent to which variations in stance orientation would influence the performance of manual control tasks during exposure to whole-body vibration. Horizontal (x- and y-axis) motions were selected as the greatest levels of exposure were identified in these directions during the field measurements (Chapter 4).

The first study investigated discrete manual control performance and was conducted during the Ergonomics and Human Factors Masters (MSc) degree program at Loughborough University. This study has been reported in: Baker, W. D. R. and Mansfield, N. J., 2010. Effects of horizontal whole-body vibration and standing posture on activity interference. *Ergonomics,* 53(3): 365-374. The second study was designed to assess continuous manual control performance.

5.1 INTRODUCTION

Humans interact with the environment on a daily basis, through which a substantial proportion of human activity has been directed toward the control of some part of this environment (Lewis and Griffin, 1978). In many situations, a high degree of manual dexterity and motor control might be required in order to successfully perform a skilled manual control task (Kam, 1981). Manual control tasks have been categorised as: i) discrete, ii) serial and iii) continuous (Schmidt, 1988). Discrete tasks were defined as having a ‘recognizable beginning and end point’, such as pressing a button. Serial tasks consisted of a series of discrete tasks that could be partitioned if necessary; while continuous tasks were characterised as having no distinct beginning or end point (for example, tracking tasks or driving simulator games on mobile devices). It must be noted that although these terms have been defined separately, the classifications form a continuum of manual control tasks. Serial tasks therefore consist of varying degrees of discrete and continuous tasks, depending of the level of partition or separation within the task.

Manual control performance has been extensively studied to represent both generalised motor skills, as well as typical task performed in the 'real world' (McLeod and Griffin, 1989). The detrimental effects of vibration exposure on manual control performance have been found to occur in many different types of tasks (for example, Griffin and Hayward, 1994; Mansfield et al., 2007 and Sundström and Khan, 2008), although the majority of research has focused predominantly on discrete and continuous manual control tasks. This could be due to the fact that these types of tasks represent the limits of the manual control continuum and tend to be more clearly defined other types, such as serial tasks.

5.2 RESEARCH HYPOTHESES

Despite the extensive research conducted to investigate the effects of whole-body vibration exposure on manual control performance, no published studies have considered the influence of standing postures, specifically stance orientation, in this context. To better understand how postural variations and vibration exposure might affect task performance, two types of manual control tasks were selected for investigation. The selection of discrete and continuous tasks ensured that distinctly different characteristics of manual control performance were investigated. Additionally, these types of tasks have been extensively studied in previous research. The research findings from the work presented in this chapter could therefore directly contribute to pre-existing literature. The aims of the studies described within in this chapter were to determine the extent to which performance (and the associated subjective workload) of two types of manual control tasks were affected by the:

i) Type of control task (discrete and continuous)

ii) Variations in stance orientation (anterio-posterior and lateral postures)

iii) Vibration magnitude,

iv) Vibration direction

It was hypothesised that:

H1: Manual control performance and ratings of workload would vary between the discrete and continuous tasks.

H2: Performance and workload measures would be significantly different between the two stance orientations and between the different directions of motion. In situations where standing stability would likely be compromised due to the positioning of the feet (base-of-support) in relation to the direction of motion, greater reductions in performance accompanied by higher workload ratings would be expected.

H3: Performance degradation and subjective workload ratings would increase with an increase in vibration magnitude.

5.3 METHODS

5.3.1 Participants

The participants in both studies were research staff and students from Loughborough University, UK. In order to determine suitability for inclusion in the studies, all participants were screened for health contra-indications (Appendix A3).

Table 5.1 Anthropometric characteristics of participants from the discrete and continuous manual control studies

Characteristic	**Discrete Pegboard Task**	**Continuous Driving Task**
Number	16	21
Gender	10 female; 6 male	11 female; 10 male
Age	19 – 30years (mean ± sd: 23.5 ± 2.1years)	20 – 31years (mean ± sd: 24.9 ± 2.7years)
Stature	1600 – 1830mm (mean ± sd: 1719.2 ± 82.7mm)	1540 – 1835mm (mean ± sd: 1728.6 ± 83.5mm)
Mass	63.1 – 90.4kg (mean ± sd: 72.4 ± 10.4kg)	53.4 – 92.8kg (mean ± sd: 73.9 ± 10.6kg)
Shoulder Width	385 – 486mm (mean ± sd: 430.3 ± 33.8mm)	377 – 487mm (mean ± sd: 439.5 ± 36.6mm)

In addition, participants received detailed information regarding the purpose of the studies, experimental protocols and possible risks associated with participation (Appendix A4). Anthropometric data was obtained prior to commencing the experimental protocols; participant characteristics from both studies are provided in Table 5.1. Informed consent was obtained from all participants (Appendix A5) and ethical clearance for the study was granted by the Loughborough University Ethical Advisory Committee.

5.3.2 Pilot Testing

Prior to conducting the experimental testing, pilot testing was performed to determine the appropriate vibration characteristics that would be used in both studies. Due to the longer duration for the individual test conditions in the continuous control task, the number of vibration conditions was reduced to ensure participants were not affected by confounding factors, such as fatigue. By removing a vibration magnitude condition from the experimental design for the continuous control study, the vibration magnitudes were adjusted so that the upper limit of the testing magnitudes were comparable to the peak magnitudes measured during the field study (Chapter 4).

Markers were placed on the floor to assist participants with foot positioning and preliminary tests were conducted to identify the number of familiarization trials required to minimise the learning effect on the pegboard task and the Lane Change Test (LCT) driving simulator. The participants used in pilot testing did not participate in the experimental testing.

5.3.3 Independent Variables

5.3.3.1 Vibration

Vibrations were generated using a 6 degree-of-freedom multi-axis vibration simulator (MAViS) at the Environmental Ergonomics Research Centre, Loughborough University. Participants were required to stand on the simulator platform and for safety reasons; a harness was worn at all times while standing on the simulator. During the discrete control study, a guard rail was mounted on three sides of the platform at a height of 1000mm to provide additional safety for the participants. For the continuous control study, the guard rail was removed, however support was provided by the steering wheel rig that was fitted to the platform.

The experimental conditions consisted of single-axis vibration, in both horizontal directions: fore-and-aft (x-axis) and lateral (y-axis), as well as dual-axis horizontal vibration (xy-axes). Single-axis vibrations were used to clearly identify the effects of direction on manual control performance; however, as single-axis whole-body vibrations would not typically be found in ‘real world’ contexts, a dual-axis condition was included. The vibration stimuli (magnitude and direction) for each study are summarised in Table 5.2.

Table 5.2 Summary of vibration stimuli used in the discrete and continuous manual control studies

Task Variable	Condition	Vibration Magnitude (ms^{-2} r.m.s., unweighted)		
		x-axis	**y-axis**	**r.s.s. ∑ axes**
Discrete Manual Control	1	0.5	---	0.5
	2	1.0	---	1.0
	3	2.0	---	2.0
	4	---	0.5	0.5
	5	---	1.0	1.0
	6	---	2.0	2.0
	7	0.5	0.5	0.71
	8	1.0	1.0	1.41
	9	2.0	2.0	2.83
	Control	---	---	---
Continuous Manual Control	1	0.75	---	0.75
	2	1.5	---	1.5
	3	---	0.75	0.75
	4	---	1.5	1.5
	5	0.75	0.75	1.06
	6	1.5	1.5	2.12
	Control	---	---	---

Where: r.m.s. = root mean square and r.s.s. = root sum of squares

For both studies, the vibration stimuli were band-limited up to a frequency of 4Hz. This frequency band was selected as the majority of horizontal vibration exposure from field measurements occurred within this range (Figure 4.5). In addition, previous studies reported the greatest influence of horizontal whole-body vibration on workload and task performance occurred between 2 – 4Hz and 1 – 3Hz (Lewis and Griffin, 1978 and Westberg, 2000, respectively). The average vibration magnitudes experienced on underground trains should not normally reach the higher magnitudes of vibration employed in these experiments (Table 4.3). The use of high vibration magnitudes served to identify clearly the effects of vibration direction on the manual control tasks. The responses to the higher magnitudes could also indicate the approximate effects that can occur when a high magnitude of vibration motion occurs for a short period.

The vibration output was validated prior to and monitored during testing using a dedicated laboratory computer (Shake 2). Participants were exposed to one control condition (no vibration) and a series of random vibration stimuli (nine for the discrete control study and six for the continuous control study) in each stance orientation.

5.3.3.2 Posture

Two standing postures were selected for both studies, based on the orientation of the feet. The anterio-posterior stance required participants to place their dominant foot in-front of the other, while the lateral stance required the feet to be placed side-by-side (Figure 5.1). The separation distance between each foot was set as shoulder width and was measured from the distal portion of the second tarsal phalange in both the anterio-posterior and lateral stances. The lateral distance between the feet in the fore-and-aft posture was limited to the length of the foot of the subject. This ensured that the base of support for both postures was the same. Participants were asked to maintain an upright posture (minimal hip flexion) with knees straight throughout the duration of the vibration stimuli.

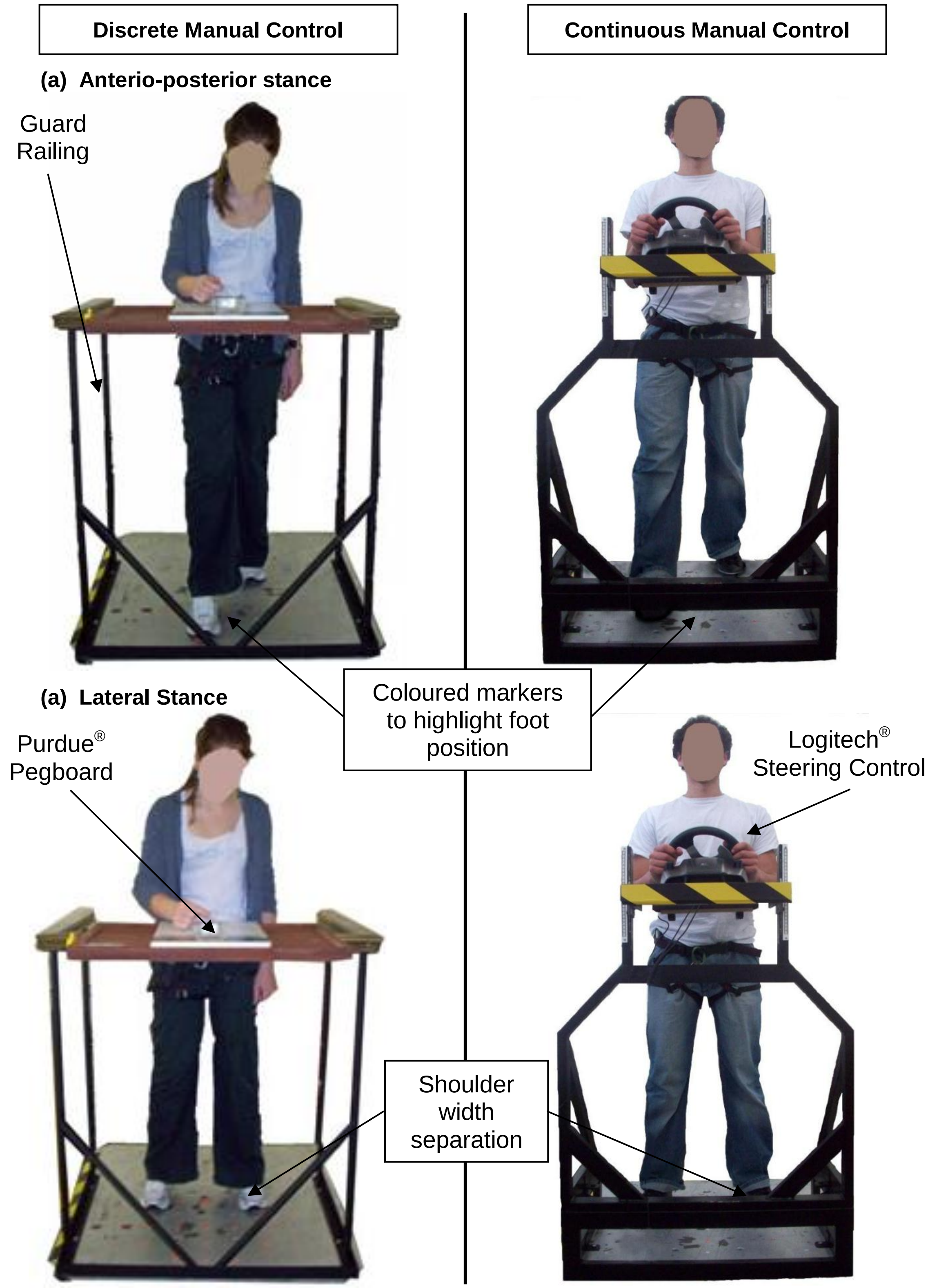


Figure 5.1 Participants demonstrating the (a) anterio-posterior and (b) lateral stance postures for the discrete and continuous manual control studies

5.3.4 Dependent Variables

5.3.4.1 Objective Measurement

5.3.4.1.1 Discrete Control Task

The performance of a discrete manual task was measured using a Lafayette Purdue® Pegboard Model 32020 (Figure 5.2). The Purdue Pegboard assessed movements of the arms, hands and fingers in terms eed and accuracy (Tiffin, 1948) to provide a measure of manual control performance. The pegboard task has been used in previous studies to assess the influence of body posture on manual control performance. Westwood *et al*. (1999) compared static seated and standing postures and found that performance was significantly reduced when participants were standing. The pegboard task could also be comparable to the type of discrete control tasks that individuals might perform in standing postures while travelling on trains (for example, pressing buttons).

A rigid metal frame with a wooden 'table-top' surface was attached to the simulator platform. The height of the frame was 1000mm above the platform surface and mounted to the side of the wooden workstation was a timing device (Casio® stop-watch; Casio Computer Co. Ltd., Tokyo, Japan). The pegboard was secured in a central position on top of the workstation, a distance of 170mm from the timer.
Due to disturbances caused by vibration transmitted through the rigid frame, a separate container (60 × 60 × 30mm) was required to store the pegs. The container was positioned in the same location as the original storage tray at the top of the pegboard.

The participants were responsible for starting and stopping the timer at the beginning and end of the task, during each of the vibration conditions. The face of the timer was positioned so the display screen was not in view and therefore the participants were not provided with any feedback concerning the level of performance. Any motion induced interruptions that required the participants to physically brace themselves in order to maintain stability were logged by the researcher.

Each test condition lasted approximately 60 – 90s and required participants to place 25 pegs into the designated holes on the pegboard, 'as quickly and as accurately as possible'. Participants selected individual pegs from the central container using only their dominant hand, while the non-dominant hand remained by the side of the participants at all times. In cases of emergency or loss of balance, participants were allowed to grasp the support rail in order to prevent falling. The railing was therefore provided for safety purposes rather than to be used as a postural support.

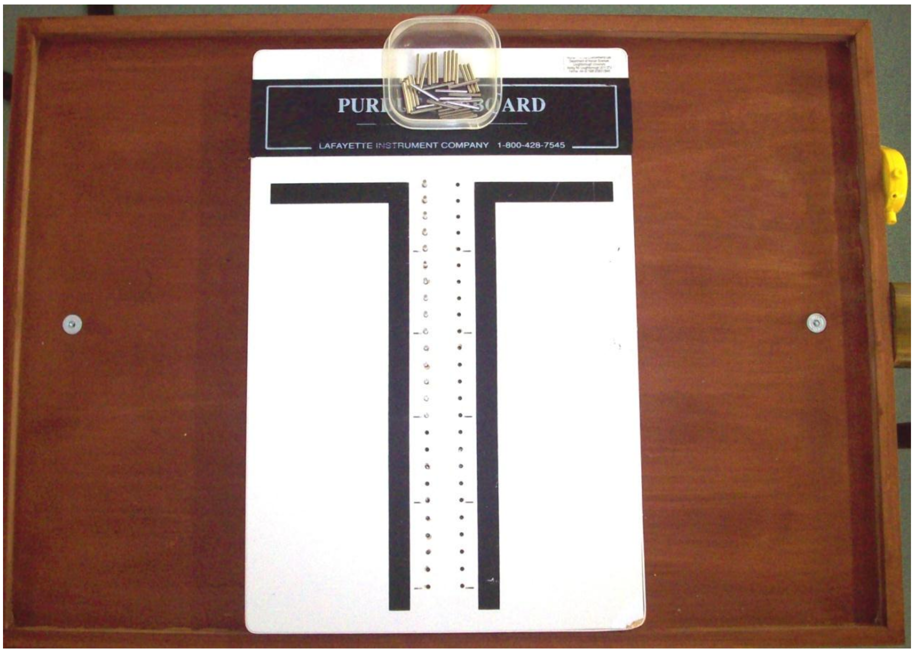


Figure 5.2 Purdue® Pegboard Model 32020 as it was mounted on the vibration simulator workstation

5.3.4.1.2 Continuous Control Task

Continuous manual control performance was evaluated using a tracking task performed on the Lane Change Test software (LCT version1.2, DaimlerChrysler, Germany). Tracking tasks have been extensively used to assess continuous manual control performance (Lewis and Griffin, 1978), specifically in situations where the operating device and the controlling limb / hand are connected (or coupled) to the source of the vibration. This provides a distinctly different situation to discrete manual control tasks where the controlling limb / hand and the vibration source would typically be separated. The use of the LCT method to assess continuous manual control performance provided an accepted means for investigating tasks where this coupling condition was present. These types of continuous tracking tasks could be found where rail passengers might use entertainment devices, such as a Nintendo DS®, to engage in more social activities while travelling (for example, playing driving games).

The LCT represented a simple, inexpensive method that has been accepted by ISO26022 (2010) for the assessment of in-vehicle task performance and estimation of task demands as a result of the operation of an in-vehicle device in a laboratory setting (Petzoldt *et al.,* 2003). The standard defines the method, minimum requirements for equipment and procedures for collecting and analysing data derived from the LCT method. This method has previously been used to assess the influence of whole-body vibration on reaction time and continuous manual control (tracking) performance, in short- and long-duration seated vibration exposures (Appan, 2009). Overall, the study concluded that exposure to vibration did not significantly influence reaction time performance or the tracking performance of the participants.

The LCT program consisted of a straight three-lane track, the image of which was projected onto a screen in-front of the participants (Figure 5.3) with a horizontal visual field of 25º±2º. The steering control (Logitech® G27) was mounted to the vibration simulator platform and could be adjusted so that the centre of the wheel was at standing elbow height of each participant. Signs located at approximately 150m intervals along the length of the track provided the participants with cues to change lanes. The speed of the simulator was pre-determined by the LCT software and maintained at 60 km^{-1} (variation of this speed was not possible once the experimental trial had commenced). Each test condition required the participants to complete a single track of the LCT simulator, lasting approximately 180s.

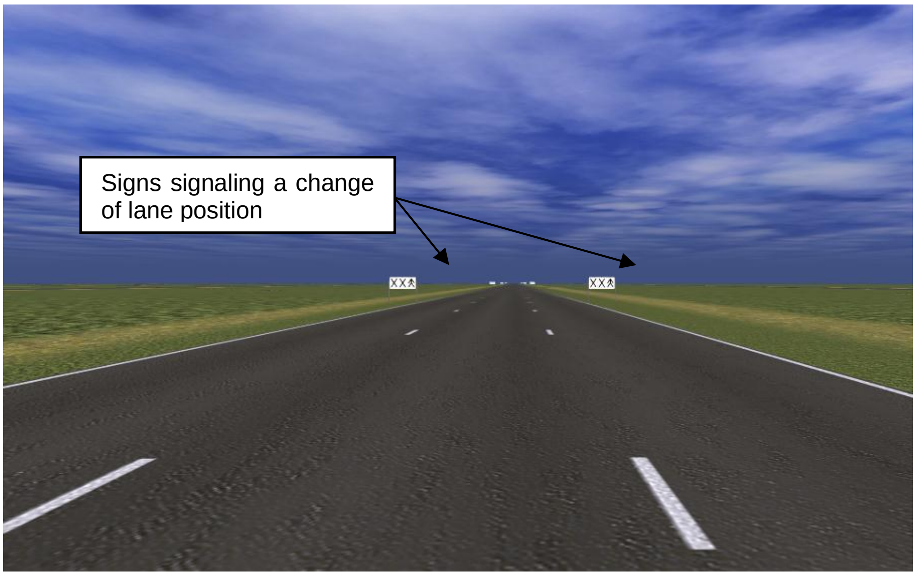


Figure 5.3 Screenshot taken during the LCT simulation

The main performance measure was the mean deviation (MDEV) from a nominal lane change model. Data were recorded at a frequency of 100Hz and using the LCT software the following additional variables were also provided: trial number, time to task completion, x- and y-coordinates of the actual position of the virtual vehicle.

Calculations of these performance metrics were conducted using the LCT analysis software.

5.3.4.2 Subjective Measurement

In both studies, participants were required to provide two subjective measures relating to task difficulty and workload following the completion of each vibration condition. These ratings were used to evaluate the overall workload experienced by the participants in order to perform the required task. The first subjective rating required the participants to assign a verbal descriptor of task difficulty, based on the following six-point semantic scale:

- Not Difficult
- A Little Difficult
- Fairly Difficult
- Difficult
- Very Difficult
- Extremely Difficult

This scale has previously been used by Corbridge and Griffin (1991) to assess the subjective experiences of task performance during whole-body vibration exposures. The semantic scale provides a clear and relatively easy method for assessing the level of difficulty associated with a specific task. The method does, however, assume that the increments between each verbal descriptor follow a linear relationship. For example, the subjective increase in task difficulty between 'Not Difficult' and 'A Little Difficult' would be the same as that between 'Difficult' and 'Very Difficult'.

In order to assess the linearity of response using the semantic scale, Corbridge and Griffin (1991) used a magnitude estimation technique to provide a numerical rating of subjective workload. By using both techniques, magnitude estimations of workloads were calculated for each semantic interval. The linearity of response from the semantic scale was found to be acceptable and numerical values ranging from 1 – 6 were assigned to the verbal descriptors. This enabled for averaging and statistical analysis to be performed on the semantic ratings.

Participants were provided with the following instructions (adapted from Stevens, 1975), for the magnitude estimation of workload:

> *'You will be presented with a series of vibration stimuli in irregular order. You are required to estimate the workload associated with the tasks by assigning numbers to them. The first stimulus will be a static condition with no vibration. Call this stimulus 100, and then assign successive numbers in such a way that they reflect your subjective impression. There is no limit to the range of numbers that you may use. You may use whole numbers, decimals or fractions. Try to make each number match the level of workload as you perceive it.'*

5.3.5 Experimental Protocol

Each study was conducted during a single laboratory session, lasting approximately 1h, which commenced with the researcher taking anthropometric measures of stature, shoulder width, foot length and body mass. In order to reduce variations in stance posture when changing between testing conditions, the positioning of the feet for each stance were located with reference points marked onto the vibration simulator platform. A safety harness was worn by participants at all times when standing on the simulator platform and the immediate area surrounding the vibration simulator was cordoned off and free of personnel before testing commenced.

Participants were allowed a familiarization period with no vibration exposure to practice performing the required task and become acquainted with providing subjective ratings of workload. The mean deviation (*Mdev*) was calculated after each familiarization trial was completed. Once the *Mdev* reached a consistent level (below 1.2m) and there were no longer any significant 'learning effects' present, the experimental conditions could begin. Following the familiarization trials, a 'reference' condition was performed without vibration exposure. This 'reference' condition was assigned a magnitude estimation rating of '100' and further subjective ratings were made in comparison to this 'reference' condition. The testing conditions included random vibration stimuli and additional control conditions (no vibration), presented to the participants in a counter-balanced order based on a balanced Latin-Square technique in order to minimise 'order-effects'.

Control conditions were conducted in each stance orientation. During each vibration condition, participants were asked to delay performing the task until the vibration simulator had stabilized at the required vibration magnitude. Once the task was completed and the vibration simulator had settled, the participants were asked to provide subjective ratings of workload using the magnitude estimation technique and the semantic scale. The time between each vibration stimuli depended on the responsiveness of the participant to provide these subjective ratings. In order to minimise the effects of fatigue, the number of stimuli were limited to 20 for the discrete control experiment and 14 for the continuous control experiment. The continuous control study had fewer stimuli as each stimulus task took longer than in the discrete control task. The short duration of the vibration exposures meant that time-dependent effects due to fatigue would have minimal influence on performance. For this reason and due to the longer time necessary to complete the driving task for the continuous manual control study; the number of vibration stimuli was reduced.

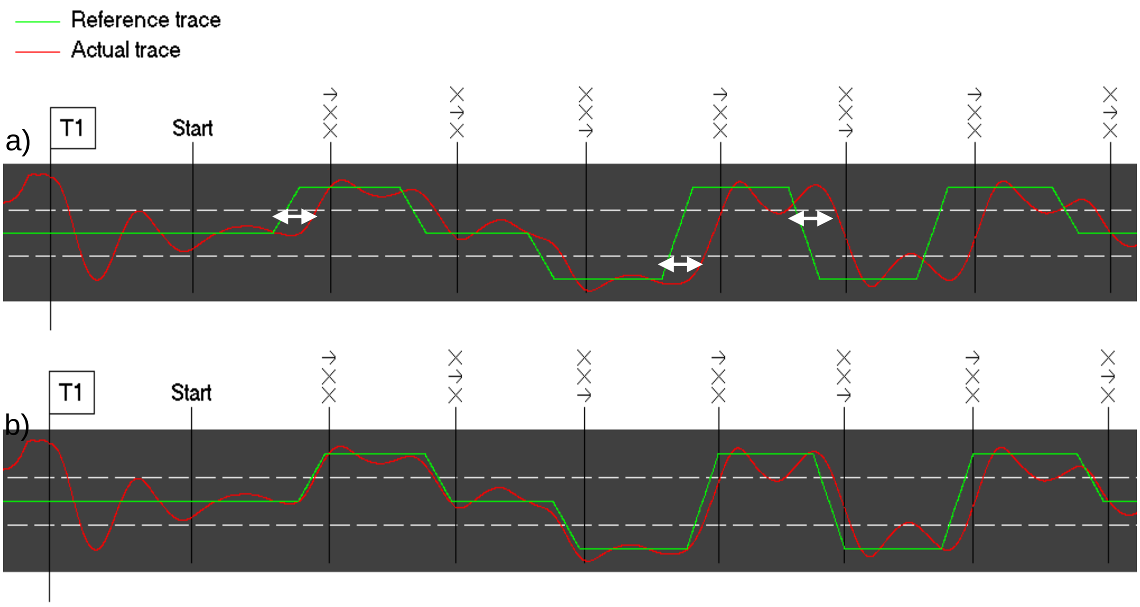
5.3.6 Data Analysis

5.3.6.1 Objective Task Performance

For the discrete pegboard task, the time taken to complete the task during each test condition was entered manually into a *Microsoft Excel®2007* spreadsheet.

The data obtained from the continuous LCT driving task was assessed using the LCT software before being entered into a *Microsoft Excel®2007* spreadsheet. The LCT software provided a ‘reference trace’ for the desired position of the virtual vehicle. The software program provided an immediate response to the appearance of the signs and changed lanes without delay. The ‘actual trace’ represented the position of the virtual vehicle controlled by the participant. Due to the reaction time required for the participants to initiate a response to the appearance of the signs, a consistent delay was observed between the ‘reference trace’ and the ‘actual trace’ (Figure 5.4a). The mean reaction time for each condition was therefore removed from the analysis of mean deviation (*Mdev*); this process has been illustrated in Figure 5.4b (Harbluk *et al.*, 2007).

In both studies, statistical analysis was conducted using *SPSS®* software (Version 15.0). A repeated measures two-way analysis of variance (ANOVA) was conducted to determine whether vibration and stance orientation had any significant effect on task performance and subjective workload.



White arrows indicate response delay between 'reference' and 'actual' traces due to reaction time of participants

Figure 5.4 'Reference' and 'actual' traces of vehicle position during LCT driving simulation, showing the removal of reaction time delay for analysis of mean deviation (*Mdev)*

5.3.6.2 Subjective Measures of Workload

As previously mentioned in Section 5.3.4.2 Subjective Measurement, the semantic scale assumed the intervals between each verbal descriptor were linear. Before statistical analysis was used on the semantic ratings, the linearity of the responses was first confirmed using a linear regression technique on magnitude estimations and semantic ratings. The resulting equivalent numerical magnitudes corresponding to each semantic descriptor are presented in Table 5.3. The results showed a strong degree of linearity (based on the Pearson correlation co-efficient, $r > 0.9$), which therefore supported the representation of the semantic data as numerical values (between 1 and 6).

Table 5.3 Calculated magnitude estimations corresponding to each semantic descriptor for discrete and continuous manual control in an anterio-posterior and a lateral stance

Semantic Descriptor	Equivalent Magnitude Estimation			
	Discrete Manual Control		Continuous Manual Control	
	Lateral	Anterio-Posterior	Lateral	Anterio-Posterior
Not Difficult	73	68	104	106
A Little Difficult	145	146	117	119
Fairly Difficult	217	224	130	131
Difficult	289	301	143	143
Very Difficult	361	379	156	156
Extremely Difficult	433	457	169	168

5.4 RESULTS

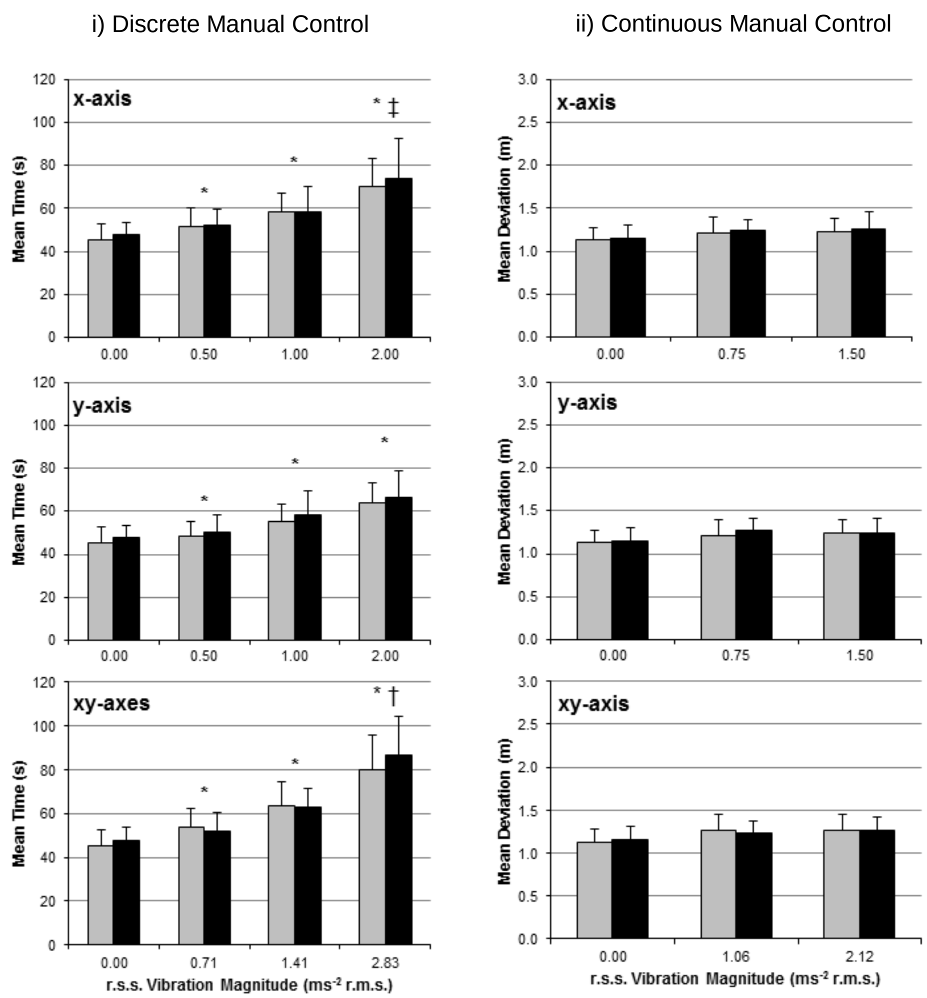
The purpose of these studies was to determine the effects of whole-body horizontal vibration and stance orientation on activity interference and workload in standing individuals. Objective measures of task performance were recorded by measuring the time taken to complete the required manual control task and subjective measures of workload were recorded using a magnitude estimation technique as well as a semantic six-point scale.

5.4.1 Objective Task Performance

Performance measures for both discrete and continuous manual control tasks are presented in Figure 5.5. Decrements in performance were based on the mean time taken to complete the pegboard task and the mean deviation (*Mdev*) in lane position on the LCT simulator. An increase in task completion time and mean deviation during vibration exposure represented a decrease in performance.

5.4.1.1 Discrete Manual Control Performance

During x-axis vibration, the mean time to complete the task (for both stances) increased significantly ($p < 0.01$), at each tested vibration magnitude between the control condition (no vibration) and 2.0ms^{-2} r.m.s. (column (i), Figure 5.5). For y-axis vibration, a significant ($p < 0.01$) increase was found in the mean times to complete the task, with increasing vibration magnitude up to 2.0ms^{-2} r.m.s., for both stances. There were no significant postural effects found at each vibration magnitude. During the highest vibration magnitude (2.0ms^{-2} r.m.s.) the mean times to complete the task were significantly ($p < 0.05$) shorter during y-axis vibration compared to x-axis vibration exposure, for both stance orientations.



Where: * = significant difference ($p < 0.05$) between vibration magnitudes for both standing postures

† = significant difference ($p < 0.05$) between anterio-posterior and lateral stances

‡ = significant difference ($p < 0.05$) between vibration directions (x-axis and y-axis)

Figure 5.5 Objective performance measures for i) discrete and ii) continuous manual control in an anterio-posterior and a lateral stance, during exposure to horizontal WBV (black = anterio-posterior stance, grey = lateral stance)

With dual-axis (xy-axes) vibration, mean task completion times increased significantly ($p < 0.01$) with an increase in vibration magnitude for both stances (column (i), Figure 5.5). The effect of stance orientation revealed some variation at vibration magnitude 2.8ms^{-2} r.m.s., with significantly ($p < 0.05$) longer mean task completion times found in the anterio-posterior stance than those obtained in the lateral stance.

Compared to single-axis vibration, dual-axis vibration produced significantly ($p < 0.05$) longer times to complete the task. This would be expected as the combined resultant r.s.s. vibration magnitude for dual-axis vibration was greater than the r.s.s. vibration magnitudes for single-axis vibration (Figure 5.5). Therefore, direct comparison between single and dual-axis vibration exposure could be misleading and has been considered separately (Figure 5.10).

5.4.1.2 Continuous Manual Control Performance

For all conditions during the LCT tracking task, no significant effects were observed for the mean deviations in lane position (column (ii), Figure 5.5). The performance of a continuous control task therefore was unaffected by increasing vibration magnitudes, nor were there any effects between the different directions of motion (x- and y-axis). Stance orientation showed no significant influence on continuous manual control performance (Figure 5.5). Comparing single and dual-axis exposures, the mean deviations in lane position were slightly higher during dual-axis vibration exposure than during single-axis vibration however, these effects were not significant.

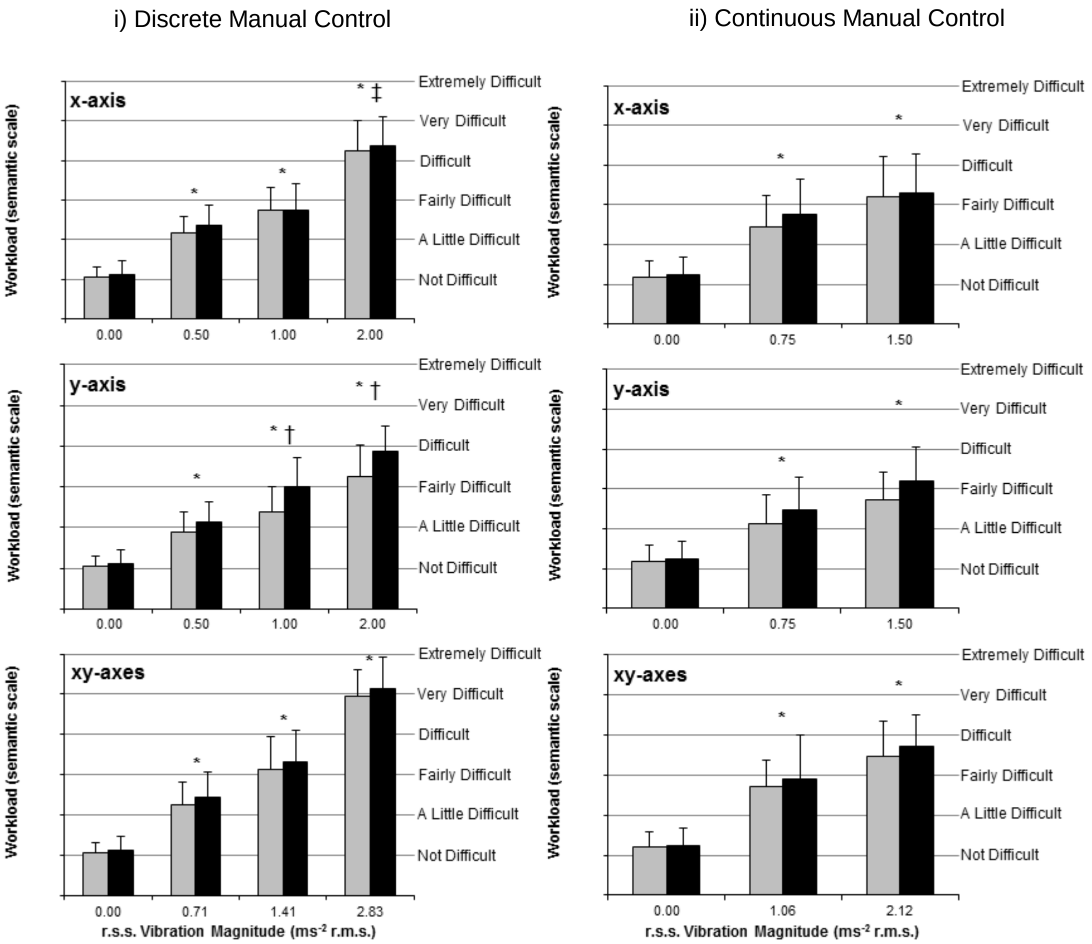
5.4.2 Subjective Measures of Workload

The two methods used to determine the workload experienced by the participants have been presented separately for the discrete and continuous tasks.

5.4.2.1 Discrete Manual Control

5.4.2.1.1 Semantic Scale Rating

The difficulty ratings obtained using the semantic scale (column (i), Figure 5.6) indicated that during x-axis vibration exposure, ratings of task difficulty significantly ($p < 0.01$) increased with an increase in vibration magnitude for both stance orientations. With y-axis vibration, mean ratings of task difficulty increased significantly ($p < 0.01$) with an increase in vibration magnitude up to 2.0ms^{-2} r.m.s., in both stances (Figure 5.6). At vibration magnitude 1.0 and 2.0ms^{-2} r.m.s. the anterio-posterior stance resulted in significantly ($p < 0.05$) higher mean ratings of task difficulty than in the lateral stance. Furthermore, at 2.0ms^{-2} r.m.s., semantic ratings during y-axis vibration were significantly ($p < 0.05$) lower than during x-axis vibration in both stances. A significant ($p < 0.01$) increase in difficulty ratings were found with a corresponding increase in dual-axis vibration magnitude for both the anterio-posterior and lateral stances.



Where: * = significant difference ($p < 0.05$) between vibration magnitudes for both standing postures

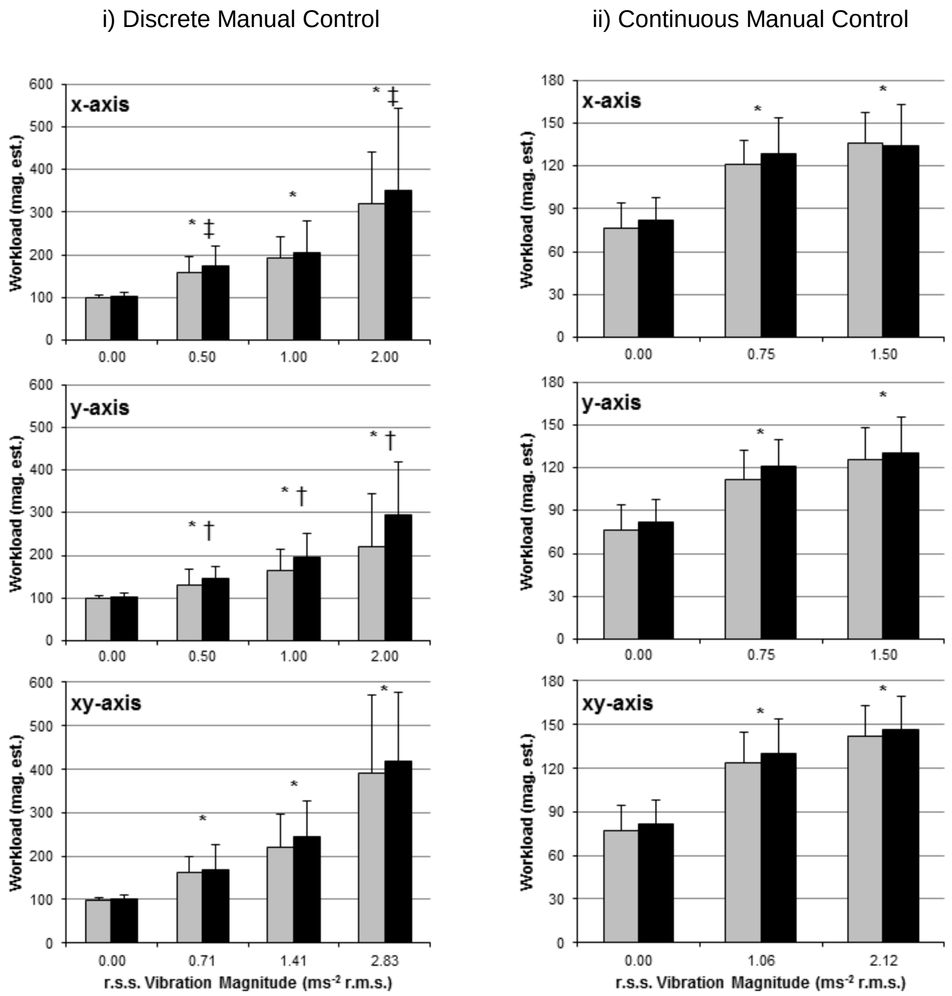
† = significant difference ($p < 0.05$) between anterio-posterior and lateral stances

‡ = significant difference ($p < 0.05$) between vibration directions (x-axis and y-axis)

Figure 5.6 Semantic ratings of workload for i) discrete and ii) continuous manual control in an anterio-posterior and a lateral stance, during exposure to horizontal WBV (black = anterio-posterior stance, grey = lateral stance)

5.4.2.1.2 Magnitude Estimation Technique

During x-axis vibration exposure, the magnitude estimations of workload increased significantly ($p < 0.01$), with increasing vibration magnitude up to 2.0ms^{-2} r.m.s., for both anterio-posterior and lateral stances (column (i), Figure 5.7). No significant differences were found between the two stances.



Where: * = significant difference ($p < 0.05$) between vibration magnitudes for both standing postures

† = significant difference ($p < 0.05$) between anterio-posterior and lateral stances

‡ = significant difference ($p < 0.05$) between vibration directions (x-axis and y-axis)

Figure 5.7 Magnitude estimations of workload for i) discrete and ii) continuous manual control in an anterio-posterior and a lateral stance, during exposure to horizontal WBV (black = anterio-posterior stance, grey = lateral stance)

Exposure to y-axis vibration, significantly ($p < 0.01$) increased magnitude estimations of workload with corresponding increases in vibration magnitude. At vibration magnitudes 0.5, 1.0 and 2.0 ms^{-2} r.m.s., workload in the anterio-posterior stance was significantly ($p < 0.05$) higher than in the lateral stance. Additionally, at vibration magnitudes 0.5 and 2.0ms^{-2} r.m.s., magnitude estimations of workload obtained during y-axis vibration were significantly ($p < 0.05$) lower than those obtained during x-axis vibration. The lower magnitude estimations indicate that performing the discrete pegboard task during y-axis vibration resulted in the participants experiencing less workload than during x-axis vibration.

Dual-axis vibration exposure resulted in significant ($p < 0.05$) increases in magnitude estimations of workload with increasing vibration magnitude up to 2.8ms^{-2} r.s.s. There were no significant differences found between the anterio-posterior and lateral stance orientations.

5.4.2.2 Continuous Manual Control

5.4.2.2.1 Semantic Scale Ratings

For all directions of motion (x-, y- and xy-axes vibration), semantic ratings of difficulty increased significantly ($p < 0.01$) with increasing vibration magnitude (column (ii), Figure 5.6). No significant postural effects were observed between the anterio-posterior and lateral stances for all test conditions.

5.4.2.2.2 Magnitude Estimation Technique

Similar patterns of response to the semantic ratings were observed for the magnitude estimation of workload during the continuous LCT tracking task (column (ii), Figure 5.7). During x-axis vibration exposure, the magnitude estimations of workload increased significantly ($p < 0.01$) with an increase in vibration magnitude up to 1.5ms^{-2} r.m.s. in both stance orientations. No significant differences were found between the two stance orientations.

For y-axis vibration, magnitude estimations showed significantly ($p < 0.01$) higher measures of workload with increased vibration magnitude during both stances. Magnitude estimations of workload showed no significant influence of stance orientation for all vibration magnitudes used in the study. Comparing workload estimations between x-axis and y-axis vibration exposures, no significant effects of vibration direction were found. Dual-axis vibration showed significantly (p <0.01) higher measures of workload with increased magnitudes up to 2.1ms^{-2} r.s.s., for both stances. No postural effects due to stance orientation were found during exposure to dual-axis vibration.

5.4.3 Postural Stability

In the discrete manual control study the participants were not provided with any postural support. A hand rail was mounted onto the vibration simulator platform; however this was necessary for safety reasons and not intended to aid stability of the standing participants. During each vibration condition, the researcher noted any loss of stability that required the participants to grasp on to the hand rail (Table 5.4). These observations showed that losses of balance occurred primarily at the highest vibration magnitudes. The cases of instability during the high magnitude condition are presented in Table 5.4. Postural instability was more prevalent in the anterio-posterior stance (76%) compared to the lateral stance (24%).

Table 5.4 Postural instability of participants performing a discrete manual control task during vibration exposure *

Vibration Axis	Stance Orientation	Cases of Instability (number)
X-axis	Lateral	6
	Anterio-posterior †	7
Y-axis	Lateral †	4
	Anterio-posterior	18
XY-axes	Lateral	12
	Anterio-posterior	43

Where: * 2.0ms^{-2} r.s.s. for x-axis and y-axis vibration, 2.8ms^{-2} r.s.s. for xy-axes vibration

† Maximum base of support (stance orientation in same direction as vibration)

In the continuous manual control task, the coupling between the limb / hand and the control device meant that cases of instability could not be clearly identified and were therefore not recorded.

5.5 DISCUSSION

The overall aims of these studies were to investigate the extent to which discrete and continuous manual control performance and the associated subjective ratings of workload were affected by variations in stance orientation and vibration magnitude and direction.

5.5.1 Manual Control Performance

Previous studies that have considered manual control performance have often presented conflicting results. Reviews published by Lewis and Griffin (1978) and McLeod and Griffin (1989) concluded that, progressive decrements in manual control performance would be expected with increasing vibration magnitudes. In contrast, studies by Catterson *et al.* (1962) and Newell and Mansfield (2008) found relatively minor influences of vibration exposure on task performance. Contributing factors to these findings could be due to differences in the type of tasks assessed, the characteristics of vibration and the physical capabilities of the participants to perform the tasks. Results from the current studies revealed significant and progressive decrements in discrete manual control performance with increasing vibration magnitude, whereas continuous manual control performance was found to be unaffected by vibration exposure.

Discrete manual performance was found to be significantly degraded at vibration magnitudes commonly experienced during rail travel (0.5 ms^{-2} r.m.s.) and which support previous findings reported in the literature for a range of tasks (Corbridge and Griffin, 1991; Griffin and Hayward, 1994 and Mansfield *et al.,* 2007). This would suggest that standing passengers exposed to vibration, would experience a degree of performance degradation when using mobile technologies. In particular, the performance of discrete controls tasks, such as pressing specific buttons, would be compromised.

It should be recognised that the sensitivity of the pegboard task could have exacerbated the effects of vibration. Additionally, the separation of the controlling limb / hand and the task could increase the relative motion of the hand and consequently lead to greater degradation in performance (Paddan and Griffin, 1995). The influence of coupling between the controlling limb / hand and the task has been demonstrated by Newell and Mansfield (2008). These results are presented in Figure 5.8 and show that an increase in reaction time (corresponding to a decrease in performance) occurred in conditions where there was no arm support or coupling.

For the continuous tracking task, coupling was provided at the control, which would reduce the relative displacement between limb / hand and the controlling device. As evidenced by the results in Figure 5.5, continuous manual control showed no performance degradation during vibration exposure. These findings could partly be explained by the sensitivity of the control device. The steering control has been developed to perform in vibration environments and would likely attenuate the vibration to a greater extent than other devices (for example, the pegboard). Nevertheless, the results would suggest that for standing passengers exposed to vibration magnitudes commonly experienced on rail transportation, the performance of tasks involving continuous manual control (for example, gaming acitivities), would not be significantly degraded.

5.5.2 Subjective Workload

Subjective measures for both studies showed a progressive increase in workload with a corresponding increase in vibration magnitude. These results support previous findings that showed a progressive increase in subjective ratings of intensity with vibration magnitude for single-axis and dual-axis vibration (Mansfield and Maeda, 2007). Furthermore, Newell and Mansfield (2008) found that subjective workload increased with corresponding increases in vibration magnitude, despite no objective reduction in performance. Individuals were therefore able to compensate for vibration interference and maintain performance levels, at the expense of increased workloads. Compared to the control condition, workload estimations in the highest magnitude conditions increased by approximately 330%, 270% and 400% for the discrete control task (during x-, y- and xy-axes respectively). For the continuous control task, workload experienced during the highest magnitude conditions increased by approximately 170%, 160% and 180% (x-, y- and xy-axes respectively).

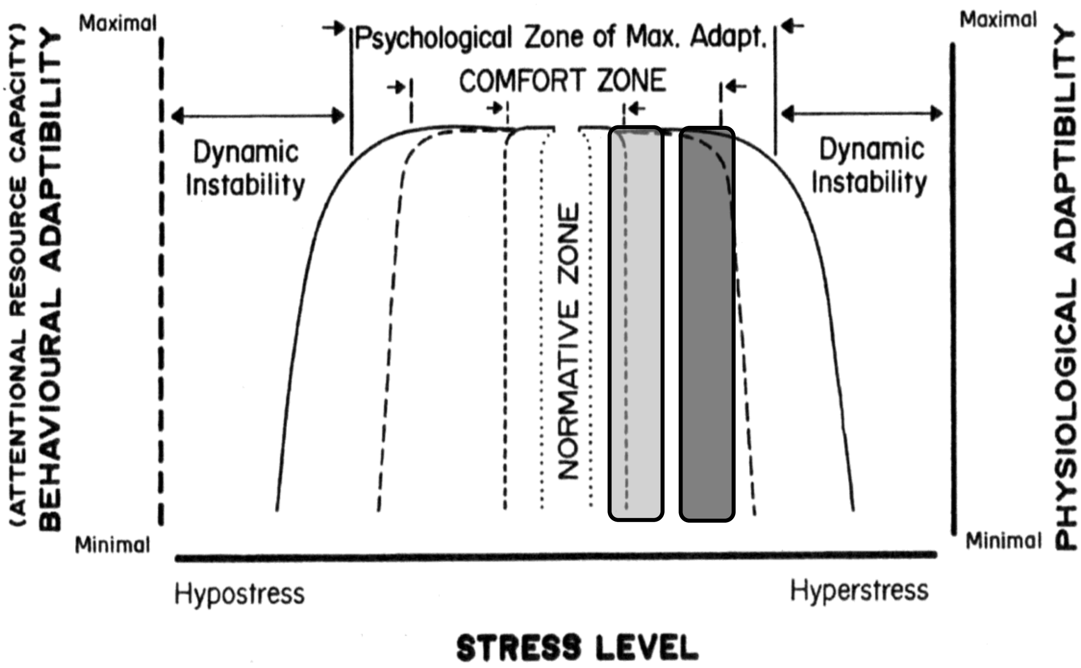
Data presented in Table 5.3 showed that the growth of workload sensation increased more rapidly for the discrete control task compared to the continuous control task. For example, a semantic rating of ‘Difficult’ equated to a workload of between 289 – 301 (approximately 3 times greater than the reference condition); while the same semantic rating for the continuous task represented a workload of only 143 (approximately 1.5 times the reference condition).

These results highlight the importance of investigating objective performance measures as well as understanding the subjective responses associated with various tasks. The influence of vibration exposure may not always be expressed in terms of performance, as demonstrated in the continuous control task. Furthermore, verbal descriptors of task difficulty may not fully describe the subjective workload experienced by an individual, as shown in Table 5.3.

5.5.3 Adaptability

The relationship between stress and performance has previously been expressed using an extended-U curve (Figure 5.9) based on the Maximal Adaptability Model developed by Hancock and Warm (1989). In the two studies presented in this chapter, the stress experienced by individuals would represent the exposure to whole-body vibration. A central feature of this model was that under most environmental conditions individuals would adapt effectively to environmental disturbances and maintain performance capacity. Such adaptation would occur on multiple levels and show an inverse relationship to increasing levels of vibration (stress). With increasing vibration exposure, adaptation would progressively fail – firstly on a subjective (comfort or workload) level, followed by a behavioural response that would influence performance and finally, physiological failures (for example, an injury due to high vibration exposure).

Both studies reported in this chapter exhibited an increase in workload representing a subjective adaptation. During the discrete control task, the progressive degradation of performance (behavioural change) highlighted an inability of the participants to adapt to the increased stress of vibration exposure. In the continuous control task, participants were able to maintain a level of performance despite increasing vibration magnitudes. Although participants were able to adapt on a behavioural level, this was at the expense of subjective workload. These levels of adaptation due to vibration exposure for the discrete and continuous control tasks are included in Figure 5.9.



Where: black = discrete control task and grey = continuous control task

Figure 5.9 The extended-U relationship between stress level and response capacity, based on the Maximum Adaptability Model (*adapted from Hancock and Warm, 1989*)

5.5.4 Stance Orientation and Vibration Direction

Body posture has been identified by Griffin (1990) as one of the main factors affecting task performance during vibration exposure. In the discrete control study, exposure to vibration produced some clear postural influences with performance significantly ($p < 0.05$) lower in the anterio-posterior stance compared to the lateral stance (at magnitude 2.8ms^{-2} r.s.s., dual-axis). Discrete control performance was also degraded to a lesser extent during y-axis vibration (significant at 2.0 ms^{-2} r.m.s.). During lower magnitudes of vibration, stance orientation and the direction of motion produced little influence on performance. Similar trends were observed for the continuous control task, although no significant stance or directional effects were found.

By increasing the base-of-support (BOS) in the direction of movement, Griffin (1990) suggested stability could be improved, potentially reducing the detrimental effects of vibration on performance. It was proposed therefore, that in conditions where the stance orientation was aligned in the direction of movement (the lateral stance during y-axis vibration and the anterio-posterior stance during x-axis vibration); the influence of vibration on performance would be less than conditions where the BOS was minimal in relation to the direction of motion. These interaction effects between the stance orientation and the direction of motions showed no significant influence on both the discrete and continuous manual control tasks. It was suggested therefore, that the effects of vibration exposure on manual control performance would occur independently of the stance adopted by individuals.

Subjective measures showed similar trends to the performance results. The anterio-posterior stance produced higher workload estimations and difficultly ratings than the lateral stance for the discrete control tasks (during y-axis vibration at all magnitudes tested between 0.5 – 2.0ms^{-2} r.m.s.). The direction of vibration showed no influence on the subjective measures for the continuous control task but directional effects were found for the discrete control task. At magnitudes 0.5 and 2.0ms^{-2} r.m.s. subjective measures of workload and difficulty were significantly ($p < 0.05$) lower during y-axis motion than in the x-axis. No interaction effects between stance orientation and direction of motion (related to the BOS) were found for either task.

5.5.4.1 Postural Instability

During the discrete control study, participants were provided with no additional postural support and observations were recorded to account for any cases of instability. Postural instability influences the surface contact with the vibration source, the position of the spine and can lead to increased muscular exertion in order to maintain balance (Mathews *et al.*, 2006). Observations of stability recorded during each vibration condition showed that most cases of instability occurred during the high vibration magnitude conditions (2.0ms^{-2} r.m.s. and 2.8ms^{-2} r.s.s. for single-axis and dual-axis vibration respectively). Cases of instability were substantially more frequent in the anterio-posterior stance, compared to the lateral stance.

Nawayseh and Griffin (2006) identified that loss of balance during horizontal vibration exposure was influenced by the base-of-support (BOS) in the direction of movement; however the results from the current study showed the greatest stability occurred when participants adopted a lateral stance, irrespective of the direction of motion. A possible explanation could be that during quiet standing the majority of individuals position the feet side-by-side in a lateral stance (McIlroy and Maki, 1999) rather than an anterio-posterior stance. As this would be the natural stance position for individuals, the lateral stance would likely provide improved balance and therefore, the direction of vibration would exhibit less influence on stability.

These observations also highlight the importance of postural supports in environments where standing individuals could be exposed to whole-body vibration. In most environments the vibration experienced by individuals would act in multiple axes, rather than in a single direction.

5.5.5 Dual-Axis Prediction

The effects of multiple-axis vibration have been found to be similar to those reported during exposure to single-axis vibration corresponding to the root sum of squares (r.s.s.) of the magnitudes in each axis (Lewis and Griffin 1978). This method (termed r.s.s. summation) combines the responses obtained during single-axis exposure in order to predict the responses expected to occur during exposure to multiple-axis vibration. The measured responses during dual-axis exposure can therefore be compared to the predicted responses calculated by the r.s.s. summation of the single-axis responses. The performance measures and subjective measures of workload are presented in Figures 5.10 and 5.11).

Comparing the measured dual-axis responses with the predicted dual-axis responses, the r.s.s. summation method showed a slight under-prediction during the discrete control task and an over-prediction during the continuous control task. These findings were consistent for performance measures as well as subjective workload estimations, in both the anterio-posterior and lateral stances. The differences between under- and over-predictions for the discrete and continuous tasks could be due to the influence of adaptation in the continuous task. With increasing vibration magnitudes the r.s.s. summation would predict greater performance decrements however, participants were able to compensate for the increase in vibration and maintain performance.

The percentage errors in r.s.s. summation predictions for performance measures were < 8% and < 12% and for subjective workload responses: < 11% and < 13% (discrete and continuous control tasks respectively). These error levels would be acceptable for response predictions and the r.s.s. summation method could therefore be used to estimate human responses to dual-axis vibration based on single-axis measurements.

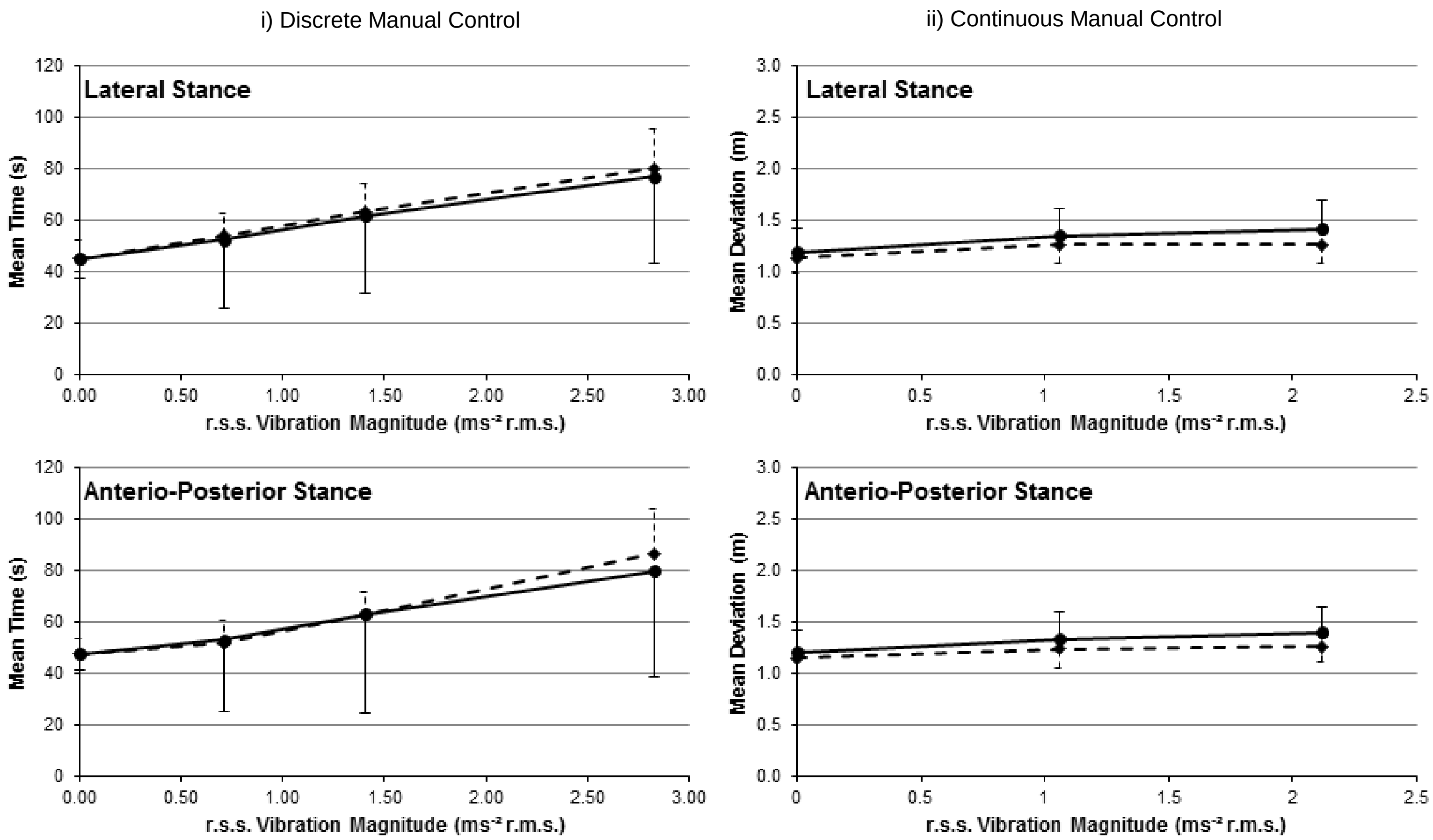


Figure 5.10 Comparison between vibration direction showing mean performance responses for discrete and continuous control tasks, including r.s.s. summation dual-axis predictions (solid line = predicted response (r.s.s. summation) and dashed line = measured response)

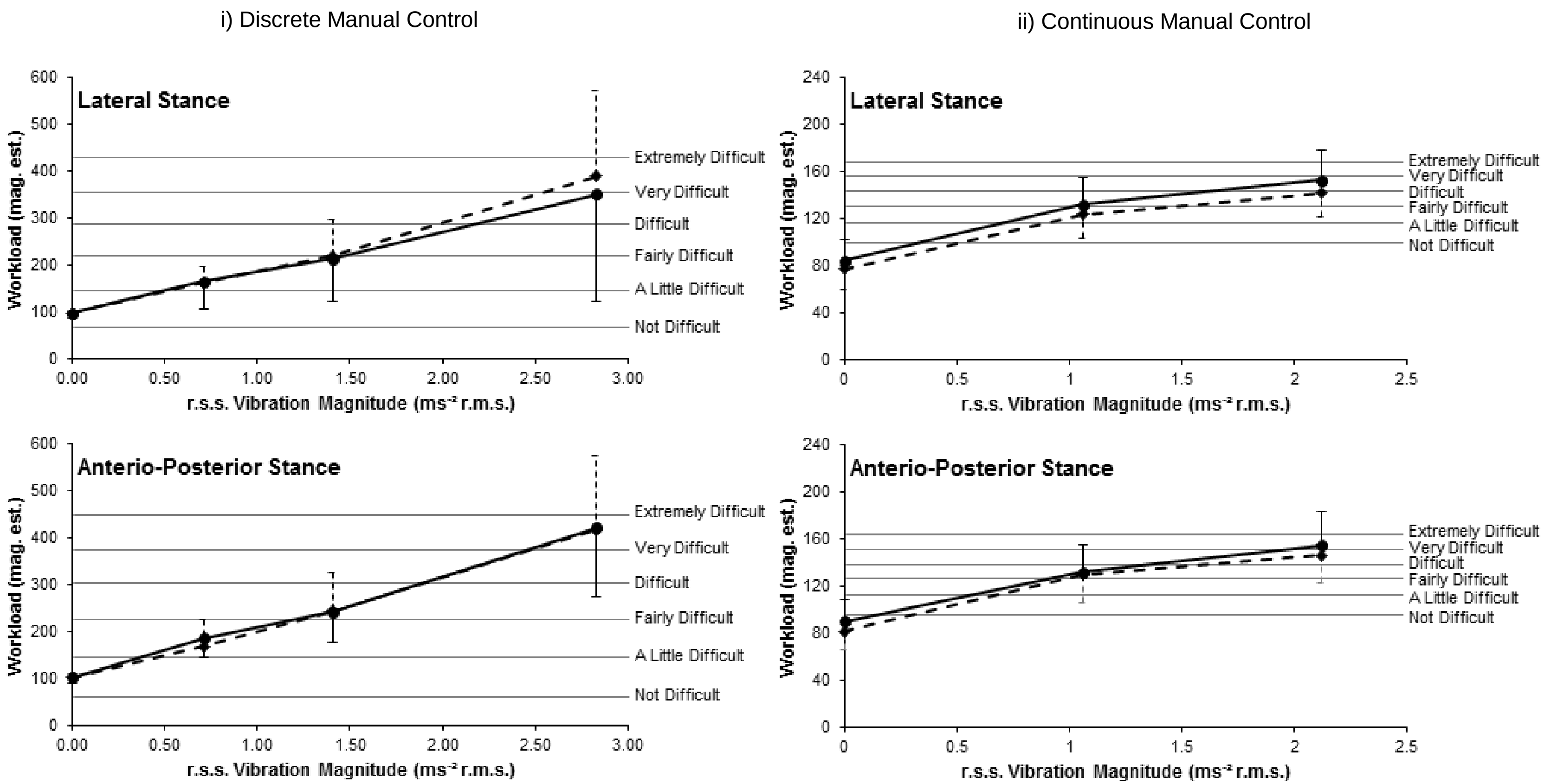


Figure 5.11 Comparison between vibration directions showing mean subjective workload responses (magnitude estimations and semantic ratings) for discrete and continuous control tasks (solid line = predicted response (r.s.s. summation) and dashed line = measured response)

5.6 CONCLUSIONS

The studies presented in this chapter were designed to investigate the extent to which manual control performance and subjective ratings of workload were affected by the type of manual control task performed, the stance orientation of the individual and the characteristics of the vibration exposure (magnitude and direction).

H1: Manual control performance and ratings of workload would vary between the discrete and continuous tasks.

Discrete manual control performance progressively degraded with increasing vibration magnitudes, whereas continuous control performance showed no adverse effects to vibration exposure. The different patterns of response between the two types of task were attributed to the ability of participants to adapt and maintain continuous manual control. In both studies, the subjective workload experienced by the participants during the vibration conditions increased progressively with increasing vibration magnitudes. The level of workload was substantially higher during the discrete control task compared with the workload experienced during the continuous control task.

H2: Performance and workload measures would be significantly different between the two stance orientations and between the different directions of motion.

Stance orientation during standing exposure to vibration showed limited effects on performance (significant effects were only found during the discrete control task at magnitude 2.8 ms^{-2} r.s.s., dual-axis vibration). Subjective workload measures showed significant differences during the discrete control task between anterio-posterior and lateral stances during y-axis vibration. No postural effects due to stance orientations were found during the continuous control task. In general, subjective workload responses tended to be greater in the anterio-posterior stance, compared to the lateral stance.

The effects of vibration direction were found during the discrete control task and showed that significantly lower performance and workload measures during y-axis vibration, compared with the responses obtained during x- and xy-axes vibration. For the continuous control task, vibration direction showed no significant influence on performance and workload measures.

H3: Performance degradation and subjective workload ratings would increase with an increase in vibration magnitude.

Increasing vibration magnitudes resulted in progressive reductions in discrete manual control performance but showed no influence on continuous control performance. In both tasks, subjective responses demonstrated similar effects where workload estimations increased significantly with increasing magnitudes.

Additionally, the results demonstrated that performance and workload responses for discrete and continuous manual control during dual-axis vibration exposure could reasonably be predicted based on responses measured during single-axis vibration exposures using the r.s.s. summation method.

The studies presented in this chapter investigated two types of manual control tasks (discrete and continuous), which represented either end of the manual control continuum. The majority of mobile devices however, would likely be a combination of both of these task classifications and would therefore be classified as serial manual control tasks. The assessment of serial manual control performance using hand-held devices would therefore enhance the applicability of this research to more realistic scenarios, such as mobile device usage on rail transportation. Additionally, a wider range of postures should be considered, rather than only assessing stance orientation. By including seated as well as standing conditions the influence of full-body postural variations could be investigated. As there have been no reported studies that have considered a direct comparison between seated and standing and manual control performance, this information could provide valuable contributions to the literature.

CHAPTER 6

INFLUENCE OF WHOLE-BODY VIBRATION ON MANUAL CONTROL PERFORMANCE IN SEATED AND STANDING POSTURES

This chapter presents a laboratory study conducted at the National Institute of Occupational Safety and Health, Japan (JNIOSH) and designed to investigate the influence of whole-body vibration (WBV) on serial manual control performance using a hand-held keypad device. Most of the devices passengers used while travelling, were found to be hand-held (as shown in Chapter 4) and required serial manual control performance (based on a combination of discrete and continuous task components). In order to improve the overall applicability of the investigation to 'real-world' situations, a hand-held device was designed to assess serial manual control performance during vibration exposure.

Passengers travelling on trains were also found to adopt a wide range of postures, such as different stance orientations (Chapter 4). Despite these postural variations, stance orientation demonstrated limited influence on manual control performance of both discrete and continuous tasks (Chapter 5). Considering a wider range of postures, such as full-body variations of seated and standing postures; would provide an improved representation of the many postures that could be adopted by rail passengers.

Due to the use of random vibration in Chapter 5, the influence of specific frequencies of motion on manual control performance could not be separately identified. To assess the frequency-dependent effects, sinusoidal vibration was selected for the study presented in the chapter. Sinusoidal motion enabled individual frequencies of motion to be considered individually.

6.1 INTRODUCTION

Previously reported studies have typically used discrete and continuous control tasks to assess the influence of WBV exposure on manual control performance (for example, Lewis and Griffin, 1978 and McLeod and Griffin, 1989). While these types of task are important considerations for assessing manual control, in reality the majority of tasks would tend to be classified as serial tasks, consisting of varying degrees of discrete and continuous components (MacLean *et al.,* 2000). These tasks would have a defined beginning and end points but would also require repeated discrete task components to be performed in a semi-continuous manner.

More recently, a number studies have investigated the performance of various serial tasks using hand-held devices (Mizobuchi *et al.*, 2005; Lin *et al.*, 2007 and Hoggan *et al*., 2008). These studies considered a range of postural variations including seated, standing and walking conditions; however, the motion characteristics to which the participants were exposed in these conditions were not reported. The extent to which task performance was affected by postural variations or motion-induced interference would therefore be difficult to validate and comparisons with other studies would likely be unreliable.

Considering the response of the human body to vibration, Matsumoto and Griffin (2000) found that the effects of vibration (z-axis) in standing postures were approximate to those in seated postures. Based on these findings, it was suggested that the effects on task performance would be similar and consequently, no published studies have investigated a direct comparison between manual control performance in seated and standing postures, during WBV exposure. By investigating manual control performance during WBV exposure in both seated and standing postures, the validity of these assumptions could be evaluated.

6.2 RESEARCH HYPOTHESES

This chapter presents a laboratory study designed to investigate the effects of whole-body vibration on serial manual control performance and the associated subjective workload experienced by individuals when using a hand-held device. These effects were assessed in both seated and standing postures to identify the influence of full-body postural variations. Performance measures included the response time (RT) and the error rate (used to determine the performance accuracy), while workload measures included semantic ratings of task difficulty.

The aims of the study were to quantify the extent to which manual control performance and workload were influenced by:

iv) Vibration frequency,
v) Vibration magnitude,
vi) Vibration direction,
vii) Variations in posture (seated and standing).

It was hypothesised that:

H1: Serial manual control performance and ratings of workload would show frequency-dependent effects within the given frequency range (1 – 8Hz).

H2: These effects would vary between different directions of motion.

H3: Increasing vibration magnitudes would result in reduced manual control performance and higher workload (based on the results in Section 5.4 Results – discrete and continuous manual control).

H4: Postural effects were expected to occur between the seated and standing postures. In the standing posture, exposure to horizontal vibration (x- and y-axis) was expected to compromise stability and result in greater effects of vibration on manual control performance and workload in the standing posture than when seated. During z-axis vibration, less influence on stability was expected and no significant differences would be found between the seated and standing postures.

6.3 METHODS

6.3.1 Participants

Participants were all Japanese post-graduate students recruited from universities in the Tokyo and Kanagawa prefectures, Japan. All participants received information concerning the experimental procedures and possible risks associated with participation. The study was approved by the Research Ethics Committee of National Institute of Occupational Safety and Health, Japan (JNIOSH). Prior to commencing the experimental testing, informed consent was obtained and anthropometric data were collected from all participants (Table 6.1).

Table 6.1 Anthropometric characteristics of participants from the serial manual control study (hand-held keypad)

Characteristic	**Hand-Held Keypad Task**
Number	16
Gender	16 male
Age	21 – 26years (mean ± sd: 22.8 ± 1.5years)
Stature	1624 – 1764mm (mean ± sd: 1693.3 ± 46.4mm)
Mass	46.2 – 77.4kg (mean ± sd: 59.9 ± 7.5kg)
Shoulder Width	368 – 472mm (mean ± sd: 429.3 ± 26.8mm)
Seated Shoulder Height	546 – 639mm (mean ± sd: 595.1 ± 26.3mm)
Standing Shoulder Height	1283 – 1455mm (mean ± sd: 1374.7 ± 58.8mm)

6.3.2 Pilot Testing

Pilot testing provided an opportunity for the experimenters to become familiar with the experimental protocols and the use of the testing equipment. Additionally, the pilot tests were used to establish the characteristics of the vibration stimuli that would be presented to the participants. It was determined that above a vibration frequency of 8.0Hz and below a magnitude of 0.4ms^{-2} r.m.s., no significant effects were found on performance measures and subjective responses of the participants. Furthermore, the capability of the vibration simulator equipment limited the maximum vibration magnitude that could be produced (up to a frequency of 8.0Hz) to 1.2ms^{-2} r.m.s.. In order to minimise the effects of fatigue, the number of vibration stimuli was limited to 48 conditions, which limited the overall length of the testing session to approximately 90minutes (excluding a 10minute break).

The participants adopted the same postures as described in Section 6.3.3.2 and the performance results obtained during the pilot tests were used to establish the number of familiarisation trials required to minimise the learning effect when using the hand-held keypad (Figure 6.1). The participants used in pilot testing did not take part in the experimental testing.

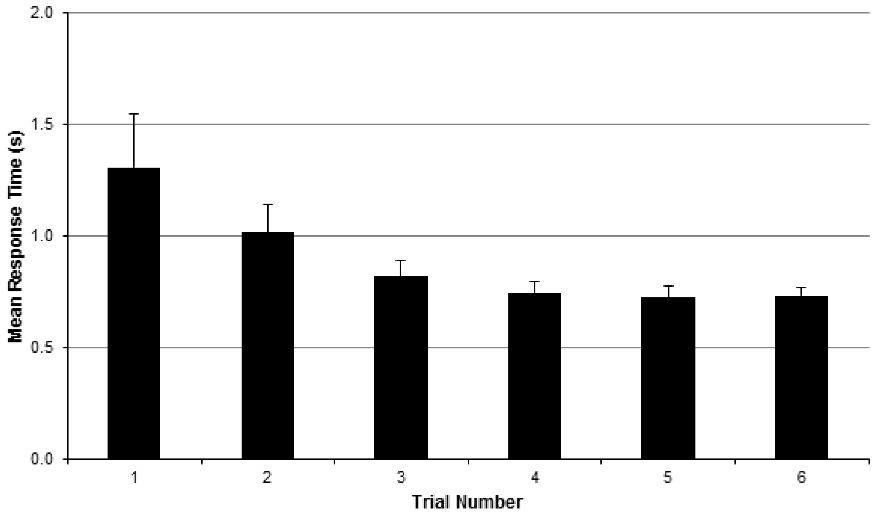


Figure 6.1 Mean (n = 4) response time (RT) taken to complete a serial manual control task using a hand-held keypad obtained during pilot testing, demonstrating a learning effect with repeated trials

6.3.3 Independent Variables

6.3.3.1 Vibration

Using a multi-axis vibration simulator (IMV Corporation, Japan) driven by 7 electro-dynamic shakers, participants were exposed to sinusoidal vibration in the fore-and-aft (x-axis), lateral (y-axis) and vertical (z-axis) directions independently. Cross-talk between the different directions of motion was limited to 5%. Sinusoidal vibration ensured the vibration energy was composed of a single frequency. Within 'real world' environments, vibration exposures tend to occur over a range of different frequencies rather than separate individual frequencies. For this reason, sinusoidal motions do not commonly occur in these environments however, these signals are particularly useful for developing an understanding of the frequency-dependent responses of the human body in laboratory conditions (Mansfield, 2005).

Table 6.2 Summary of the sinusoidal vibration stimuli used during the hand-held keypad performance study

Condition	Vibration Magnitude (ms^{-2} r.m.s. unweighted)	Vibration Frequency (Hz)		
		x-axis	y-axis	z-axis
Control	---	---	---	---
1	0.4	1.0	---	---
2		2.0	---	---
3		4.0	---	---
4		8.0	---	---
5	0.4	---	1.0	---
6		---	2.0	---
7		---	4.0	---
8		---	8.0	---
9	0.4	---	---	1.0
10		---	---	2.0
11		---	---	4.0
12		---	---	8.0
13	1.2	1.0	---	---
14		2.0	---	---
15		4.0	---	---
16		8.0	---	---
17	1.2	---	1.0	---
18		---	2.0	---
19		---	4.0	---
20		---	8.0	---
21	1.2	---	---	1.0
22		---	---	2.0
23		---	---	4.0
24		---	---	8.0

In each direction of motion, four octave-band frequencies were investigated: 1.0, 2.0, 4.0 and 8.0Hz, and two vibration magnitudes were selected: a low condition ($0.4ms^{-2}$ r.m.s.) and a high condition ($1.2ms^{-2}$ r.m.s.). The experimental conditions are presented in Table 6.2 and a description of the randomisation of the test conditions is provided in Section 6.3.5.2. Participants were exposed to the vibration stimuli in two postures: seated and standing (representing a total of 48 vibration conditions and 8 control conditions). During the control conditions, the vibration simulator equipment remained pressurised to minimise the influence of possible confounding factors (such as the noise generated when the system is operated) on the performance and subjective responses of the participants.

6.3.3.2 Posture

Two postures were adopted by participants during the experimental conditions: (i) a ‘comfortable upright’ seated posture on a rigid flat seat with no backrest and (ii) an upright free-standing posture (Figure 6.2). In the standing posture participants were instructed to keep their knees locked and place their feet shoulder-width apart in a lateral stance. Foot separation was measured as the distance between the distal portions of the second tarsal phalange on each foot. Coloured markers were placed on the seat surface and on the floor of the simulator platform to ensure participants adopted the correct seated and standing postures. No upper body support was provided in either the seated or standing postures however, for safety reasons participants wore an adjustable harness which was secured to a frame mounted above the simulator platform. This harness did not provide any additional support for the participants.

Seated Posture   Standing Posture

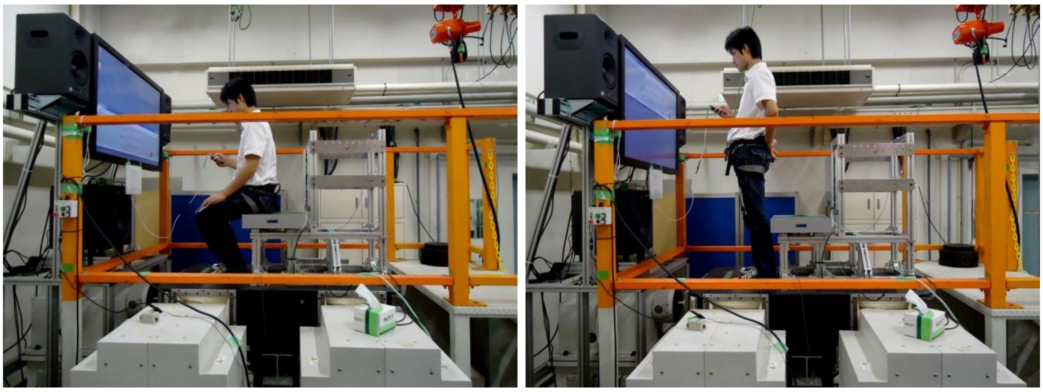


Figure 6.2 Seated and standing postures adopted by the participants on the motion platform (safety harness not shown for purposes of clarity)

6.3.4 Dependant Variables

6.3.4.1 Objective Measurement

Using a generic non-tactile membrane keypad (manufactured by Apem Components Limited, UK), participants were required to enter a sequence of numbers that were displayed on a screen. The keypad was fitted into a rigid plastic moulding (manufactured by RION Company Ltd, Japan) to approximate the dimensions (size and mass: 115 × 60 × 12mm and 130g) of commonly observed hand-held devices used by standing passengers (Chapter 4). The keypad and moulding are shown in Figure 6.3.

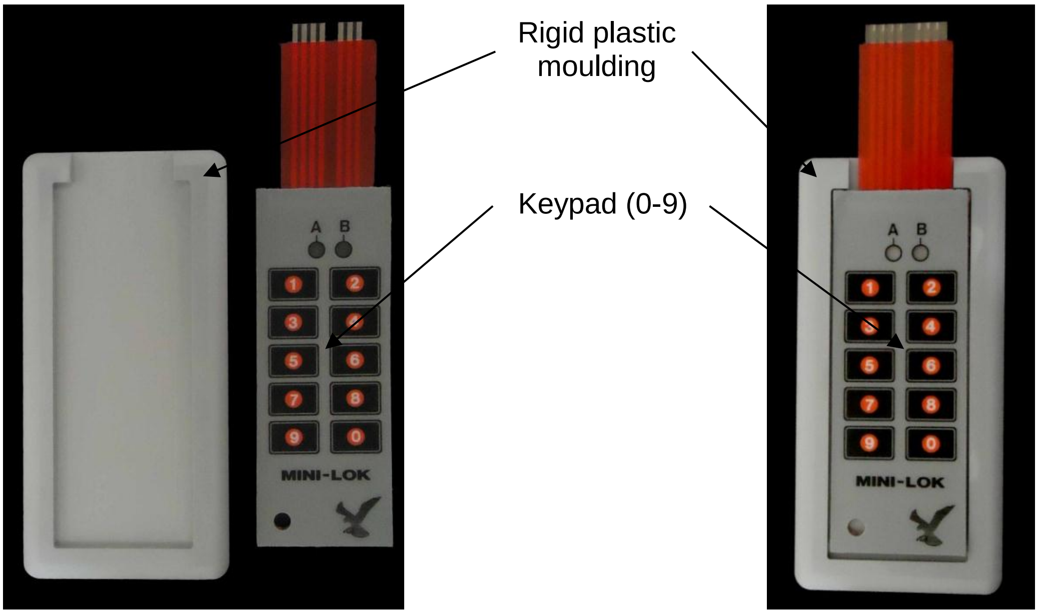


Figure 6.3 Non-tactile membrane keypad fitted into the rigid plastic moulding

LabVIEW software (version 8.2) was used to develop an in-house program to generate random single-digit numbers between one and nine, which represented the 'target' numbers for the serial manual control task. These numbers were displayed in clusters of five (determined to be within the capacity for short-term working memory (Miller, 1956)) on a screen located in front of the participant (Figures 6.4i and 6.4ii). The 'target' numbers were displayed on a separate screen to the hand-held device in order to simulate the type of interactions that occur when people use mobile devices while travelling. Holleis *et al.* (2007) noted that when operating a hand-held device, individuals tended to divide their attention between mobile device and the real world surroundings, shifting visual focus between near and distant locations.

(i) Seated Posture (posterior view)

(ii) Zoomed screenshot of task display

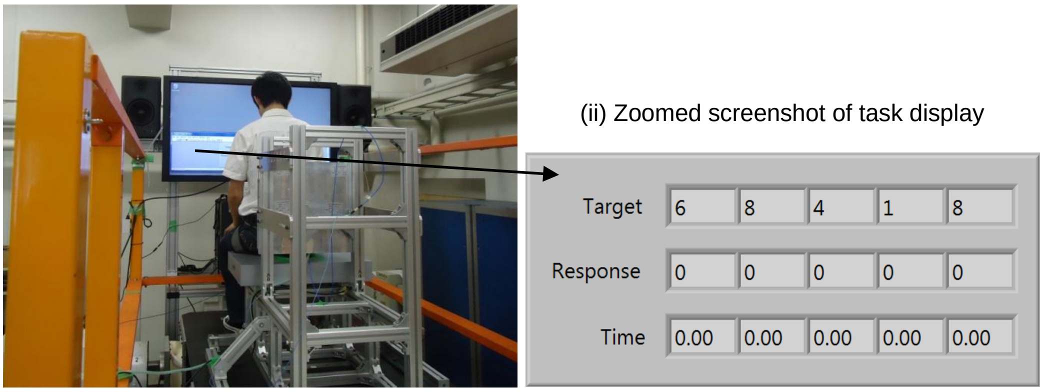


Figure 6.4 Posterior view of seated posture showing: i) the display in front of the participant, ii) a zoomed screenshot view of the task display showing the 'target' and response numbers, as well as the response time

The participants were instructed to respond 'as accurately and as quickly as possible' by pressing the corresponding number on the keypad. A correct input response was required before the subsequent 'target' number could be selected. The response time (RT) taken to correctly register the corresponding 'target' number and selection errors caused by pressing incorrect numbers on the keypad were automatically recorded by the LabVIEW program. The response time for each selection was displayed on the screen to provide the participants with immediate performance feedback. Performance feedback has been found to act as a positive motivating factor for reaction time tasks and may promote more consistent reaction time performance compared to testing programs that do not provide any feedback (Eckner *et al.,* 2011). Once five correct responses were completed the display refreshed with a new cluster and this process was repeated five times (representing 25 'target' numbers) for each experimental condition.

Manual performance using a hand-held device was evaluated based on the mean response time (RT) taken to complete a single correct input. Incorrect responses were recorded and expressed as a percentage of the total input responses to provide a measure of performance accuracy. The response time (RT) and input errors were recorded automatically using an in-house program developed in LabVIEW (Version 8.2) software (National Instruments Corporation, UK).

6.3.4.2 Subjective Measurement

Following the completion of each experimental condition the participants were asked to assign a verbal descriptor of task difficulty, using the same six-point semantic scale described in Section 5.3.4.2 Subjective Measurement.

6.3.5 Experimental Protocol

The experimental protocol was conducted during a single laboratory testing session at the National Institute of Safety and Health, Japan (JNIOSH). The session commenced with three familiarisation trials, which provided the participants with an opportunity to practice operating the keypad, as well as gain an understanding of the semantic scale for rating task difficulty. Based on the measured anthropometric data, markers were placed on the seat surface and on the motion platform to ensure the participants adopted the correct seated and standing postures during the testing conditions. The image of the LabVIEW program on the screen was set at seated and standing shoulder height in the seated and standing postures respectively (Figure 6.2). This ensured the viewing angle between the participant and the screen was the same in both postures.

The experimental conditions were presented in two testing 'blocks', separated according to vibration magnitude ('low' and 'high' conditions), with each 'block' consisting of 24 vibration conditions and four control conditions. Participants were given a 10minute rest-break between each testing 'block'. This served to minimise any fatigue effects due to WBV exposure and helped the participants maintain motivation for the remaining experimental trials. Prior to and immediately after each testing 'block', a static control condition (no vibration) was conducted in each posture. The control conditions served as a reference for subjective ratings and provided a baseline measure of performance. The experimental setup is shown in Figure 6.5. The order in which the control conditions were presented alternated between postures within each testing 'block' and for each participant. The vibration conditions were counter-balanced for posture, randomised and for vibration direction and vibration frequency using a balanced Latin-square technique.

The simulator platform was controlled by a dedicated laboratory computer system, while a secondary laptop computer was used to run the LabVIEW software and testing program. Two separate researchers were responsible for operating these computers. The LabVIEW testing program was only started once the vibration platform had stabilised at the required magnitude (approximately 5seconds after initiating the motion file on the computer). Once the participant had completed the input task, the LabVIEW program stopped automatically, the vibration input ceased and the platform was returned to a 'neutral' position.

BLOCK 1 (45minutes)		
Control Conditions (2) Seated/Standing	**Vibration Conditions (24)** Balanced Latin-square design	**Control Conditions (2)** Standing/Seated
BREAK (10minutes)		
Control Conditions (2) Standing/Seated	**Vibration Conditions (24)** Balanced Latin-square design	**Control Conditions (2)** Seated/Standing
BLOCK 2 (45minutes)		

Figure 6.5 Diagrammatic representation of experimental setup showing testing ‘blocks’ used during the serial manual control study for seated and standing individuals

6.3.6 Data Analysis

Objective performance was evaluated using the mean response times taken to enter ‘target’ numbers and the accuracy of performance (based on incorrect inputs). The number of incorrect inputs was recorded and performance accuracy was calculated as a percentage of the total number of inputs (Equation 6.1).

$$Perf.\ Accuracy\ (\%) = \frac{No.\ Correct\ Responses - No.\ Incorect\ Responses}{No.\ Correct\ Responses} \times 100 \quad \text{Equation 6.1}$$

The response times were divided into two classifications: the response time to enter the initial ‘target’ number ($RT_{INITIAL}$) and the time taken to enter the subsequent four ‘target’ numbers (RT_{SUB}). Figure 6.6 provides an example of the variation in mean response times for each of the ‘target’ numbers within the five digit sequence. The initial response time ($RT_{INITIAL}$) was located at position 1, whereas the subsequent response time (RT_{SUB}) was calculated as the mean of positions 2 – 5.

In order to perform averaging and statistical analysis on the subjective workload responses, the verbal descriptors provided in the semantic were converted to a numerical expression between one (1) and six (6). This technique was validated in Section 5.3.6.2 Subjective Measures of Workload, where semantic ratings were found to show an acceptable linear relationship when plotted against numerical ratings for subjective workload.

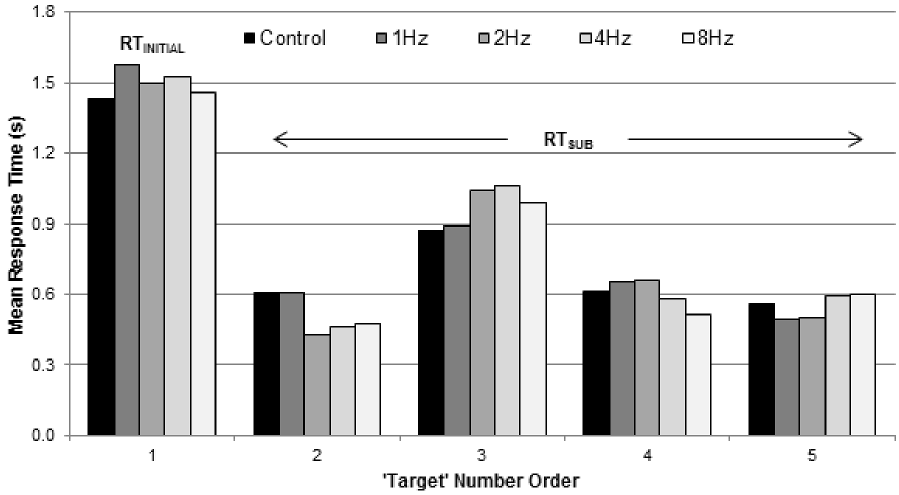


Figure 6.6 Mean response times taken to input a correct 'target' number, based on the order in which the number appeared in the five digit sequence (condition: y-axis, 1.2ms^{-2} r.m.s., standing posture)

Statistical analysis was conducted using *SPSS*® software (Version 15.0). A repeated measures analysis of variance was used to determine whether vibration magnitude, direction and posture had significantly influenced objective performance and subjective workload. These results were analysed across all the tested frequencies.

6.4 RESULTS

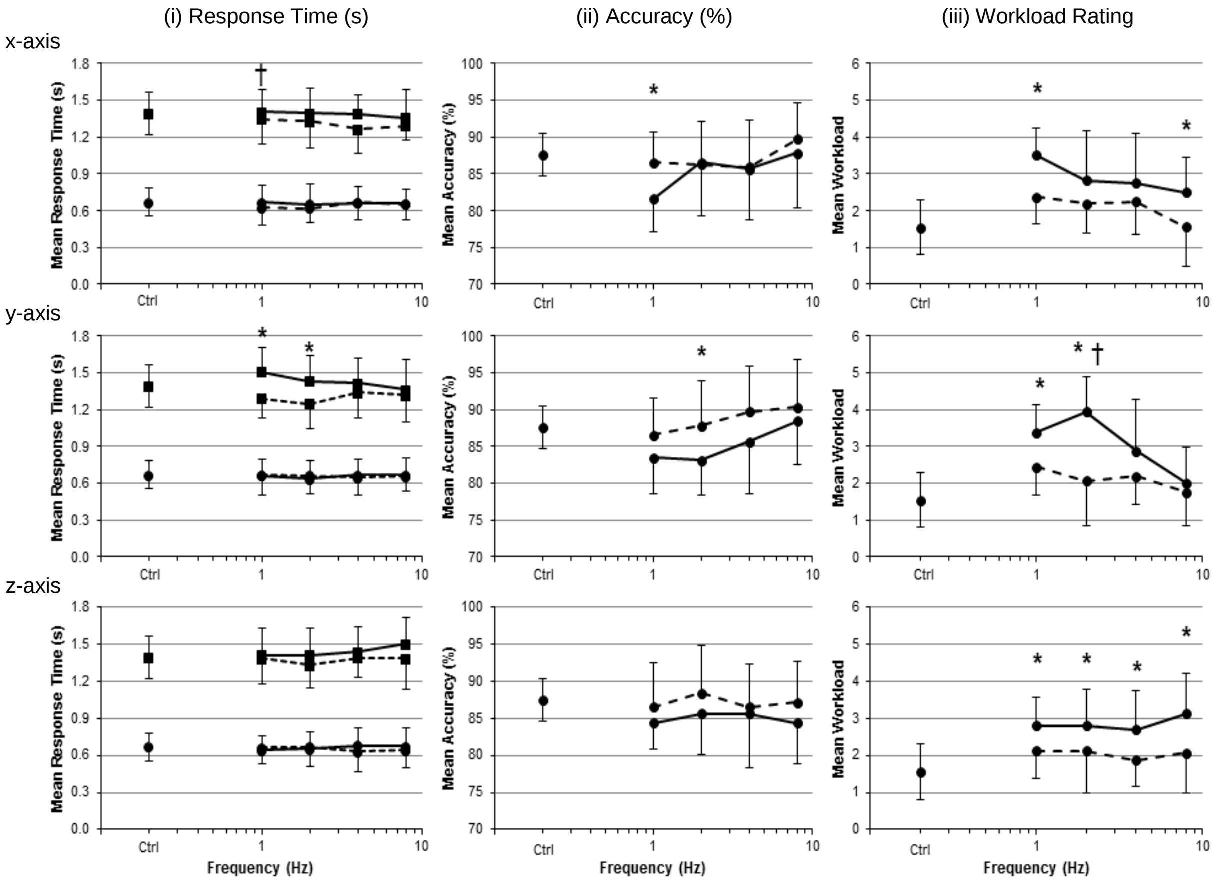
The results for the seated posture are presented first (Figure 6.7), followed by the standing posture (Figure 6.8) and finally, a summary and comparison of both postures is presented in Section 6.4.3 Results Summary and Comparison).

6.4.1 Seated Posture

6.4.1.1 Objective Task Performance

Considering the mean response time for the subsequent 'target' numbers (RT_{SUB}) in the seated posture, no significant effects were found during exposure to vibration (column (i), Figure 6.7). These findings were consistent between the low and high magnitude conditions, in each direction of motion (x-, y- and z-axis) as well as across all frequencies tested (1 – 8Hz).

Significant ($p < 0.05$) effects of WBV exposure were found in the response time for the initial 'target' number ($RT_{INITIAL}$) – during y-axis vibration, the $RT_{INITIAL}$ was significantly ($p < 0.05$) greater during exposure to 1 and 2Hz vibration in the high magnitude condition (1.2 ms^{-2} r.m.s.) than during exposure to low magnitude vibration (0.4ms^{-2} r.m.s.). The significant effects of vibration frequency on response time and accuracy have not been indicated on the graphs in Figure 6.7 as the number of indicators could make interpretation of the curves difficult. Instead, these are presented in Section 6.4.3 Results Summary and Comparison.



Where: * = significant ($p < 0.05$) difference between low and high magnitude conditions.
† = significant ($p < 0.05$) difference between seated and standing postures.
■ = initial target number input (1)
● = subsequent target number inputs (2 – 5)

Figure 6.7 Mean response time, performance accuracy and subjective workload for seated individuals exposed to single-axis sinusoidal vibration between 1 and 8Hz (dashed line = 0.4ms^{-2} r.m.s., solid line = 1.2ms^{-2} r.m.s. and ctrl = no vibration)

Performance accuracy (column (ii), Figure 6.7) was significantly lower ($p < 0.01$) during exposure to high magnitude vibration than during the low magnitude exposure, at frequencies of 1Hz (x-axis) and 2Hz (y-axis). In the z-axis, accuracy tended to be lower during high magnitude exposure than during low vibration magnitudes (although this trend was not found to be significant). There was no significant influence of vibration direction on performance accuracy in a seated posture.

6.4.1.2 Subjective Measures of Workload

Ratings of subjective workload (column (iii), Figure 6.7) tended to be higher during the high magnitude condition than those obtained during the low condition. These effects were significant ($p < 0.05$) at 1 and 8Hz (x-axis), 1 and 2Hz (y-axis) and at all frequencies tested between 1 – 8Hz (z-axis).

Considering the direction of motion, subjective workload showed distinctly different trends between horizontal and vertical directions of motion. In the x- and y-axes, the workload experienced by participants tended to decrease as the frequency of vibration exposure increased from 2 to 8Hz (Figure 6.7). In the z-axis, the opposite trend was observed, where the highest subjective workload ratings were found to occur at 8Hz.

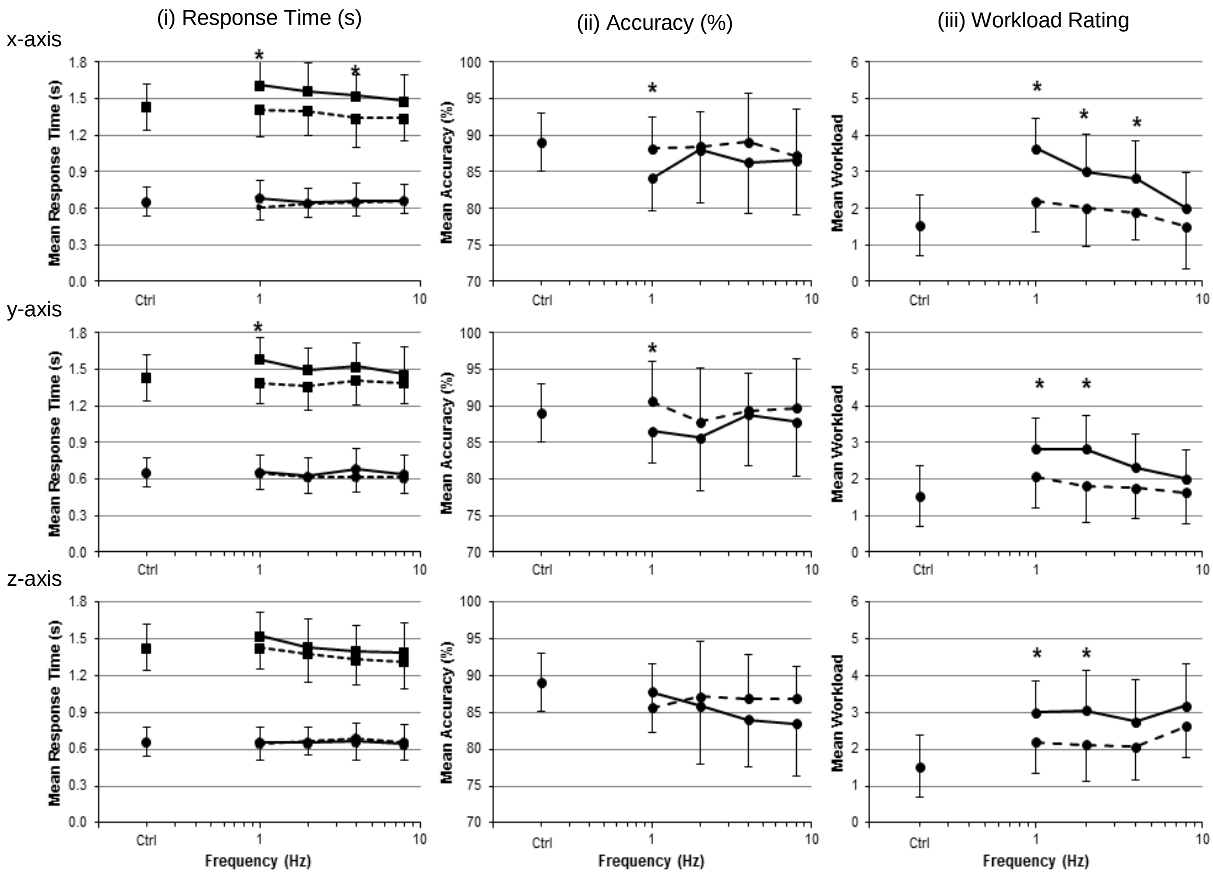
6.4.2 Standing Posture

6.4.2.1 Objective Task Performance

As was seen with the seated posture, the mean response time to enter the subsequent 'target' numbers (RT_{SUB}) showed no significant effects due to WBV exposure in the standing posture (column (i), Figure 6.8). These findings were consistent between each direction of motion, across all the tested frequencies between 1 – 8Hz (both the low and high magnitude conditions). Compared to the low magnitude conditions, the results obtained for the initial 'target' number response times ($RT_{INITIAL}$) during high magnitude vibration exposures were significantly ($p < 0.05$) greater at 1 and 4Hz (x-axis) and at 1Hz (y-axis). No significant difference between magnitude conditions was found in the z-axis, although the $RT_{INITIAL}$ during high magnitude vibration tended to be greater than during low magnitude exposure (column (i), Figure 6.8).

Performance accuracy (column (ii), Figure 6.8 and Table 6.3) in the high magnitude conditions resulted in significantly ($p < 0.01$) lower accuracy at 1Hz (x-axis), 1 and 2Hz (y-axis) and 4 and 8Hz (z-axis). Furthermore, performance accuracy tended to improve with increasing vibration magnitude in the x- and y-axes; however, in the z-axis accuracy was progressing degraded with increasing vibration frequency. These results clearly demonstrate a frequency-dependent effect between different directions of motion, with the greatest decrements in accuracy occurring at lower frequencies in the horizontal directions than in the vertical direction.

Comparing the seated and standing postures, a significant ($p < 0.05$) postural effect was found during x-axis vibration (1Hz, $1.2ms^{-2}$ r.m.s.). The mean $RT_{INITIAL}$ in the seated posture was significantly lower than the mean $RT_{INITIAL}$ in the standing posture during the same vibration condition.



Where: * = significant ($p < 0.05$) difference between low and high magnitude conditions.

† = significant ($p < 0.05$) difference between seated and standing postures.

■ = initial target number input (1)

● = subsequent target number inputs (2-5)

Figure 6.8 Mean response time, performance accuracy and subjective workload for standing individuals exposed to single-axis sinusoidal vibration between 1 and 8Hz (dashed line = $0.4 ms^{-2}$ r.m.s., solid line = $1.2 ms^{-2}$ r.m.s. and ctrl = no vibration)

6.4.2.2 Subjective Measures of Workload

Workload ratings during the high magnitude condition were significantly higher ($p < 0.05$) than those obtained during the low condition at 1, 2 and 4Hz (x-axis), at 1 and 2Hz (y-axis) and at 1 and 2 Hz (z-axis) (column (iii), Figure 6.8). A postural effect was found during y-axis vibration (2Hz, $1.2 ms^{-2}$ r.m.s.), where the workload ratings in the seated posture were significantly ($p < 0.05$) lower than those in the standing posture during the same vibration condition.

6.4.3 Results Summary and Comparison

The results summarised in Table 6.3 provide a comparison between the seated and standing postures and highlight the vibration conditions under which exposure to WBV influenced performance measures and associated subjective workload. Overall, the accuracy of responses (between 83% and 91%) in both the seated and standing postures was consistent with the accuracy reported in previous studies for a range of tasks (Hall *et al*., 1988).

6.4.3.1 Seated Posture

The $RT_{INITIAL}$ significantly ($p < 0.05$) increased compared to the control conditions during exposure to 1Hz vibration in the y-axis (1.2ms^{-2} r.m.s.) and at 8Hz in the z-axis (1.2ms^{-2} r.m.s.), compared to the control condition (column (i), Figure 6.7 and Table 6.3). Furthermore, performance accuracy demonstrated frequency-dependent effects during the high magnitude conditions. Accuracy was significantly ($p < 0.05$) lower (compared to the control condition) during WBV exposure at 1Hz (x-axis), at 1 and 2Hz (y-axis) and at 1 and 8Hz (z-axis).

The results in Table 6.3 indicate that subjective workload showed extensive frequency-dependent effects. During the low magnitude condition, a significant increase ($p < 0.05$) in subjective responses was found at 1, 2 and 4Hz (x-axis), 1 and 4Hz (y-axis) and at 1Hz (z-axis), compared to the control condition. In the high magnitude conditions, these effects (compared to the control condition) were significant ($p < 0.05$) for all frequencies tested, with the exception at 8Hz (y-axis).

6.4.3.2 Standing Posture

The results in Table 6.3 show that the $RT_{INITIAL}$ significantly ($p < 0.05$) increased during high magnitude exposure (compared to the control conditions) at 1Hz in the x- and y-axis ($p < 0.05$) and the z-axis ($p < 0.1$).

Considering the workload responses across the frequency range tested (Table 6.3), in the low magnitude conditions workload was significantly ($p < 0.05$) higher than in the control conditions at: 1Hz (x- and y-axes) and at 8Hz (z-axis). During high magnitude vibration exposure, workload ratings were significantly ($p < 0.05$) higher than the control condition at 1, 2 and 4Hz (x- and y-axes) and at all frequencies tested between 1 – 8Hz (z-axis). These results show similar trends to the workload responses obtained in the seated posture, where the influence of vibration in the horizontal directions occurred at lower frequencies than in the vertical direction.

Table 6.3 Conditions in which mean response time (RT), performance accuracy and increased subjective workload in seated and standing individuals were significantly degraded (in relation to the control), during exposure to sinusoidal WBV

Vibration		**Posture**	**Performance Measure**			
Direction	**Magnitude** (ms^{-2} r.m.s. unweighted)		**$RT_{INITIAL}$**	**RT_{SUB}**	**Accuracy**	**Subjective Workload**
X-axis	0.4	Seated	---	---	---	1 – 4Hz
		Standing	---	---	---	1Hz
	1.2	Seated	---	---	1Hz	1 – 8Hz
		Standing	1Hz	---	1Hz	1 – 4Hz
Y-axis	0.4	Seated	---	---	---	1 and 2Hz
		Standing	---	---	---	1Hz
	1.2	Seated	1Hz	---	1 and 2Hz	1 – 4Hz
		Standing	1Hz	---	1 and 2Hz	1 – 4Hz
Z-axis	0.4	Seated	---	---	---	1Hz
		Standing	---	---	1Hz	8Hz
	1.2	Seated	8Hz	---	1 and 8Hz	1 – 8Hz
		Standing	1Hz	---	4 and 8Hz	1 – 8Hz

Conditions during which objective performance measures (response time and accuracy) were significantly ($p < 0.05$) degraded were generally associated with high magnitudes of vibration exposure (1.2 ms^{-2} r.m.s.). During low magnitude (0.4 ms^{-2} r.m.s.) conditions, the only significant influence on performance was a reduction in performance accuracy in the standing posture at 1Hz (z-axis). Subjective workload ratings however, showed significant increases ($p < 0.05$) during both the low and high magnitude conditions.

Additionally, the significant effects of WBV exposure on manual control performance and subjective workload showed variation between the directions of motion. During horizontal vibration, significant effects ($p < 0.05$) were typically found at lower frequency ranges (at tested frequencies between 1 – 2Hz (x-axis) and 1 – 4Hz (y-axis)). The responses obtained during z-axis vibration were found to occur at higher frequencies (up to 8Hz). These effects were closely matched between the seated and standing postures.

6.5 DISCUSSION

The aim of the current study was to investigate performance of an input task and perceived workload during WBV exposure in seated and standing postures. Key factors to consider include: the postures adopted by participants, the task characteristics and the nature of the vibration.

Based on the results presented in Figures 6.7 and 6.8, it would seem that participants generally focused on response time rather than accuracy. The mean response times (RT_{SUB}) showed no significant variation between vibration frequency, magnitude or posture; whereas some significant ($p < 0.05$) effects were found on performance accuracy. This suggested a speed-accuracy trade-off where performance accuracy was sacrificed in order to maintain response speed, which support previous findings reported by Lin *et al*. (2007) for task performance using a hand-held device. Other studies, for example, Hoggan et al. (2008), have found different speed-accuracy relationships, where participants maintained performance accuracy which resulted in longer task completion times. Such variations would be influenced by differences in task characteristics and the performance strategies adopted the participants.

6.5.1 Performance Strategy (Attention Shift)

The response time results were divided into the mean time taken to input the initial number in the five digit sequence ($RT_{INITIAL}$) and the mean time taken to input the subsequent remaining four numbers (RT_{SUB}). The RT_{SUB} consisted of a visual scanning component (to locate the appropriate number on the keypad) and a physical manual control component (moving and pressing the selected button). In addition to these processes, the $RT_{INITIAL}$ further included a cognitive processing (CP) period where participants reviewed and committed the set of ‘target’ numbers into working memory, before inputting the corresponding number on the keypad ($RT_{INITIAL} = RT_{SUB} + CP$). The results presented in Figures 6.7 and 6.8 showed no significant influence of WBV exposure on the RT_{SUB}, which would suggest the differences found in $RT_{INITIAL}$ were due to disturbances in the processing of the new number sequences. The level of activity interference experienced by rail passengers could therefore be influenced by the cognitive processing requirements of the tasks performed.

In developing a Keystoke-Level Model (KLM) for advanced mobile interaction, Holleis *et al.* (2007) noted that individuals shifted the focus of attention between the real-world surroundings and the mobile device in hand (this was termed the 'Macro Attention Shift'). Due to this attention shift associated with mobile device interaction, the study presented in this chapter separated the display and the keypad device. In order to identify whether this shift resulted in any variation in the response time; frequency distributions for the individual RT_{SUB} measures were calculated (the control conditions are presented in Figure 6.11), in the seated and standing postures. The frequency distributions for RT_{SUB} obtained during the vibration conditions demonstrated similar trends to the control conditions are in Appendix A6.

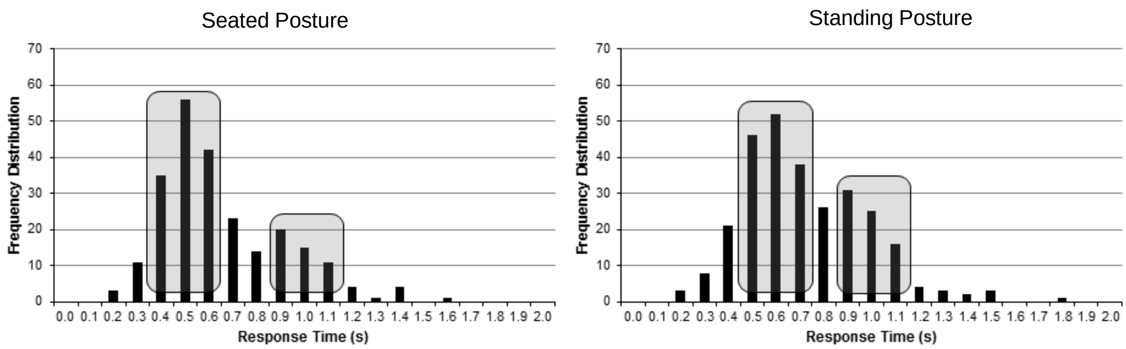


Figure 6.11 Frequency distributions of response times (RT_{SUB}) for correct inputs during the control conditions for seated and standing individuals (highlighting a bimodal distribution)

The frequency distributions were similar in both the seated and standing postures and furthermore met the requirements for normality. These distributions however, tended to show a bimodal pattern, with increased frequency distributions identified firstly, between 0.4 – 0.7s and secondly between 0.9 –1.1s (Figure 6.11). It was proposed that the occurrence of a second peak in the frequency distributions represented a change in focus (by the participants) between the keypad and the display, in a similar manner to the 'Macro Attention Shift' described by Holleis *et al.* (2007). This pattern of response has not previously been reported by studies that have investigated the influence of whole-body vibration exposure on manual control performance. By identifying the different components of the task, the influence of vibration exposure on specific aspects of manual control performance could be investigated.

As no additional supports, such as backrests or grab-rails, were used to maintain stability and the device was not coupled to the vibration source. Additionally, the input device was hand-held and was therefore not mounted to any structure. Activity interference leading to degraded performance would likely be due to a potential loss of stability, the transmission of vibration through the body from the driving-point to the hand controlling the device, or cognitive effects.

6.5.2 Influence of Biomechanical Response on Activity Interference

An understanding of the dynamic interactions between the human body and supporting structures is essential in order to minimise the undesirable effects of vibration exposure (such as activity interference). Apparent mass and transmissibility frequency response functions have previously been used to represent the general dynamic response of the body at the driving-point (Matsumoto and Griffin, 2000) and remote locations (Mansfield, 2005; Paddan, 1994; Paddan, 1995 and Paddan and Griffin, 1995), respectively.

In seated postures, Fairley and Griffin (1990) identified two peaks in apparent mass during horizontal vibration exposure at about 0.7Hz and between 2 – 2.5Hz (lateral and fore-and-aft motions respectively). With fore-and-aft vibration, Nawayseh and Griffin (2005) identified an additional peak between 3 – 5Hz. Matsumoto and Griffin (2000) reported that the principal resonance of apparent mass in seated and standing postures occurred between 4 – 6Hz during vertical vibration (z-axis) exposure.

In the seated posture in this study, the greatest effect on $RT_{INITIAL}$ was found during the high magnitude condition (1.2 ms^{-2} r.m.s.) at 1Hz (y-axis) and 8Hz (z-axis). Performance accuracy was lowest at 1Hz (x-axis), between 1 – 2Hz (y-axis) and at 1 and 8Hz (z-axis). Subjective responses showed greater variation than the performance measures, with significant effects found generally between 1 – 4Hz (x- and y-axis) and between 1 – 8Hz (z-axis). These results illustrate the frequency-dependent effects within the directions of motion. Based on the results from studies on biomechanical responses of the human body to WBV exposure (Fairley and Griffin, 1990; Matsumoto and Griffin, 2000 and Matsumoto and Griffin, 2011), it was proposed that the degradation in $RT_{INITIAL}$ and performance accuracy measures was associated with the resonance frequencies of the apparent mass in the direction of movement.

Additionally, transmission of vibration through the body could cause direct interference with task performance. In a series of studies, Paddan (1994 and 1995) and Paddan and Griffin (1995) found that the transmission of vibration to the hand in an upright, seated posture showed peak transmissibility at frequencies of 1Hz (x-axis, no backrest condition), between 1 – 2Hz (y-axis, no backrest condition) and between 5 – 6Hz (z-axis). The results presented in this study, showed that $RT_{INITIAL}$ and performance accuracy were degraded at similar frequencies of vibration as those reported by Paddan and Griffin (1995). This supported the proposal that activity interference could be related to the transmission of vibration through the body.

The majority of results for response time, accuracy and workload (Figures 6.7 and 6.8) showed similar patterns for standing and seated participants, implying that postural effects could generally be compensated for. The similarities between seated and standing postures support those proposed by Matsumoto and Griffin (2000), referring to the biomechanical responses of the human body. Circumstances in which participants were unable to adapt to vibration exposure were limited to the high magnitude conditions ($1.2ms^{-2}$ r.m.s.) during horizontal vibration exposure. In the x-axis (1Hz), the mean $RT_{INITIAL}$ in the standing posture was greater than that in the seated posture; and during y-axis motion (2Hz), subjective ratings showed the participants experienced higher workloads in the seated posture than when standing. No postural variations were found during vertical vibration. In this direction of motion, the main influence on performance measures and workload would likely be the biomechanical responses of the body. Under horizontal vibration exposure, additional issues such as postural stability (particularly in the standing posture) could further influence performance and workload.

6.5.3 Postural Instability

The probability of losing balance during horizontal WBV exposure was determined to be highest at frequencies below 2Hz (Nawayesh and Griffin, 2006) which could contribute to the response time, accuracy and workload results shown in Figures 6.7 and 6.8. An increased likelihood of losing balance could distract the individual from the task at hand, leading to an increase in response time (as well as cognitive processing in the $RT_{INITIAL}$) or reduction in the accurate operation of the keypad.

To understand how postural instability might contribute to activity interference and workloads, consider the conditions during which significant postural effects were found in this study:

(i) standing $RT_{INITIAL}$ > seated $RT_{INITIAL}$ (x-axis, 1Hz),

(ii) seated workload > standing workload (y-axis, 2Hz).

Griffin (1990) stated that increasing the base-of-support (BOS) in the direction of motion would improve stability, restricting the movement of the upper body and consequently could improve performance and lower the workload experienced by individuals. In the standing posture participants stood with the feet separated side-by-side and so the BOS was therefore maximised in the lateral (y-axis) direction. In the seated posture, participants positioned the legs with the feet comfortably in front of the seat (increasing the BOS in the anterio-posterior (x-axis) direction). During x-axis vibration, the standing posture offered little BOS to maintain stability and the $RT_{INITIAL}$ was greater in the standing posture than when seated. During y-axis motion, the BOS was smallest in the seated posture, which resulted in greater instability, possibly leading to higher workload than in the standing posture.

The influence of additional contributing factors could also be evident from the relationship between objective performance and subjective workload measures. Conditions in which the $RT_{INITIAL}$ and performance accuracy were affected by vibration exposure, generally corresponded to situations where individuals experienced the greatest workloads. In both seated and standing postures, there was no clear correlation between $RT_{INITIAL}$ and workload (R^2 = - 0.049 and - 0.092, seated and standing respectively); however, a correlation was found between workload and performance accuracy. This relationship (presented in Figure 6.12) was found to be significant ($p < 0.05$, Pearson correlation coefficient) in both the seated and standing postures. In the seated posture, workload ratings showed a negative correlation (R^2 = - 0.732) with performance accuracy, indicating that the participants experienced greater subjective workload as the performance accuracy decreased. In the standing posture the correlation between these measures was weaker (R^2 = - 0.456). The poorer correlation could suggest that subjective workload responses were influenced by additional contributing factors (for example, feelings of instability) in the standing posture.

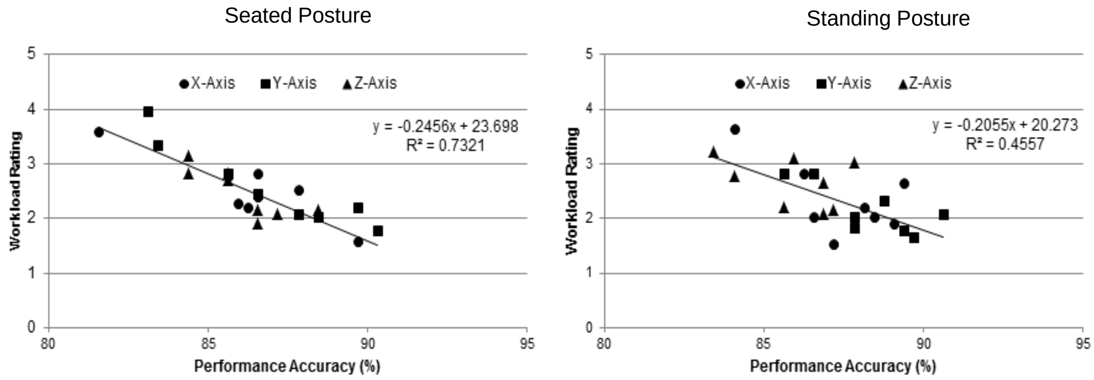


Figure 6.12 Mean subjective ratings of workload plotted versus performance accuracy for the x-, y- and z-axis in seated and standing postures.

6.6 CONCLUSIONS

H1: Serial manual control performance and ratings of workload would show frequency-dependent effects within the given frequency range (1 – 8Hz).

Response times for the initial 'target' number ($RT_{INITIAL}$), were significantly greater during exposure to high magnitude vibration (compared to the control conditions) in the seated posture at 1Hz (y-axis, 1.2 ms^{-2} r.m.s.) and at 8Hz (z-axis, 1.2 ms^{-2} r.m.s.). In the standing posture, these effects were seen to occur at 1Hz (x- and y-axes, 1.2ms^{-2} r.m.s.) There was no influence of vibration exposure on the mean response times for the subsequent 'target' numbers (RT_{SUB}), in either the seated or standing postures.

The $RT_{INITIAL}$ was consistently greater than the RT_{SUB}, which could be related to the additional cognitive processing time associated with the $RT_{INITIAL}$. Further analysis of the RT_{SUB} revealed distinct patterns of response (Figure 6.11), which could be attributed to the participants shifting focus between the keypad and the display.

Performance accuracy showed frequency-dependent effects with the lowest accuracy levels obtained at frequencies below 2Hz (x- and y-axes) and typically above 4Hz (z-axis). These results of performance accuracy demonstrate a frequency-dependent influence which closely matches the frequency weighting curves proposed in ISO2631-1 (1997). The results from this study could contribute to ISO2631-1 (1997) for the inclusion of the frequency-dependant influence of WBV on task performance. Currently, the standard only considers the effects of vibration on health, comfort, perception and motion sickness.

H2: These effects would vary between different directions of motion.

Variations were found between different directions of motion in the performance accuracy and subjective responses. In the horizontal directions (x- and y-axes), performance accuracy tended to improve and workload decreased with increasing vibration frequency (up to 8Hz). In the vertical direction, the opposite trend was found with degraded accuracy and increased workloads found at 8Hz.

Consideration should be given to the type of vibration to which participants were exposed. Sinusoidal motion (particularly at low frequencies) is not commonly experienced in 'real world' situations and could become predictable, allowing individuals to anticipate the motion and introduce measures to counter-act any influence on performance.

H3: Increasing vibration magnitudes would result in reduced manual control performance and higher workload.

During exposure to the low magnitude conditions, participants were generally able to compensate for the influence of vibration and maintain a consistent level of performance. With increasing magnitude the effects of WBV exposure on response time (RT), accuracy and workload were more extensive. In the high magnitude conditions, performance accuracy was degraded to a greater extent than during low magnitude exposures (Figure 6.7 and 6.8). Compared to the control conditions, subjective workload progressively increased with corresponding increases in magnitude.

H4: Postural effects were expected to occur between the seated and standing postures.

Differences between seated and standing postures were limited to two conditions: the first, showed that $RT_{INITIAL}$ was significantly greater in the standing posture (than when seated) during high magnitude, x-axis vibration at 1Hz. The second condition revealed that subjective workload responses were greater in the seated posture during high magnitude, y-axis vibration at 2Hz, compared to the standing posture.

Interventions to reduce WBV exposure at frequencies below 2Hz (x- and y-axis) and above 4Hz (z-axis) could promote improved performance and lower subjective workloads. Furthermore, tasks that involve a greater cognitive demand or require shifting of attention between different locations within the surrounding environment could be more susceptible to the effects of WBV exposure.

Future studies should investigate performance effects during exposure to multi-axis random vibration to more accurately represent ‘real’ environmental conditions. The results in this study demonstrated frequency-dependant effects which were associated with the biomechanical response of the human body exposed to vibration. The greatest influence of performance accuracy and subjective workload occurred at frequencies that have previously been found to result in peak (resonance) responses of seated ad standing individuals (Matsumoto and Griffin, 2000 and 2011). In order to gain a better understanding this association within the context of standing rail passengers, the biomechanical responses of the human body in postures typically adopted in these environments will be investigated and presented in Chapter 7.

CHAPTER 7

BIOMECHANICAL RESPONSES OF THE STANDING HUMAN BODY EXPOSED TO WHOLE-BODY VIBRATION: INFLUENCE OF POSTURAL SUPPORTS

The results presented in Chapter 6 demonstrated a frequency-dependent effect on manual control performance and workload during WBV exposure. Consequently, it was proposed that the influence of WBV on these factors could be associated with the biomechanical responses of the body. As there have been no previous studies that have reported the influence of postural supports in standing postures (such as those used by standing rail passengers in Chapter 4); this chapter presents a laboratory study designed to investigate the influence of such support strategies on the biomechanical responses of the standing human body to whole-body vibration (WBV). The study was conducted in the Environmental Ergonomics Research Centre at Loughborough University.

7.1 INTRODUCTION

The vibration to which travelling individuals are exposed could result in adverse effects on health, performance and comfort. In order to minimise such undesirable effects, an understanding of the dynamic interactions between the body and supporting structures is essential. Apparent mass (APMS) frequency response functions (i.e. the ratio of the force to the acceleration as a function of vibration frequency) and vibration transmissibility (the ratio between two motions measured at distant points), have been widely used to describe the response characteristics of individuals exposed to vibration (Matsumoto and Griffin, 2000 and Wang *et al.*, 2008).

The responses of the seated human body have been investigated in numerous studies using these methods however, there have been few studies conducted with standing individuals (Matsumoto and Griffin, 1998). The apparent mass functions characterise the 'to-the-body' force-motion relationship at the driving-point interface (the floor in the case of standing individuals), while the transmissibility function describes the 'through-the-body' vibration transmission properties (Wang *et al.*, 2008).

7.1.1 Apparent Mass

In seated postures, peaks in apparent mass have been identified at about 0.7Hz and between 2 – 2.5Hz during lateral and fore-and-aft motions, respectively (Fairley and Griffin, 1990). Recently, Matsumoto and Griffin (2011) found that in a normal upright standing posture lateral apparent mass showed a resonance between 0.375 – 0.75Hz. During fore-and-aft vibration, no clear peak was observed in apparent mass however, the apparent mass increased greatly as the frequency reduced from 1Hz to 0.125Hz. It was suggested that the peak in fore-and-aft apparent mass would occur at a frequency below 0.125Hz (Figure 2.5, Section 2.2.1.1). In the vertical direction, Matsumoto and Griffin (2000) reported a principal resonance in apparent mass between 4 – 6Hz in both seated and standing postures (Figure 2.4, Section 2.2.1.1).

Although the influence of postural supports on the apparent mass in standing postures has not been addressed in published studies, contact with a backrest in seated conditions has been found to increase the resonance frequency of apparent mass (Mansfield and Maeda, 2007). Arm supports, such as holding onto a steering wheel (Toward and Griffin, 2010), have shown no influence on resonance frequency however, the magnitude of apparent mass at resonance was found to decreased. This was attributed to the steering wheel supporting some of the mass of the arms.

7.1.2 Transmissibility

The propagation of vibration through the body depends on many variables, including: the charactersitics of the vibration, the system (source of the vibration-human coupling) and the human body itself (Harazin and Grzesik, 1998). During horizontal vibration exposure (x- and y-axis), the resonance frequencies for vibration transmission to the head were found at about 1.5Hz in both directions (Figures 2.8 and 2.9, Section 2.2.2.1). Furthermore, when participants held tightly to a rigid handrail while standing, fore-and-aft vibration transmission to the head was significantly greater at all frequencies above 1Hz, compared with a loose grip (Paddan and Griffin, 1993). The transmission of vertical vibration showed a peak at about 5Hz, with legs locked. Similar results were found while standing with legs unlocked, although the transmissibilities were slightly lower. In a ‘legs bent’ posture however, resonance in vibration transmission to the head was found at about 3Hz (Figure 2.10, Section 2.2.2.1).

In terms of activity interference in manual control tasks, transmission of vibration to the hand has been proposed as a contributing factor (Paddan and Griffin, 1993). A study by Paddan (1994) found a peak in fore-and-aft transmissibility to the hand at about 1Hz in the 'back-off' condition (contact with a backrest resulted in an increase in the resonance frequency to between 4 – 5Hz). In the lateral direction, similar results were found to the fore-and-aft transmissibility, with a resonance frequency between 1.5 – 2Hz in the 'back-off' condition. During lateral vibration, contact with a backrest showed little influence on the frequency of resonance (Paddan, 1995). In both directions (x- and y-axis), the presence of a backrest resulted in higher magnitudes of the transmissibility at the frequency of resonance. Lastly, during vertical vibration, Paddan and Griffin (1995) found two clear peaks in the transmission of vertical vibration to the hand in a 'back-on' posture: the first at about 2Hz and the second around 5Hz.

Despite this research, there remain variables that have yet to investigated, for example: the types of postural supports commonly used in public transport systems and the transmission of vibration to the hand in standing individuals. By considering the context in which standing individuals are exposed to vibration and the supports used in these environments, the applicability of the research could be improved.

7.2 RESEARCH HYPOTHESES

This chapter presents a laboratory study designed to investigate the influence of postural supports on the biomechanical responses of the human body to whole-body vibration. The objectives were to investigate the influence of postural support strategies commonly used in rail transportation systems (Chapter 4) and to further the understanding of the characteristics of the biomechanical responses of standing individuals exposed to x-, y- and z-axis vibration. The study was designed to investigate the apparent mass and floor-to-hand transmissibility in standing individuals.

Based on the findings published within the literature (as described in Sections 7.1.1 Apparent Mass and 7.1.2 Transmissibility), it was hypothesised that:

H1: The use of postural supports would restrain the motions of the upper body compared to an unsupported (free standing) posture, increasing the damping within the body. The resonance frequency of apparent mass of participants in supported postures would therefore increase.

H2: The magnitude of apparent mass in supported postures was expected to decrease at resonance.

H3: Contact with postural supports was expected to increase the resonance frequency of vibration transmission to the hand (compared to an unsupported posture).

H4: The magnitude of vibration transmission to the hand at resonance would increase during supported postures (compared to an unsupported posture).

H5: Variations between the types of support strategies would occur, such that the influence of supports on the biomechanical response of standing participants would be dependent on the contact between the support and the individual. Body-supported postures were expected to result in greater effects on apparent mass and transmissibility, compared to hand- supported postures.

7.3 METHODS

7.3.1 Participants

Twelve participants aged between 24 and 39 years volunteered to take part in the study, the anthropometric data for the participant group are presented in Table 7.1. Each participant received information regarding the experimental protocol prior to the testing session and informed consent was obtained from all participants. The experimental protocol was approved by the Loughborough University Ethical Advisory Committee.

7.3.2 Pilot Testing

Pilot testing provided an opportunity for the experimenters to become familiar with the experimental protocols and the use of the testing equipment. Additionally, the pilot tests were used to establish the characteristics of the vibration stimuli that would be presented to the participants. From these tests, it was decided that both single- and multi-axis stimuli would be used in the experimental protocols. Multi-axis stimuli provided a better representation of ‘real-world’ exposures however, these signals contained more noise than the single-axis stimuli (justifying the inclusion of the single-axis stimuli). The duration of each test exposure was limited to 60s. This timeframe provided a sufficient period for data collection, while minimising potential confounding factors due to fatigue (Griffin, 1990 and Mansfield, 2005).

Table 7.1 Anthropometric characteristics of participants from the study designed to assess the influence of postural supports on the biomechanical response of standing individuals

Characteristic	**Biomechanical Response Study**
Number	12
Gender	7 female; 5 male
Age	24 – 39years (mean ± sd: 29.0 ± 6.1years)
Stature	1635 – 1820mm (mean ± sd: 1726.3 ± 60.4mm)
Mass	61.3 – 82.2kg (mean ± sd: 71.7 ± 8.1kg)
Foot Length	230 – 285mm (mean ± sd: 259.2 ± 16.5mm)

7.3.3 Independent Variables

7.3.3.1 Vibration

Participants were exposed to 24 experimental conditions. Vibration was produced by the 6 degree-of-freedom multi-axis vibration simulator (MAViS) in the Environmental Ergonomics Research Centre, Loughborough University. During each standing posture, vibration exposure comprised three single-axis (x-, y- and z-axis independently) random stimuli at 1.0ms^{-2} r.m.s. Each stimulus lasted 60s, with equal energy between 1 – 10Hz. This frequency range was used to ensure that all frequency responses were included in the testing protocol. For safety reasons, participants were required to wear a loose harness secured above the simulator during all testing conditions.

Table 7.2 Summary of the random vibration stimuli used during the biomechanical response study

Variable	Condition	Vibration Magnitude (ms^{-2}r.m.s., unweighted)			
		x-axis	**y-axis**	**z-axis**	**r.s.s. ∑ axes**
Biomechanical Response	1	1.0	---	---	1.00
	2	---	1.0	---	1.00
	3	---	---	1.0	1.00
	Repeated for six standing postures				

Where: r.m.s. = root mean square; r.s.s. = root sum of squares

7.3.3.2 Posture

Participants adopted six standing postures (Figure 7.1) on the vibration simulator, based on observations of standing passengers on public rail transportation (Chapter 4). Postural supports were provided by a rigid metal frame secured to the simulator platform. An additional support, the 'Overhead Handle', was included as an experimental condition. Although this type of support was not observed on the trains during the field study (Chapter 4), these supports are common in other public transportation systems (for example, buses in the UK and underground trains in Japan). The participants were instructed to stand on a Kistler 9286AA force plate (Kistler Instrument Corporation, USA) mounted in the centre of the platform with their knees locked during vibration exposure. Measurements were obtained with the participants barefoot in order to eliminate any effects of footwear. Standing postures included:

1. 'Free – Hand Held': a normal upright standing posture with measurement accelerometer held in the dominant hand.

2. 'Lean Back': participants leant backwards against a rigid vertical board which provided support from the upper back to the buttocks. The feet were positioned with the heels a distance of one foot length in front of the board, producing an inclination of approximately 15º to the vertical.

3. 'Lean Shoulder': participants leant sideways against a rigid vertical board, providing support at the dominant shoulder (on the same side the device was held) with the mid-sagittal plane parallel to the board. The feet were parallel and together, positioned one foot length from the board with the body straight, producing an inclination of approximately 7º to the vertical.

4. ‘Overhead Bar’: participants adopted a normal upright standing posture and held a rigid horizontal bar positioned 50-100mm above head height.

5. ‘Overhead Handle’: identical to the ‘overhead bar’ posture, however the support was a loose handle attached to the frame with fabric webbing, at the same height above the participants.

6. ‘Vertical Bar’: participants adopted a normal upright standing posture and held onto a rigid vertical bar at shoulder height with the elbow unlocked.

The measurement accelerometer (for transmissibility data) was held horizontally in the dominant hand of the participant (at standing elbow height, with the elbow in contact with the torso) while the other hand remained free, or was used to hold onto a support (depending on the condition). The frame structure in which the participants stood was adjustable, designed to accommodate left- or right-handed individuals however, no left-handed individuals took part in the study. Participants were instructed to look straight ahead, stand with their knees locked and place their feet one foot length apart (measured from the lateral border of each foot). Based on the results from Chapter 5, the influence of stance orientation on manual control performance and workload was found to be minimal, therefore only a lateral stance orientation was considered in this study. However, the base-of-support (BOS) at the feet was consistent in both the fore-and-aft (x-axis) and lateral (y-axis) directions and coloured markers were placed on the platform to indicate the location of each foot. In the ‘Lean Shoulder’ posture the feet were positioned together as it was not feasible to accommodate both requirements of locked knees and separated feet.

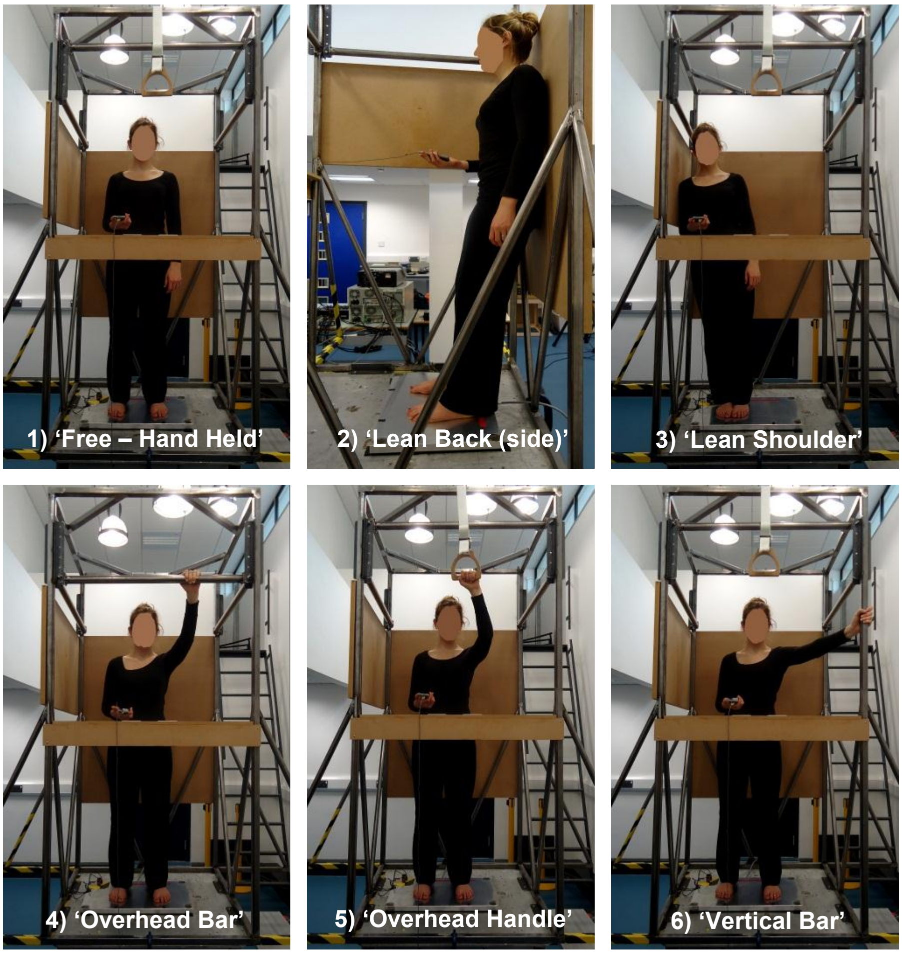


Figure 7.1 Participant demonstrating the postures adopted while holding measurement device (with accelerometer attached) and standing on a force plate mounted to the motion platform (safety harness not shown for purposes of clarity)

7.3.4 Dependant Variables

7.3.4.1 Apparent Mass Measurement

Apparent mass measurements were recorded using a Kistler 9286AA force plate (Kistler Instrument Corporation, USA), mounted onto the multi-axis vibration simulator (MAViS) in the Environmental Ergonomics Research Centre, Loughborough University (Figure 7.2). The force measurements were automatically recorded and stored onto a laboratory computer running LabVIEW software (Version 7.1, National Instruments, UK).

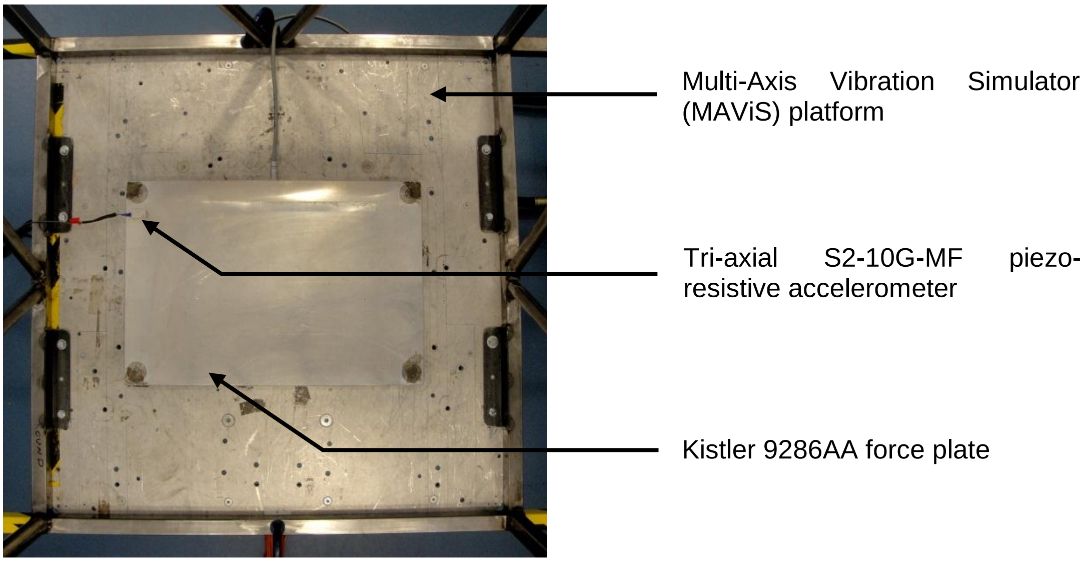


Figure 7.2 Superior (aerial) view of the vibration simulator platform showing the force plate and accelerometer setup for measuring apparent mass and transmissibility

7.3.4.2 Transmissibility Measurement

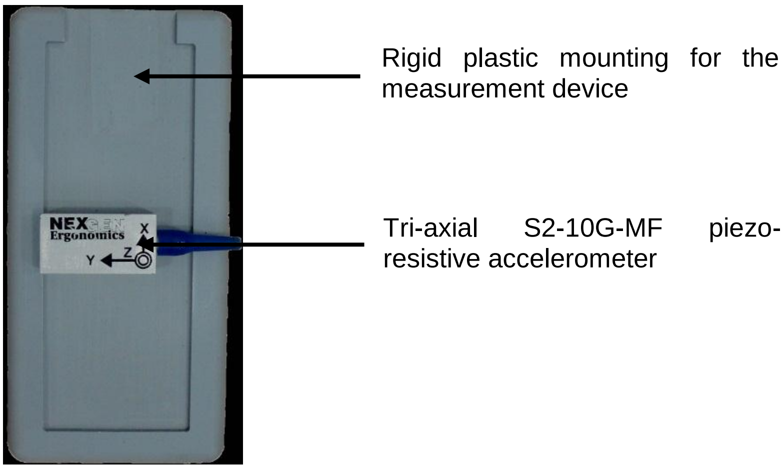


Figure 7.3 Superior view showing the accelerometer fitted onto the plastic moulding

The floor-to-hand transmissibility was measured using two tri-axial S2-10G-MF (Biometrics Ltd, UK) piezo-resistive accelerometers, one mounted onto the surface on which the participants were standing (Figure 7.2) and a second one fitted onto the device held in the hand of the participant (Figure 7.3). A data acquisition system (P3X8 v2.11, Biometrics Ltd, UK) was used to store discrete waveforms obtained from the accelerometers, which were analysed using Biometrics software and in-house LabVIEW (Version 7.1) programs to calculate transmissibility responses. The orientation of the accelerometer axes was based on the whole-body co-ordinate system (as opposed to the hand-arm co-ordinate system).

7.3.5 Experimental Protocol

7.3.5.2 Procedures and Design

The experimental protocol was conducted during a single laboratory testing session in the Environmental Ergonomics Research Centre, Loughborough University. The session commenced with anthropometric measurements, following which, markers were placed on the motion platform and force plate to ensure the participants adopted the correct standing postures during the testing conditions.

The order in which the experimental conditions were presented was randomised using a balanced Latin-square technique. The randomisation occurred between each direction of motion and between the six standing postures. The sequence of conditions was therefore, not repeated between individuals and the participants were not able to predict the subsequent experimental conditions. Following each experimental condition, the measurement equipment (accelerometer and force plate) were calibrated and zeroed to prevent measurement errors occurring due to disturbances caused by exposure to vibration.

The simulator platform was controlled by a dedicated laboratory computer system, while a secondary laboratory computer was used to run the LabVIEW software which measured and recorded the apparent mass data. The transmissibility data was stored on the Biometrics data logger and transferred to a laboratory computer following the completion of all experimental trials. The LabVIEW testing program was only started once the vibration platform had stabilised at the required magnitude (approximately 5seconds after initiating the motion file on the computer). Once an experimental condition was completed, the LabVIEW program stopped automatically, the vibration input ceased and the platform was returned to a ‘neutral’ position.

7.3.6 Data Analysis

All transfer functions for apparent mass and transmissibility were calculated using the cross-spectral density (CSD) function method (Equation 3.4, Section 3.5.5 Measurement of Biomechanical Response), with a resolution of 0.25Hz. Prior to the calculation of apparent mass, a mass cancellation of the mass of the force plate (17.5kg) was performed (Equation 3.7, Section 3.5.5.1 Standing Apparent Mass) to remove any influence of the measured force. The apparent mass and transmissibility at the primary resonance frequency was assumed to be the greatest apparent mass and transmissibility over the measurement range. The primary resonance frequency was therefore defined as the frequency at which the apparent mass or transmissibility was the greatest. The phase and coherence data are produced as a consequence of the CSD analysis of apparent mass and transmissibility. The phase represents the relative movements of the output and input motions, while the coherency provides an estimation of how the output motions relate to the input motions. A lower coherency could be caused by noise or non-linearity of the system (Fahy and Walker, 1998).

Statistical analysis was performed using *SPSS*® software (Version 15.0). Due to the 0.25Hz frequency resolution, the use of mean averaging methods would have produced values that were associated with frequencies that were not technically measured. Consequently, median values were calculated and non-parametric tests were selected to analysis the data. This representation of biomechanical responses to WBV has been commonly reported in previous studies published in the literature (for example, Matsumoto and Griffin 2011). The use of median results within this study would enable better comparison therefore with the literature. A Friedman two-way analysis of variance, followed by post hoc Wilcoxon tests, was used to compare the apparent mass and transmissibility responses during supported postures to the unsupported (free standing) control condition in each direction of motion.

7.4 RESULTS

Section 7.4 shows the biomechanical responses (apparent mass and transmissibility) obtained during single-axis exposure to whole-body vibration in the x-, y- and z-axis independently.

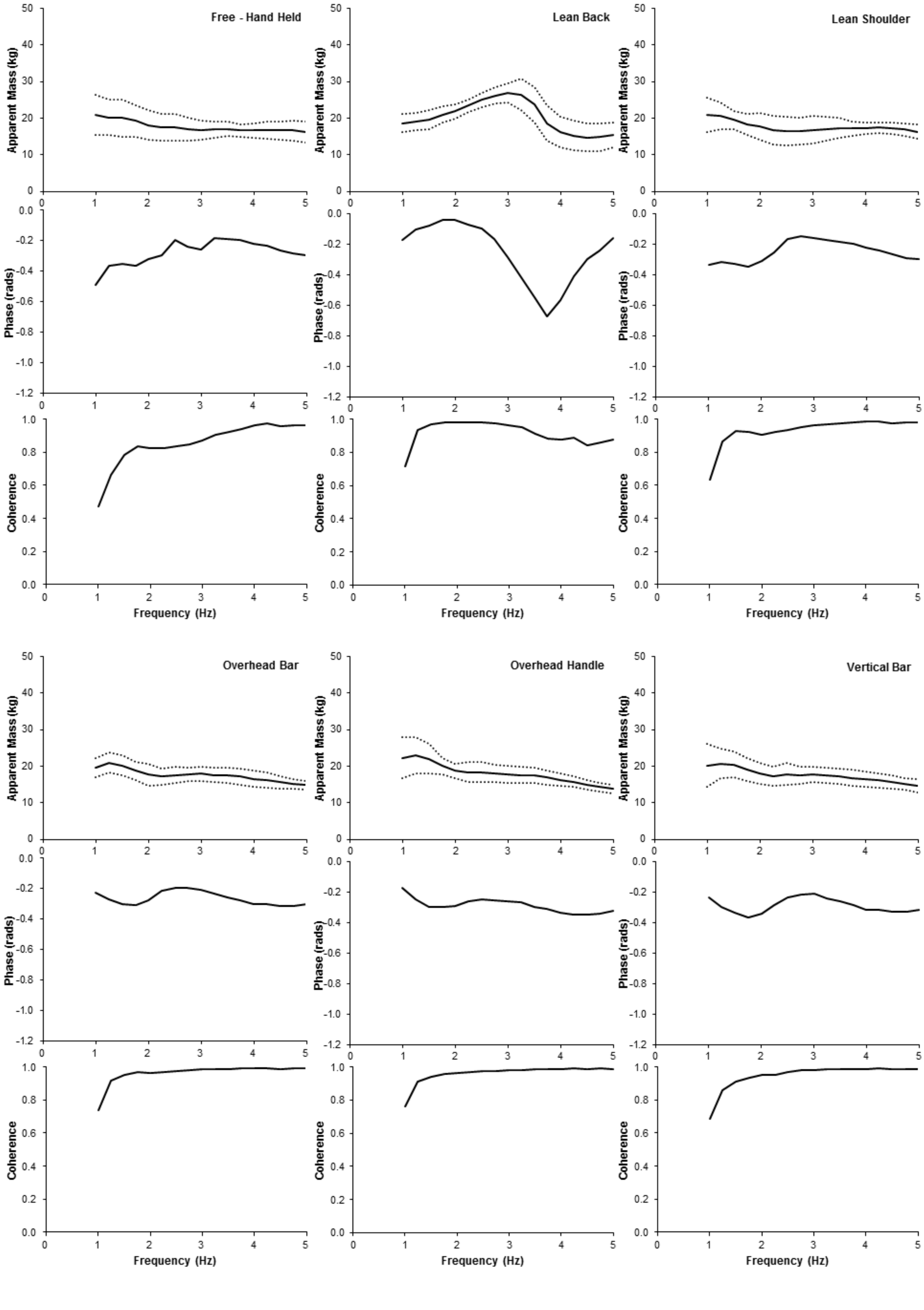
7.4.1 Apparent Mass Responses

7.4.1.1 Fore-and-aft Apparent Mass

The median apparent masses with corresponding phase and coherence data for twelve participants have been presented in Figure 7.4, separated to distinguish between each standing posture. Data are not shown above 5Hz in the fore-and-aft and lateral directions of motion for clarity. In the ‘Free – Hand Held’ posture, no clear peak was found and the fore-and-aft apparent mass was less than 22kg over the tested frequency range. These trends were generally observed for the remaining standing postures; however, a peak in apparent mass was found in the ‘Lean Back’ posture at around 3Hz. The coherence in all standing postures was above 0.9 for all measured frequencies between 1.5 – 5Hz, at frequencies lower than 1.5Hz the coherences decreased below 0.8.

7.4.1.2 Lateral Apparent Mass

As with the fore-and-aft apparent mass, posture exerted a limited influence on apparent mass in the lateral direction. In all standing postures, the lateral apparent mass was reduced to less than 19kg at all tested frequencies between 2 – 5Hz. Significant ($p < 0.05$) increases in apparent mass were found in the ‘Lean Back’ and ‘Lean Shoulder’ postures compared to the ‘Free – Hand Held’ posture, at 1Hz and between 1 – 1.5Hz respectively. Coherencies showed a marked decrease (below 0.8) between 1 – 2Hz for all postures, as well as at 2.75Hz in the ‘Lean Shoulder’ posture (Figure 7.10).



Free - Hand Held
Lean Back
Lean Shoulder
Overhead Bar
Overhead Handle
Vertical Bar
Apparent Mass (kg)
Phase (rads)
Coherence
Frequency (Hz)

Figure 7.4 Median fore-and-aft apparent mass, phase and coherence data for 12 standing participants (dashed lines = interquartile range)

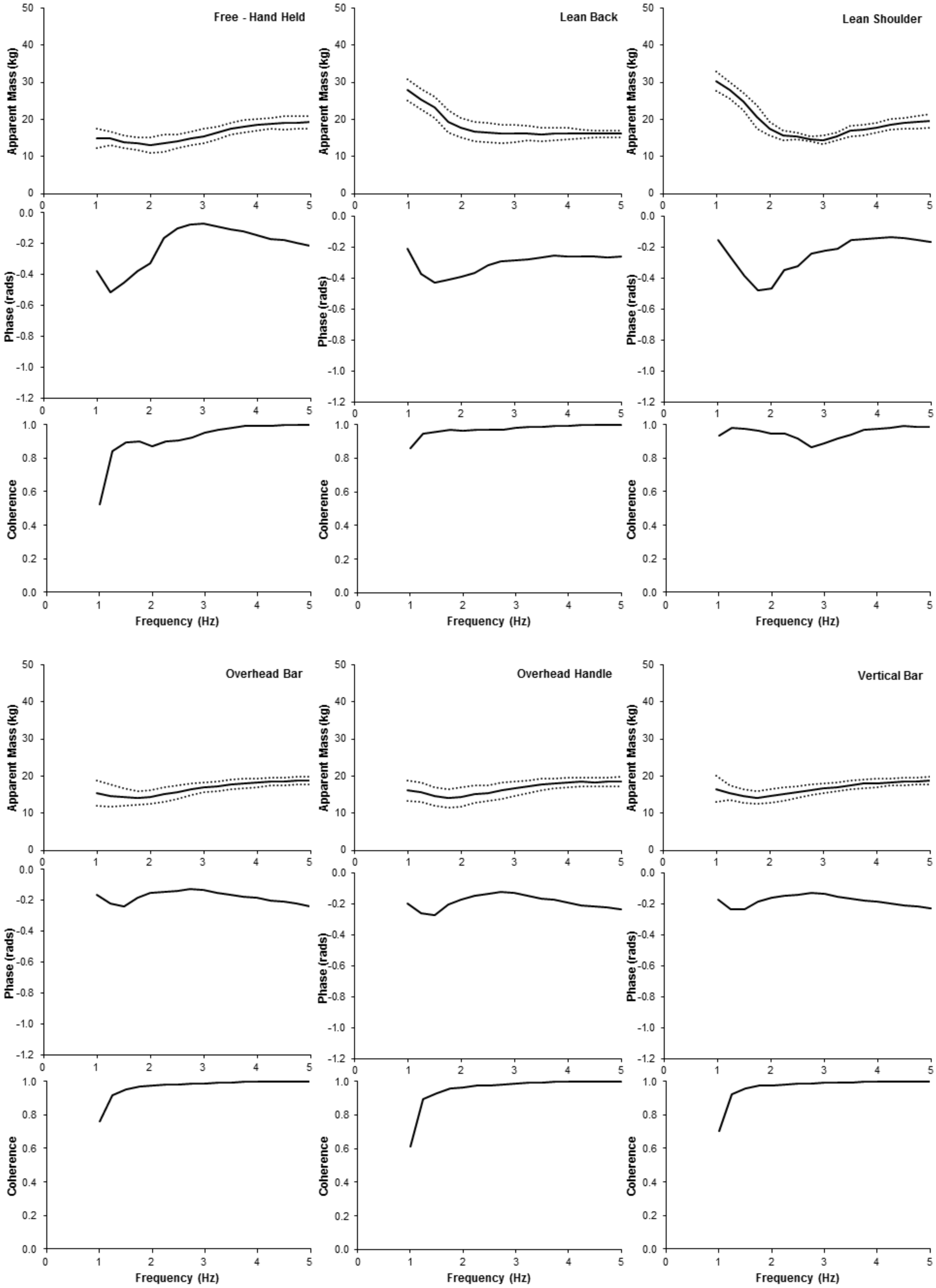


Figure 7.5 Median lateral apparent mass, phase and coherence data for 12 standing participants (dashed lines = interquartile range)

7.4.1.3 Vertical Apparent Mass

The resonance frequency for vertical apparent mass in the standing postures was found to occur at around 5Hz (Figure 7.6). In the supported postures, the resonance frequency was slightly higher at 5.5Hz, although this was not significantly different from the resonance in the 'Free – Hand Held' posture (5Hz). The magnitude of apparent mass at resonance was significantly ($p < 0.05$) lower in the 'Overhead Bar' and 'Vertical Bar' postures, compared to the 'Free – Hand Held' posture. Vertical apparent mass in the 'Lean Back' posture began to increase above 3.5Hz. At this frequency, the apparent mass in the 'Lean Back' posture was significantly ($p < 0.05$) lower than that in the 'Free Standing' posture, indicating a possible increase in damping due to the influence of postural support. The apparent masses at 1Hz were between 3 – 9% lower in the supported postures than the 'Free – Hand Held' posture, which suggests a proportion of body weight was held up by the various support strategies based on the type of posture adopted. As expected, the 'Lean Back' and 'Lean Shoulder' postures supported the greater proportions of body weight than the remaining hand-supported postures (Table 7.3).

Despite the body-supported ('Lean Back' and 'Lean Shoulder') postures exhibiting the greatest influence on body mass, the magnitude of apparent mass at resonance was significantly ($p < 0.05$) reduced by two of the hand-supported postures ('Overhead Bar' and 'Vertical Bar'). Considering the variations in the amount of body weight supported the peak ratios of vertical apparent mass (i.e. the ratio of the magnitude of apparent mass at 1Hz to that at resonance frequency) have been provided for each posture (Table 7.3). The peak ratios show the 'Lean Back' posture accounted for the greatest effect on the magnitude of vertical apparent mass, followed by the 'Lean Shoulder' posture. The 'Overhead Handle' posture produced a similar ratio to the 'Free –Hand Held' posture, while the 'Overhead Bar' and the 'Vertical Bar' significantly ($p < 0.05$) reduced the vertical apparent mass in standing individuals at resonance.

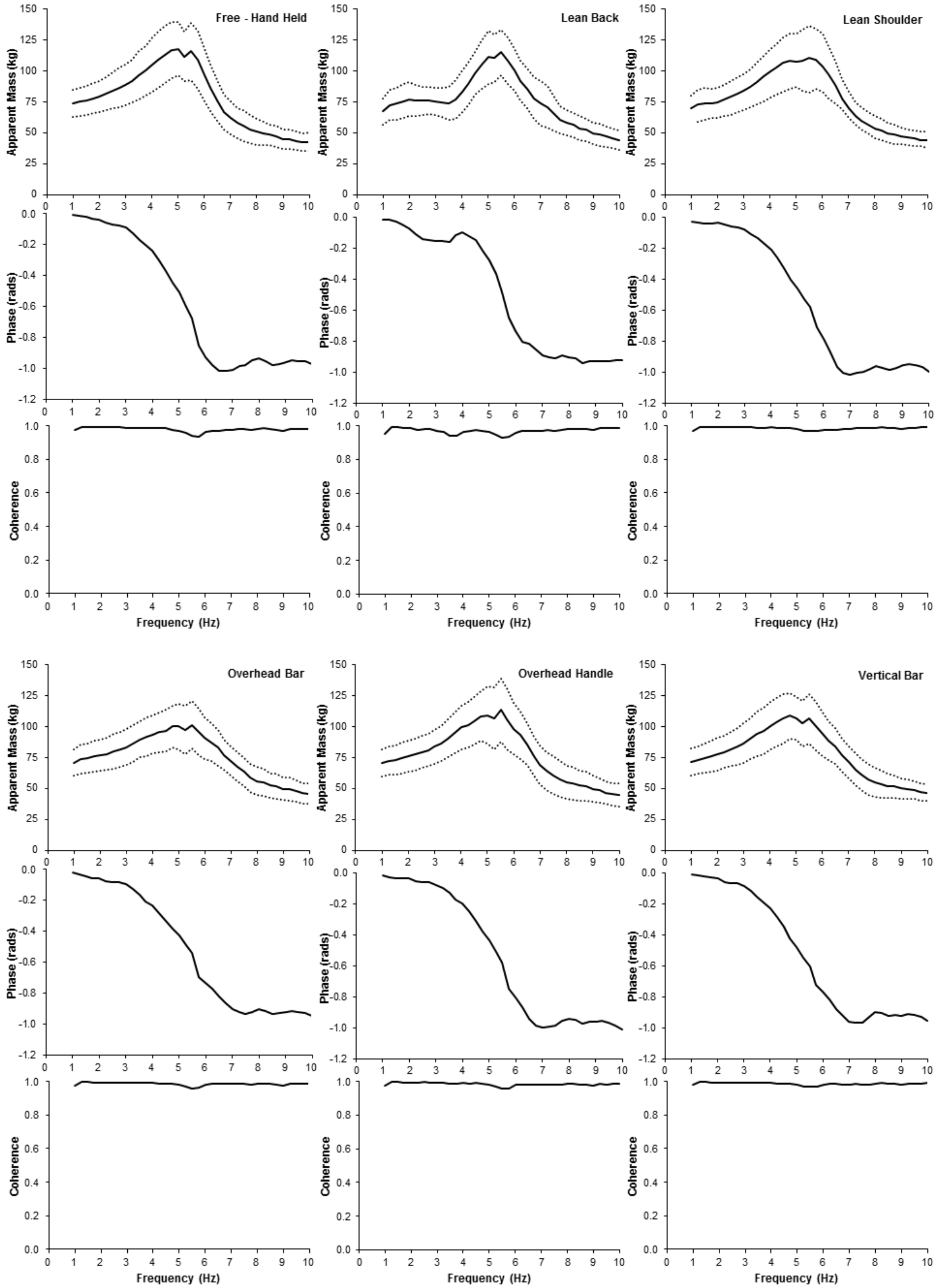


Figure 7.6 Median vertical apparent mass, phase and coherence data for 12 standing participants (dashed lines = interquartile range)

Table 7.3 Peak ratios of the median vertical apparent mass for standing individuals

Median Apparent Mass (kg)						
Posture	**Free Standing**	**Lean**		**Overhead**		**Vertical Bar**
		Back	**Shoulder**	**Bar**	**Handle**	
1Hz	73.79	67.12 *****	69.67 *****	70.89	70.82	71.56
Resonance	117.64	114.96	113.93	101.47 *****	111.33	106.26 *****
Ratio	**1.59**	**1.71**	**1.65**	**1.43**	**1.57**	**1.48**

Where: ***** indicates significant difference ($p < 0.05$) compared to the 'Free – Hand Held' posture

7.4.2 Transmissibility Responses

7.4.2.1 Fore-and-aft Transmissibility

The median floor-to-hand transmissibility data with corresponding and coherences for twelve participants have been presented in Figure 7.7, based on six standing postures. Data are not shown above 5Hz in the fore-and-aft and lateral directions of motion. The 'Free – Hand Held' and 'Overhead Handle' postures showed no clear peak in vibration transmissibility and furthermore, the magnitude of fore-and-aft vibration transmission from the floor to the hand was less than 0.5 across all tested frequencies between 1 – 5Hz. Considering the remaining hand-supported standing conditions: the 'Overhead Bar' and Vertical Bar' postures, minor peaks in fore-and-aft transmissibility were evident at about 3Hz in both postures (transmissibility at the resonance frequency were 0.59 and 0.65 respectively). The transmissibility found in these four standing postures indicated the body attenuated the vibration transmitted to the hand. In the body-supported conditions: 'Lean Back' and 'Lean Shoulder' postures, distinct peaks in transmissibility were found to occur between 2 – 3Hz and between 3 – 4Hz, respectively. The 'Lean Back' posture showed the greatest transmissibility at the resonance frequency (1.65), while the peak transmissibility in the 'Lean Shoulder' posture was 1.10. Transmissibilities greater than 1.0 meant the postural supports provided in the 'Lean Back' and 'Lean Shoulder' lead to greater motions at the hand, compared to the vibration input at the floor. The coherences in all standing postures were above 0.6 for all the tested frequencies between 1 – 5Hz.

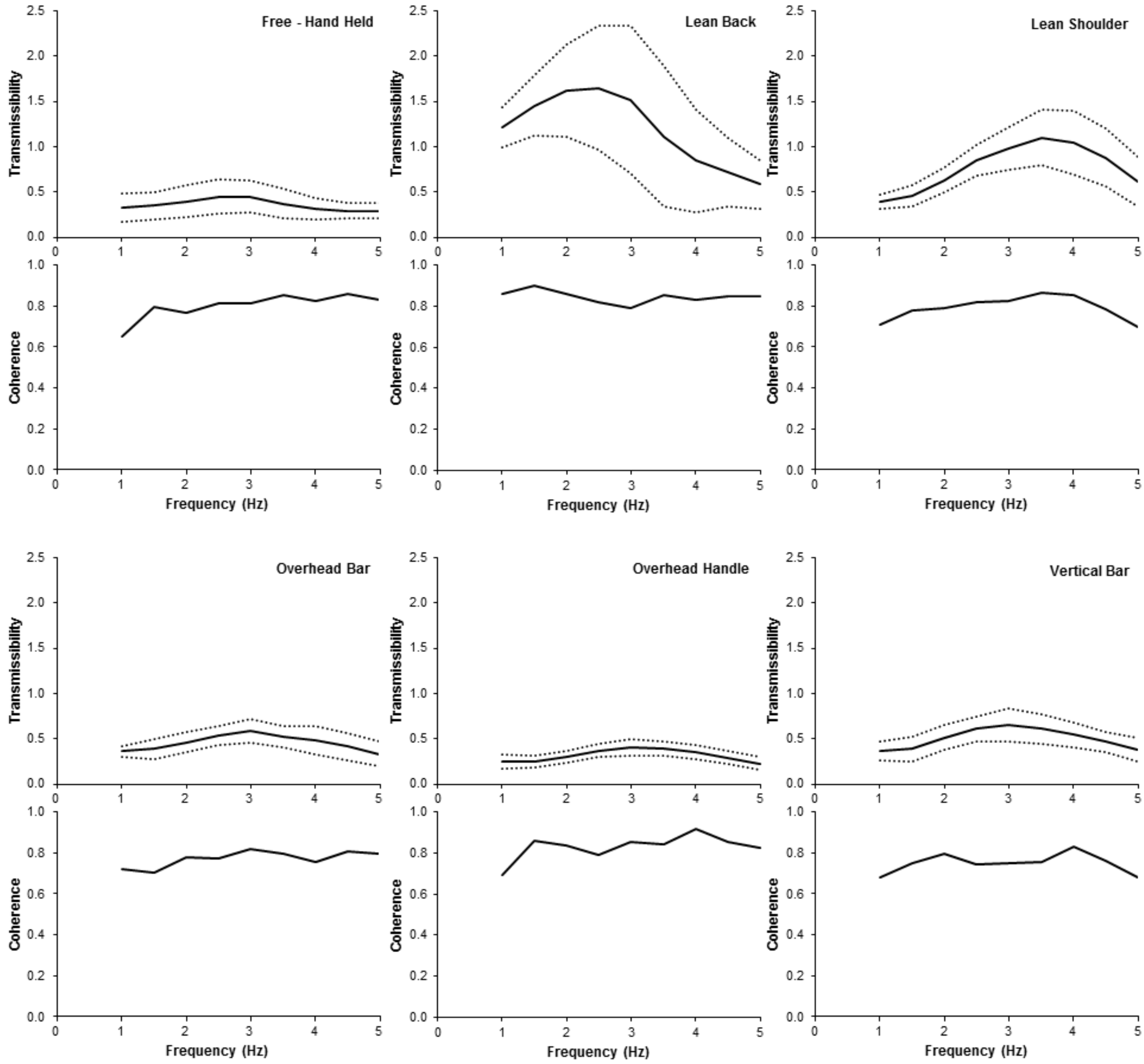


Figure 7.7 Median fore-and-aft transmissibility and coherence data for 12 standing participants (dashed lines = interquartile range)

7.4.2.2 Lateral Transmissibility

As with the fore-and-aft vibration transmissibility results, the transmission of lateral motions from the floor to the hand exhibited limited influence in the ‘Free – Hand Held’ and hand-supported postures: ‘Overhead Bar’, ‘Overhead Handle’ and ‘Vertical Bar’. The ‘Free – Hand Held’ and ‘Overhead Handle’ postures both showed transmissibility magnitudes less than 0.5, whereas vibration transmission in ‘Overhead Bar’ and ‘Vertical Bar’ tended to be higher between 1.5Hz – 2Hz (transmissibilities of 0.63 and 0.67 respectively). The ‘Lean Back’ and ‘Lean Shoulder’ postures were associated with the greatest transmission of lateral vibration at 1Hz, with transmissbilities of 1.12 and 1.75 respectively. Coherencies were generally above 0.6 for all postures, with slight decreases between 2 – 3Hz (Figure 7.8).

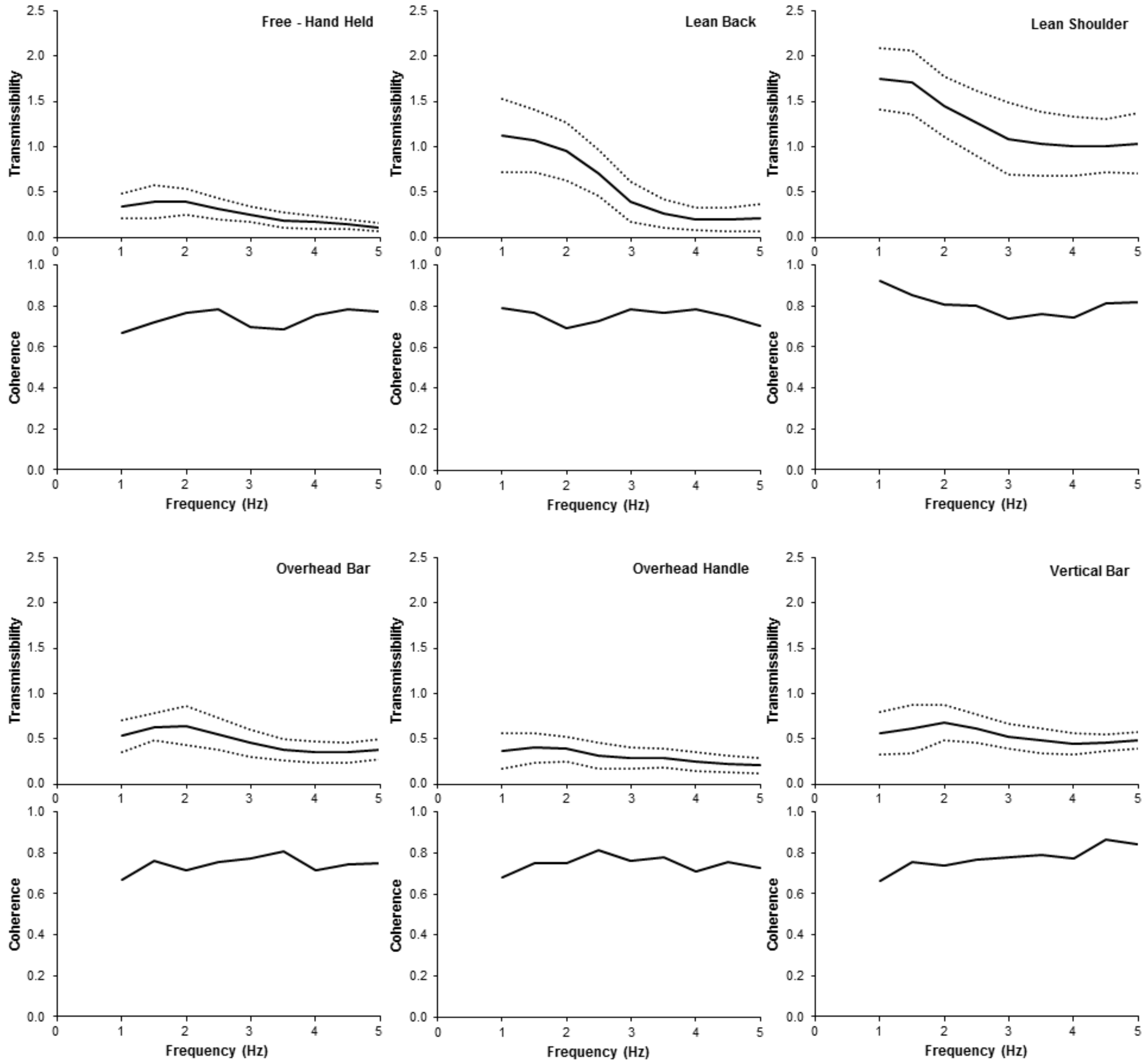


Figure 7.8 Median lateral transmissibility and coherence data for 12 standing participants (dashed lines = interquartile range)

7.4.2.3 Vertical Transmissibility

Overall, in all standing postures the transmission of vertical vibration to the hand was greatest within the frequency range 4 – 6 Hz. A small primary peak was observed at about 2Hz, however the main resonance frequencies for vertical transmissibility in standing individuals occurred at 5Hz in the 'Free – Hand Held' and 'Overhead Handle' postures and at about 5.5Hz in the remaining four conditions (Figure 7.9). The body-supported postures showed the peak transmissibilities of 3.14 in the 'Lean Back' posture and 3.25 in the 'Lean Shoulder' posture. The hand-supported postures showed slightly lower peak transmissibilities: 2.86, 2.71 and 2.89 for the 'Overhead Bar', 'Overhead Handle' and 'Vertical Bar' postures, respectively. The lowest vertical transmissibility was found in the 'Free – Hand Held' posture, with a magnitude of 2.61. In all postures, the vertical transmissibility was greater than 1.0 between frequencies 1 – 10Hz, indicating that the vertical vibration at the hand was generally greater than that experienced at the floor.

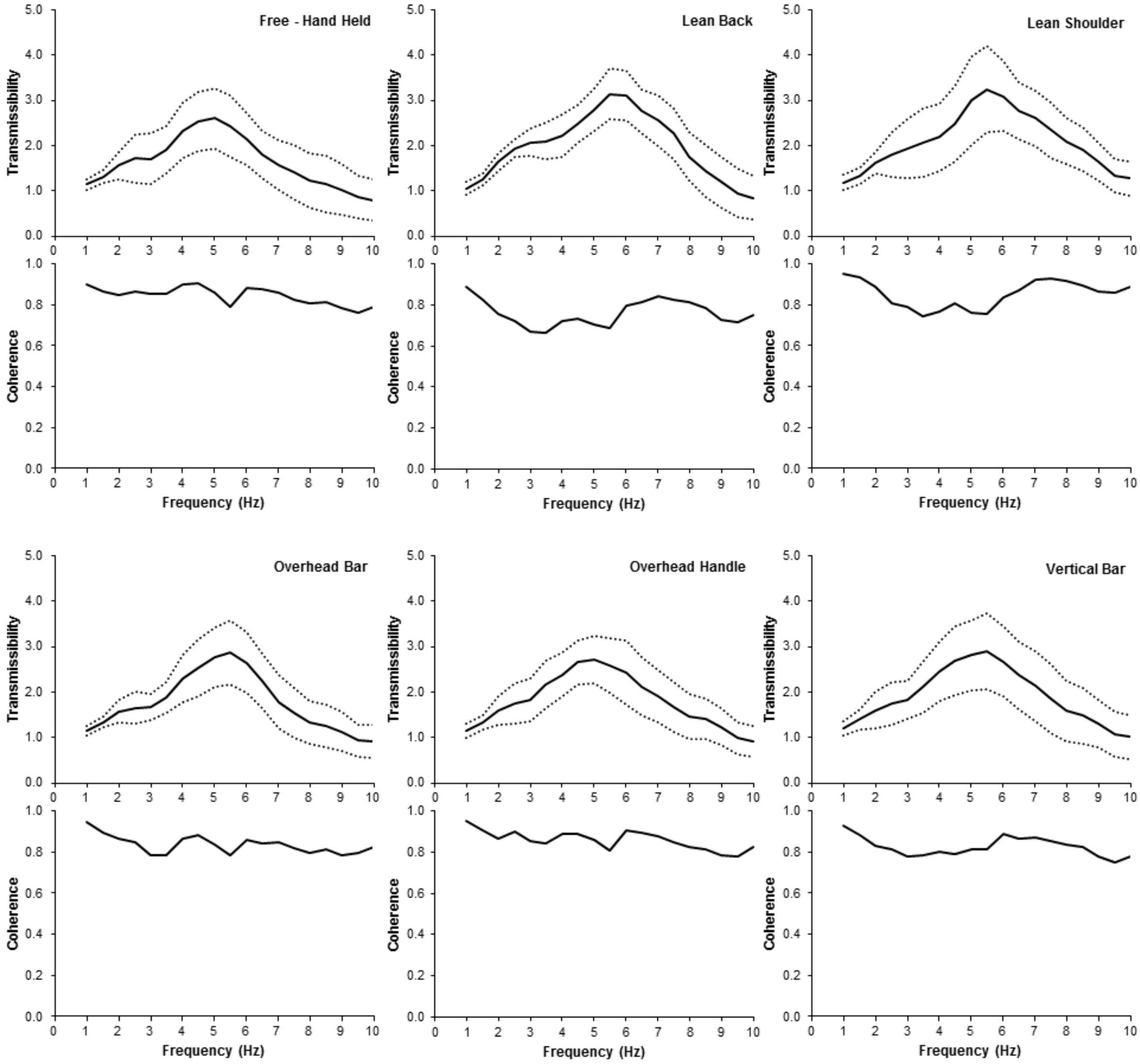


Figure 7.9 Median vertical transmissibility and coherence data for 12 standing participants (dashed lines = interquartile range)

7.5 DISCUSSION

7.5.1 Apparent Mass Responses

During fore-and-aft vibration, the absence of a clear peak in apparent mass for all but one of the standing postures could be due to the lower limit of frequency range used in the study. Matsumoto and Griffin (2011) found that fore-and-aft apparent mass increased substantially at frequencies below 1Hz in a standing posture while the apparent mass remained below 15kg at frequencies above 1Hz (Figure 2.5, Section 2.2.1.1 Influence of Body Posture). With no clear peak identified above 1Hz in the study presented in this chapter, the results would tend to support these findings. The influence of postural supports was limited to the ‘Lean Back’ posture, where a peak was observed at 3Hz. In a seated posture, contact with a backrest has been shown to produce a resonance frequency at 3.25 and 3.5Hz in the fore-and-aft direction (Mansfield and Maeda, 2007; and Fairley and Griffin, 1990); and it would appear that contact with a back support in standing individuals had a similar effect on the resonance frequency (Figure 7.4).

Contact with a leaning support in the ‘Lean Shoulder’ posture revealed no significant influence on the fore-and-aft apparent mass. The orientation of the support and the body in relation to the direction of motion could be an important contributing factor to the dynamic response of the body. In the ‘Lean Shoulder’ posture, the direction in which the participants leant against the support was perpendicular to the direction of vibration and there was no influence on the biomechanical response of the body, unlike in the ‘Lean Back’ posture where the leaning angle on the support and the vibration were aligned in the same direction.

Considering lateral motion, Matsumoto and Griffin (2011) found apparent mass peaked at a frequency between 0.325 – 0.75Hz; a possible explanation for the lack of a peak in the study presented in this chapter. Additionally, there was little variation between 2 – 5Hz and the magnitude of lateral apparent mass was reduced to less than 10kg within this frequency range (Figure 2.5, Section 2.2.1.1 Influence of Body Posture). Although the magnitudes of horizontal apparent mass vary between the results reported in this chapter and those published in the literature, the trends are generally similar. Lateral apparent mass between 2 – 5Hz was slightly lower than the fore-and-aft apparent mass which is consistent with the results reported by Matsumoto and Griffin (2011).

Comparing these results to seated postures, Mansfield and Maeda (2007) reported a resonance frequency for lateral apparent mass at 1.5Hz while in contact with a backrest. In this chapter the results showed an increase in apparent mass in the ‘Lean Back’ and ‘Lean Shoulder’ postures between frequencies of 1 – 1.5Hz (the apparent mass in ‘Lean Shoulder’ condition was slightly higher). During lateral vibration, the ‘Lean Shoulder’ supported posture would be aligned with the direction of motion and this could explain the difference between the apparent masses in the ‘Lean Back’ and ‘Lean Shoulder’ postures between 1 – 1.5Hz.

In addition to the orientation of postural support with the direction of motion, other factors may contribute to the increased lateral apparent mass during the 'Lean Back' posture. The dynamic response of the body could be influenced by the level of contact and the leaning angle between the body and the support. In the 'Lean Shoulder' posture, only the side of the shoulder was supported and the posture was more upright than the 'Lean Back' posture. In comparison, individuals adopting the 'Lean Back' posture were supported from the buttocks to the upper back, at a greater angle to the floor (Figure 7.1). Apparent mass was only influenced in the 'Lean Shoulder' posture during lateral vibration exposure, whereas the 'Lean Back' posture showed an increase in apparent mass during the fore-and-aft and lateral motions. In both directions of motion, the hand supports showed no effects on apparent mass compared to the 'Free – Hand Held' posture, lending further support to the notion that the contact area between the support and the body plays a crucial role in determining the response of the body to vibration exposure.

Apparent mass in the vertical direction in this study, were found to support previous findings by Matsumoto and Griffin (1998) which reported a resonance frequency for individuals in a normal upright posture at about 5.5Hz, within a range of 4 – 6Hz. Variations in standing postures have been found to reduce the resonance frequency of vertical apparent mass however, these effects have generally been limited to lower limb postural changes, such as bending the knees (Subashi *et al.,* 2006). Furthermore, such postural variations have shown only minor influence on the magnitude of apparent mass at resonance. In the study presented in this chapter, participants stood with straight legs in all postures and consequently there was only a minor change in the resonance frequency between the 'Free – Hand Held' (5Hz) and the other supported postures (5.5Hz). Mansfield and Maeda (2007) reported an increase in resonance frequency from 4.25 to 5Hz when contact was made with a backrest in seated postures, yet the magnitude of apparent mass was generally unaffected. Toward and Griffin (2010) found that although holding onto a steering wheel did not influence the resonance frequency, it tended to lower the magnitude of apparent mass at resonance. This effect was attributed to the steering wheel supporting some of the mass of the arms. Results from Figure 7.6 show the 'Overhead Bar' and 'Vertical Bar' postures significantly ($p < 0.05$) reduced the magnitude of apparent mass at resonance, in a similar manner to the steering wheel support for seated individuals (Toward and Griffin, 2010). In the 'Lean Back' posture, a damping influence was evident between 1 – 3Hz, above which the apparent mass increased.

7.5.2 Transmissibility Responses

During horizontal motions (fore-and-aft and lateral vibration) the transmissibility in the ‘Free – Hand Held’ posture showed that the body attenuated vibration, limiting the motions at the hand across all frequencies tested between 1 – 5Hz. In this posture, a single driving-point of vibration was located at the floor and the measurement site was at the hand. It would therefore be expected that the vibration transmitted to the hand would be low. In the supported postures, the contact with the support provided an additional driving-point which would likely increase the transmission of vibration to the hand, depending on the location of the contact site. In the body-supported postures (‘Lean Back’ and ‘Lean Shoulder’) contact with the support was closer to the hand than in the hand-supported postures, which could explain the increased transmissibility in these postures. The nature of the support could also influence vibration transmission. The ‘Overhead Bar’ and ‘Vertical Bar’ supports were rigid, while the ‘Overhead Handle’ support was loose in comparison.

During fore-and-aft vibration, the increase in transmissibility at 3Hz in the ‘Overhead Bar’ and ‘Vertical Bar’ postures suggests that the supports increased transmission of vibration to the upper body but not to the same extent as the body-supported postures. Without a rigid support to transmit vibration, the ‘Overhead Handle’ posture exerted no influence on transmissibility to the hand. Paddan and Griffin (1993) found peak fore-and-aft transmissibility occurred at about 4Hz when holding lightly onto a handrail, with a reduction to 2Hz when the participants held tightly. The current study shows similar results, with evidence of an increase in transmissibility at about 3Hz in the ‘Overhead Bar’ and ‘Vertical Bar’ postures. Contact with a backrest has been found by Paddan (1994) to increase the resonance frequency of fore-and-aft vibration transmission to the hand from 1Hz (‘back-off’) to 4 – 5Hz (‘back-on’). In the study presented in this chapter, contact with a body-support (‘Lean Back’ and ‘Lean Shoulder’ postures, showed a peak in transmissibilities between 2 – 3Hz and 3 – 4Hz respectively. The differences between the results in this chapter and those reported by Paddan (1994) could reflect the differences between seated and standing postures; although, consideration must also be given to other factors such as vibration characteristics and variations in experimental protocols.

During lateral motion the ‘Lean Shoulder’ posture aligned the body in the same direction as the vibration. From Figure 7.8, it is evident that this postural alignment resulted in greater transmissibility at all measured frequencies between 1 – 5Hz. In the ‘Lean Back’ posture, the additional driving-point for vibration associated with the support could account for the increased transmissibility between 1 – 2Hz however, above this frequency lateral transmissibility decreased below 0.5. Differences between the responses in the ‘Lean Back’ and ‘Lean Shoulder’ postures could be related to the different alignments associated with each support and the direction of motion.

The results for vertical transmissibility presented in this chapter support previous findings by Paddan and Griffin (1995) that reported two distinct peaks on transmissibility around 2Hz and 5Hz during vertical vibration exposure in a ‘back-on’ posture. The transmission of vertical could be linked to the location of the additional driving-point between the support and the body, as well as the nature of the support. The rigid hand-supports (‘Overhead Bar’ and ‘Vertical Bar’) showed slightly higher transmissibilities at the resonance frequency than the loose support in the ‘Overhead Handle’ posture.

In standing individuals, Paddan and Griffin (1993) noted that transmission of lateral vibration to the head showed a resonance frequency at about 1.5Hz (with the feet separated by 30cm). Additionally, Paddan (1995) found similar resonance frequencies (around 2Hz) for the transmission of lateral vibration to the hand in seated participants. The results reported in this chapter current study support these findings from the literature, particularly in the ‘Lean Back’ and ‘Lean Shoulder’ postures. The presence of a backrest was found to increase the transmissibility to the hand in seated postures, although there was no influence on the resonance frequency (Paddan, 1995). Figure 7.8 clearly illustrates the influence of body-supports on the transmission of lateral vibration to the hand of standing individuals. In the ‘Lean Back’ and ‘Lean Shoulder’ postures, transmissibility increased significantly ($p < 0.05$) at frequencies between 1 – 2Hz, compared with transmissibility in the ‘Free – Hand Held’ posture.

7.6 CONCLUSIONS

This chapter presented a laboratory study designed to investigate the influence of postural supports on the biomechanical responses of the human body to whole-body vibration.

H1: The use of postural supports would restrain the motions of the upper body compared to an unsupported (free standing) posture, increasing the damping within the body. The resonance frequency of apparent mass of participants in supported postures would therefore increase.

During horizontal motions in the fore-and-aft and lateral directions, the influence of postural supports on apparent mass was predominantly found in the 'Lean Back' and 'Lean Shoulder' postures. As no distinct peaks were observed for the horizontal apparent mass in the other postures, it seems likely that the resonance frequencies occur outside the frequency range used in the study described in this chapter. During vertical vibration, apparent mass showed a resonance frequency around 5Hz in the 'Free Hand – Held' posture. Contact with postural supports showed an increase in resonance frequency from 5 to 5.5Hz.

H2: The magnitude of apparent mass in supported postures was expected to decrease at resonance.

During horizontal vibration exposure, the magnitude of apparent mass in the 'Lean Back' posture, showed an increase at about 3Hz (x-axis) and in the 'Lean Back' and 'Lean Shoulder' posture between 1 – 1.5Hz (y-axis). Vertical apparent mass was significantly ($p < 0.05$) reduced at resonance in the 'Overhead Bar' and 'Vertical Bar' postures, as well as at 3.5Hz in the 'Lean Back' posture. In these postures, the individual may use the support to hold up a portion of body mass, influencing the biomechanical response of the body.

H3: Contact with postural supports was expected to increase the resonance frequency of vibration transmission to the hand (compared to an unsupported posture).

H4: The magnitude of vibration transmission to the hand at resonance would increase during supported postures (compared to an unsupported posture).

Transmissibility responses showed similar results to the apparent mass responses, although the effects were emphasized to a greater extent, particularly at the resonance frequencies. In the fore-and-aft direction, peak transmissibilities were found between 2 – 3Hz and 3 – 4Hz for the 'Lean Back' and 'Lean Shoulder' postures, respectively. In the ‘Overhead Bar’ and ‘Vertical Bar’ postures, fore-and-aft transmissibility showed an increase at about 3Hz. In the lateral direction, the greatest transmissibilities were found between 1 – 2Hz in the body-supported and at about 2Hz in the ‘Overhead Bar’ and ‘Vertical Bar’ postures.

During vertical vibration, the apparent mass and transmissibility responses were generally comparable, with resonance frequencies around 5Hz. Postural supports showed an increase in resonance frequency from 5 to 5.5Hz (with the exception of the ‘Overhead Handle’).

H5: Variations between the types of support strategies would occur, such that the influence of supports on the biomechanical response of standing participants would be dependent on the contact between the support and the individual. Body-supported postures were expected to result in to greater effects on apparent mass and transmissibility, compared to hand-supported postures.

It was evident from the apparent mass and transmissibility responses that the body-supported postures (‘Lean Back’ and ‘Lean Shoulder’) were responsible for the greatest influence in biomechanical responses. Considering the transmissibility results, additional effects were found in the rigid hand-supports (‘Overhead Bar’ and ‘Vertical Bar’). These supports produced a peak (although less than in the body-supported postures) in transmissibility during horizontal vibration exposure. The biomechanical responses obtained in the ‘Overhead Handle’ posture were generally consistent with those found in the ‘Free – Hand Held’ posture.

The results from the study presented in this chapter suggest that the use of postural supports would alter the dynamic response of the human body exposed to vibration (with the possible exception of the ‘Overhead Handle’). Based on these findings, and the frequency-dependent performance and workload results obtained in Chapter 6; it would be expected that the greatest decrements to manual control performance would be associated with postures that exhibited the most substantial influence on the biomechanical responses of the body. The following chapter (Chapter 8) considers the influence of serial manual control performance and workload during exposure to vibration in similar standing postures to those used in this chapter. Serial manual control will be investigated for the purposes of continuity from Chapter 6 and in order to represent the use of hand-held devices typically adopted by standing rail passengers (Chapter 4).

CHAPTER 8

INFLUENCE OF WHOLE-BODY VIBRATION AND POSTURAL SUPPORT ON MANUAL CONTROL PERFORMANCE IN STANDING INDIVIDUALS

This chapter presents a laboratory study designed to investigate the influence of whole-body vibration (WBV) and postural support strategies on manual control performance of a serial task using a hand-held keypad device. This device and the serial control task were the same used in Chapter 6. The study was conducted in the Environmental Ergonomics Research Centre at Loughborough University.

There are many situations where standing people are exposed to vibration and therefore require supports to maintain stability. The vibration that standing individuals are commonly exposed to while travelling on rail transport systems have been shown to influence the performance of variety of tasks, including discrete and continuous control tasks (Chapter 5) as well as serial control tasks (Chapter 6). Previous research has suggested that degraded manual control performance is associated with the transmission of vibration to the upper body (Lewis and Griffin, 1978 and McLeod and Griffin, 1989). The influence of postural supports on the biomechanical response (apparent mass and transmissibility) of the standing human body was determined in Chapter 7.

The study presented in this chapter was designed to build from the studies presented in Chapters 4 – 7, and assess the extent to which manual control performance and workload measures were influenced by vibration exposure in similar standing postures to those tested in Chapter 7.

8.1 INTRODUCTION

In all forms of transportation, passengers are exposed to whole-body vibration (WBV) that could lead to activity interference. Advances in technology have meant that modern mobile equipment (such as, smart-phones or tablet computers) is no longer constrained by the need to be supported on tables or in the lap of passengers. Instead, such equipment can be operated while standing; either held in the hand or by resting the device on an elevated surface. Consequently, passengers are able to perform meaningful activities with greater postural freedom.

While it has been widely accepted that exposure to whole-body vibration impairs performance (Lewis and Griffin, 1978 and McLeod and Griffin, 1989) and that body posture represents a main contributing factor; the majority of studies have focused on seated postures. Little consideration has been given to motion-induced activity interference in standing individuals and there are no reported studies that have investigated the influence of postural supports on performance in standing postures.

The impact of postural supports (such as a backrest) is an important consideration for standing passengers, as it is often necessary to use various supports to maintain stability or to relieve muscles that fatigue while standing unsupported. The observational study presented in Chapter 4, indicated that a substantial proportion of standing passengers use vertical bars or leant sideways with one shoulder against a wall for support. Other commonly used support strategies included holding an overhead bar or leaning backwards against a wall.

8.2 RESEARCH HYPOTHESES

This chapter presents a laboratory study designed to evaluate the manual control performance of a serial task (participants were required to enter a sequence of five numbers into a hand-held keypad) and the related subjective workload experienced during standing exposure to whole-body vibration. Furthermore, this study aimed to quantify the influence of different support strategies on these performance and workload measures, as well as investigate the influence of mechanical coupling in two device locations: i) holding the device in the hand and ii) mounting the device to the vibrating structure (grounded). Performance measures included the response time (RT) and the error rate (used to determine the performance accuracy).

It was hypothesised that:

H1: Serial manual control performance would decrease and subjective workload ratings would increase with increasing vibration magnitudes (based on the results obtained for manual control performance in Chapters 5 and 6).

H2: Serial manual control performance and subjective workload ratings would vary between the types of support strategies used by individuals. Supports which were found to influence the biomechanical response of the body (Chapter 7) were expected to show the greatest influence on task performance and workload.

H3: Serial manual control performance and subjective workload ratings would be greater in the grounded condition compared to the hand-held conditions, due to differences in mechanical coupling between the hand and the control device.

8.3 METHODS

8.3.1 Participants

All (fourteen) participants were screened for any medical contra-indications that would have deemed them unfit to take part in the study. The participants comprised of students and research staff from Loughborough University, UK (anthropometric data has been provided in Table 8.1). Each participant received information regarding experimental procedure and informed consent was obtained prior to testing. The study was granted approval from the Loughborough University Ethical Advisory Committee.

Table 8.1 Anthropometric characteristics of participants from the study designed to assess the influence of postural supports on manual control performance using a hand-held keypad

Characteristic	**Hand-Held Keypad Task**
Number	14
Gender	9 female; 4 male
Age	20 – 33years (mean ± sd: 27.3 ± 4.7years)
Stature	1610 – 1830mm (mean ± sd: 1740.8 ± 73.3mm)
Mass	51.5 – 91.1kg (mean ± sd: 72.1 ± 12.3kg)
Foot Length	250 – 300mm (mean ± sd: 278.8 ± 17.1mm)
Standing Shoulder Height	1322.5 – 1517.1mm (mean ± sd: 1434.1 ± 65.2mm)

8.3.2 Pilot Testing

Using the same method presented in Chapter 6, performance results (response times) were used to establish the number of familiarisation trials required to minimise the learning effect when using the hand-held keypad (Figure 8.1). The keypad was operated in two conditions: i) hand-held and ii) grounded (where the keypad was secured to a rigid support frame). The familiarisation trials presented in Figure 8.1 show the mean response times (RTs) for both conditions. The mean RTs for both conditions stabilised after three familiarisation trials – this was validated statistically using a dependent *t*-test to compare each trial to Trial 6 and identify where the difference in RTs was no longer significant. Although the grounded condition resulted in consistently greater mean RTs than those in the hand-held condition, the learning effect showed a similar trend. The participants used in pilot testing did not take part in the experimental testing.

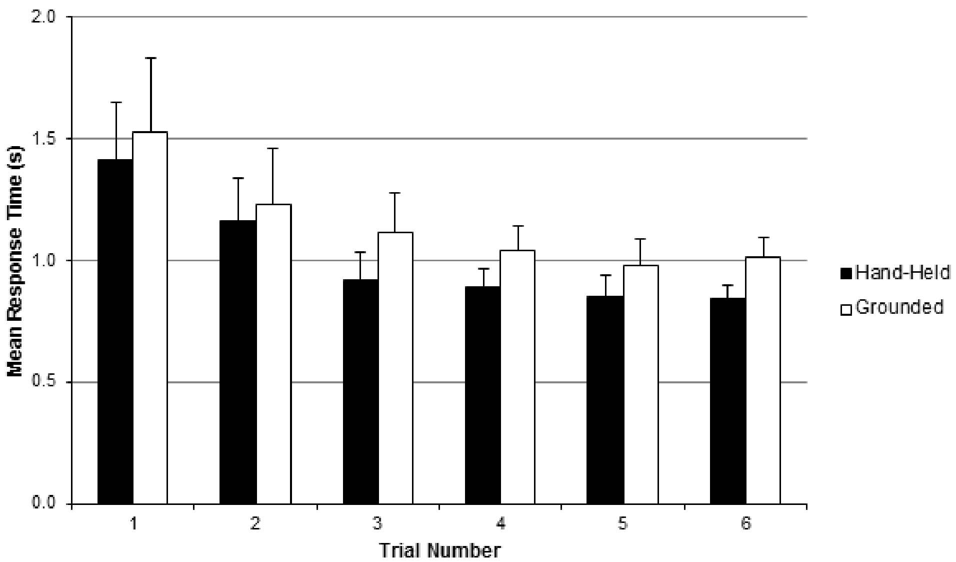


Figure 8.1 Mean (n = 3) response times for the keypad input task obtained during pilot testing, demonstrating a learning effect with repeated trials in the hand-held and grounded conditions

8.3.3 Independent Variables

8.3.3.1 Vibration

During the experimental conditions, participants were exposed to random, multi-axis (simultaneous x-, y- and z-axis) vibration stimuli. The vibration was generated using a 6 degree-of-freedom multi-axis vibration simulator (MAViS) at the Environmental Ergonomics Research Centre, Loughborough University. Participants were required to stand on the simulator platform and, for safety reasons a harness was worn at all times while standing on the simulator. Depending on the posture adopted by the participants, additional support was provided by a rigid frame mounted on the vibration platform.

The vibration frequency was band-limited up to 4Hz and two vibration magnitudes were selected: a low magnitude condition (0.519ms^{-2} r.s.s.) and a high magnitude condition (1.039 ms^{-2} r.s.s.). These magnitudes were selected based on measurements obtained during the field study presented in Chapter 4. The values represent the resultant vibration magnitudes calculated using the root sum of squares (r.s.s.) method based on simultaneous exposures in the x-, y- and z-axes (Table 8.2). The control conditions were used to obtain a reference level for performance and subjective workload measures and were conducted at the beginning and the end of the testing session, in two posture conditions ('Free – Hand Held' and 'Free – Grounded'). The vibration stimuli lasted approximately 30s and were repeated in seven posture conditions (representing a total of 14 vibration conditions and 4 control conditions).

Table 8.2 Summary of the vibration stimuli used during the hand-held keypad (serial manual control) performance study

Task Variable	**Condition**	**Vibration Magnitude (ms^{-2} r.m.s., unweighted)**			
		x-axis	**y-axis**	**z-axis**	**r.s.s. ∑ axes**
Serial Manual Control	1	0.3	0.3	0.3	0.519
	2	0.6	0.6	0.6	1.039
	Control (hand-held)	---	---	---	---
	Control (grounded)	---	---	---	---

Where: r.m.s. = root mean square and r.s.s. = root sum of squares

The order in which the experimental conditions were presented was randomised using a balanced Latin-square technique. The randomisation occurred between both vibration magnitude conditions (low and high) and the seven posture conditions adopted by the participants. This ensured that the sequence of conditions was not repeated between individuals and the participants were not able to 'predict' the subsequent experimental conditions. During the control conditions, the vibration simulator equipment remained pressurised to minimise the influence of possible confounding factors (such as the noise generated when the system is operated) on the performance and subjective responses of the participants.

8.3.3.2 Posture

Participants adopted seven standing postures (Figure 8.2) on the vibration simulator, based on observations of standing passengers on public rail transportation (Chapter 4). These postures were the same as those adopted in by participants in Chapter 7 (with the inclusion of the 'Grounded' posture). Postural supports were provided by a rigid metal frame secured to the simulator platform. The postures included:

1. 'Free – Hand Held': a normal upright standing posture with the keypad device held in the dominant hand of the participant.

2. 'Free – Grounded': a normal upright standing posture with the keypad device attached to the support frame, mounted on the vibration platform.

3. 'Lean Back': participants leant backwards against a rigid vertical board which provided support from the upper back to the buttocks. The feet were positioned with the heels a distance of one foot length in front of the board, producing an inclination of approximately 15º to the vertical.

4. 'Lean Shoulder': participants leant sideways against a rigid vertical board, providing support at the dominant shoulder (on the same side the device was held) with the mid-sagittal plane parallel to the board. The feet were parallel and together, positioned one foot length from the board with the body straight, producing an inclination of approximately 7º to the vertical.

5. 'Overhead Bar': participants adopted a normal upright standing posture and held a rigid horizontal bar positioned 50-100mm above head height.

6. 'Overhead Handle': identical to the 'overhead bar' posture, however the support was a loose handle attached to the frame with fabric webbing, at the same height above the participants.

7. 'Vertical Bar': participants adopted a normal upright standing posture and held onto a rigid vertical bar at shoulder height with the elbow unlocked.

With the exception of the 'Free – Grounded' posture, the input device was held in the dominant hand of the participant (all participants were right handed) while the other hand remained free, or was used to hold onto a support (depending on the condition). In the 'Free – Grounded' posture, participants used their index finger to input the target numbers on the keypad, while for the other postures where the device was hand-held, the thumb was used. Participants were instructed to stand with their knees locked and place their feet one foot length apart (measured from the lateral border of each foot). This ensured the base of support at the feet was equal in both the fore-and-aft (x-axis) and lateral (y-axis) directions and coloured markers were placed on the platform to indicate the location of each foot. In the 'Lean Shoulder' posture, the feet were positioned together as it was not feasible to accommodate both locked knees and separated feet.

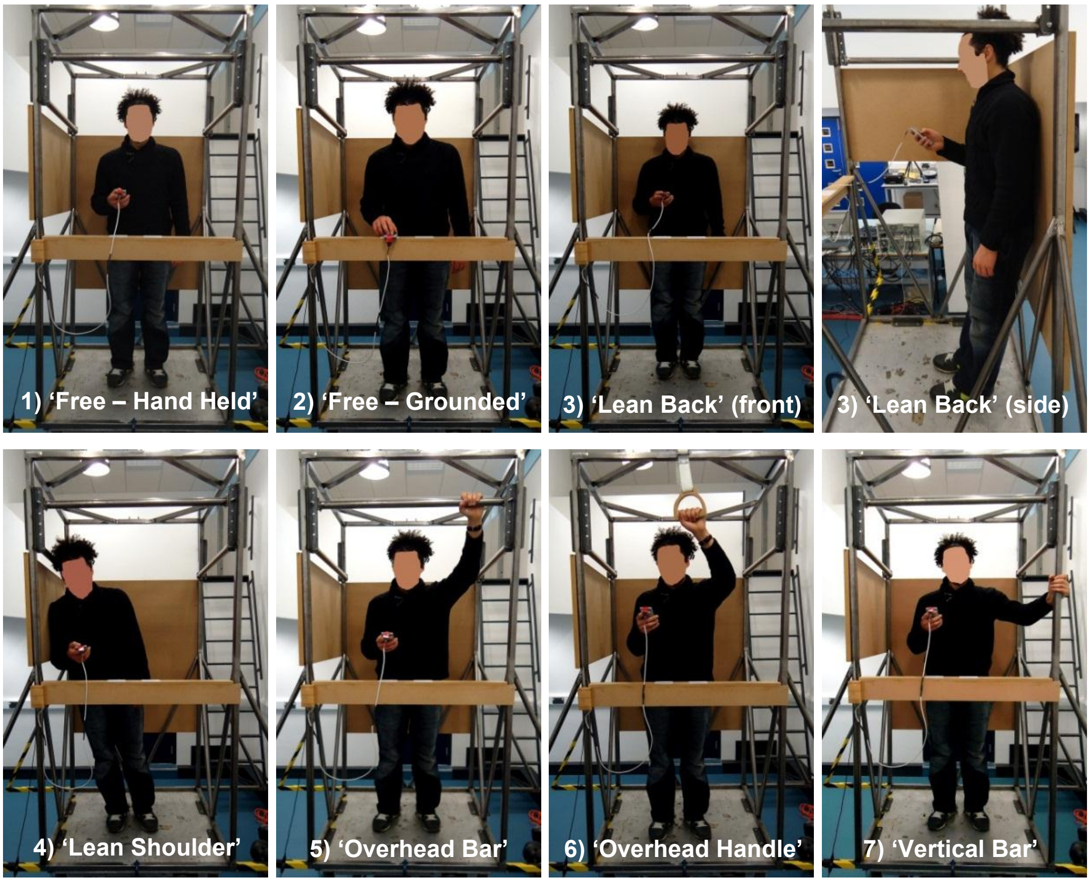


Figure 8.2 Standing postures adopted by the participants on the motion platform (safety harness not shown for purposes of clarity)

8.3.4 Dependant Variables

8.3.4.1 Objective Measurement

The same methods employed to assess manual performance in Chapter 6 were used in this study. Performance was evaluated based on the mean response time (RT) taken to complete a single correct input. Incorrect responses were therefore excluded from the measurement of mean response time however; these were recorded and expressed as a percentage of the total input responses to provide a measure of performance accuracy. The response time (RT) and input errors were recorded automatically using an in-house program developed in LabVIEW (Version 8.2) software (National Instruments Corporation, UK).

8.3.4.2 Subjective Measurement

Previous studies (Chapters 5 and 6) evaluated subjective workload responses using semantic rating scales and estimation techniques. These methods provide an overall measurement of workload but make no reference to the individual components that contribute to this expression of subjective workload. Therefore, in order to account for these individual aspects of workload experienced by individuals during WBV exposure, the NASA Task Load Index (NASA-TLX) method was used in this study (Hart, 1988). This method consisted of a multi-dimensional rating procedure that provided an overall workload score based on the weighted average ratings of six sub-scales; namely: Mental demand, Physical demand, Temporal demand, Performance, Effort and Frustration (Figure 8.3).

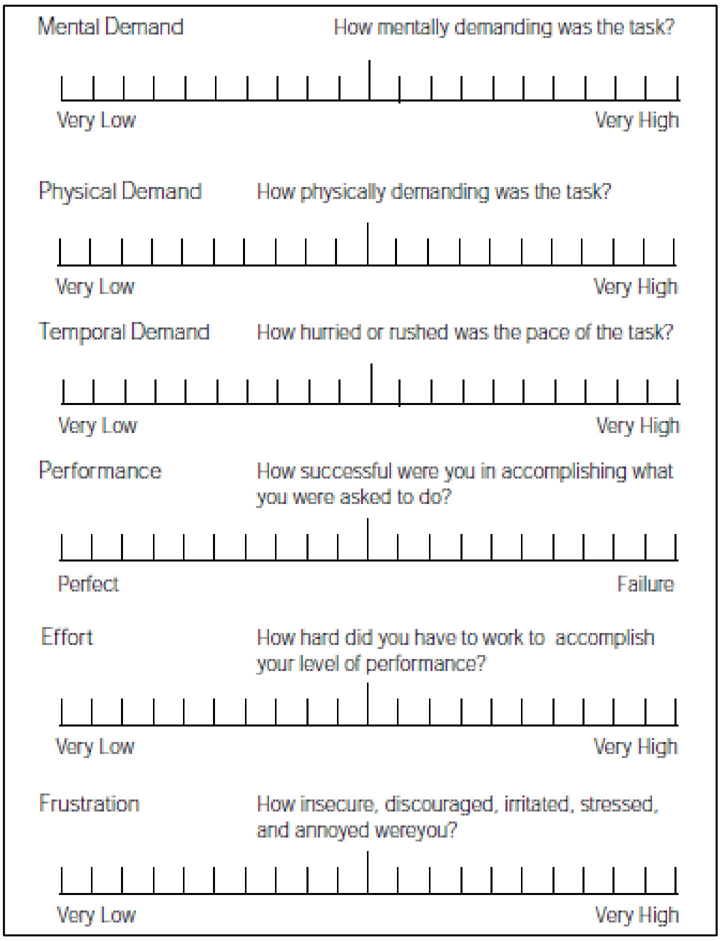


Figure 8.3 NASA Task Load Index (TLX) assessment subscales

The degree to which each of these factors contributed to the workload of a specific task was determined by the responses given to 15 pair-wise comparisons between the six factors. A description of each subscale has been provided in Table 8.3 (Hart and Staveland, 1988). The participants provided ratings of workload retrospectively, following the completion of each experimental condition. The NASA-TLX software (version 2.0, NASA Ames Research Centre, USA) displayed the sub-scales to the participants on the test screen. The ratings and weighted scores were recorded automatically by the software and saved onto the laboratory PC.

8.3.5 Experimental Protocol

8.3.5.1 Task

The task equipment for this study was the same as that used in Chapter 6; consisting of a generic non-tactile membrane keypad (manufactured by Apem Components, UK) and a laptop PC running LabVIEW software (version 8.2). Participants were required to enter a sequence of numbers that were displayed on a screen, situated 1000mm in front of the participant. Due to the variations in standing posture, the screen was mounted on a movable frame to ensure it could be positioned correctly and maintain a constant viewing distance. The keypad was fitted into a rigid plastic moulding (manufactured by RION Company Ltd, Japan) to approximate the size and mass (115 × 60 × 12mm and 130g) of commonly observed hand-held devices used by standing passengers (Chapter 4). The keypad and moulding are shown in Figure 6.3 (Section 6.3.5.1, Chapter 6).

LabVIEW software (version 8.2) was used to develop an in-house program to generate random single-digit numbers between one and nine, which represented the ‘target’ numbers for the serial manual control task. These numbers were displayed in clusters of five (based on short-term working memory capacity, (Miller, 1956)) on a screen located in front of the participant (Figure 8.5iii).

The keypad device was located in two positions, i) a ‘grounded’ position where the device was secured to the support frame mounted onto the vibration shaker and ii) a ‘hand-held’ position where the participant held the device (Figure 8.4). The ‘Grounded’ condition was included to represent the influence of direct mechanical coupling between the vibration source and the device. Similar conditions were evaluated in Chapter 5 where the discrete and continuous manual control tasks were secured to the vibrating platform. Due to the different locations of the device, the participants used the index finger to enter the response numbers into the keypad in the ‘grounded’ position and the thumb to enter the numbers in the ‘hand-held’ position. Silfverberg *et al*. (2000) reported the average movement times for successive key presses to be 273 and 309ms for the index finger and thumb respectively.

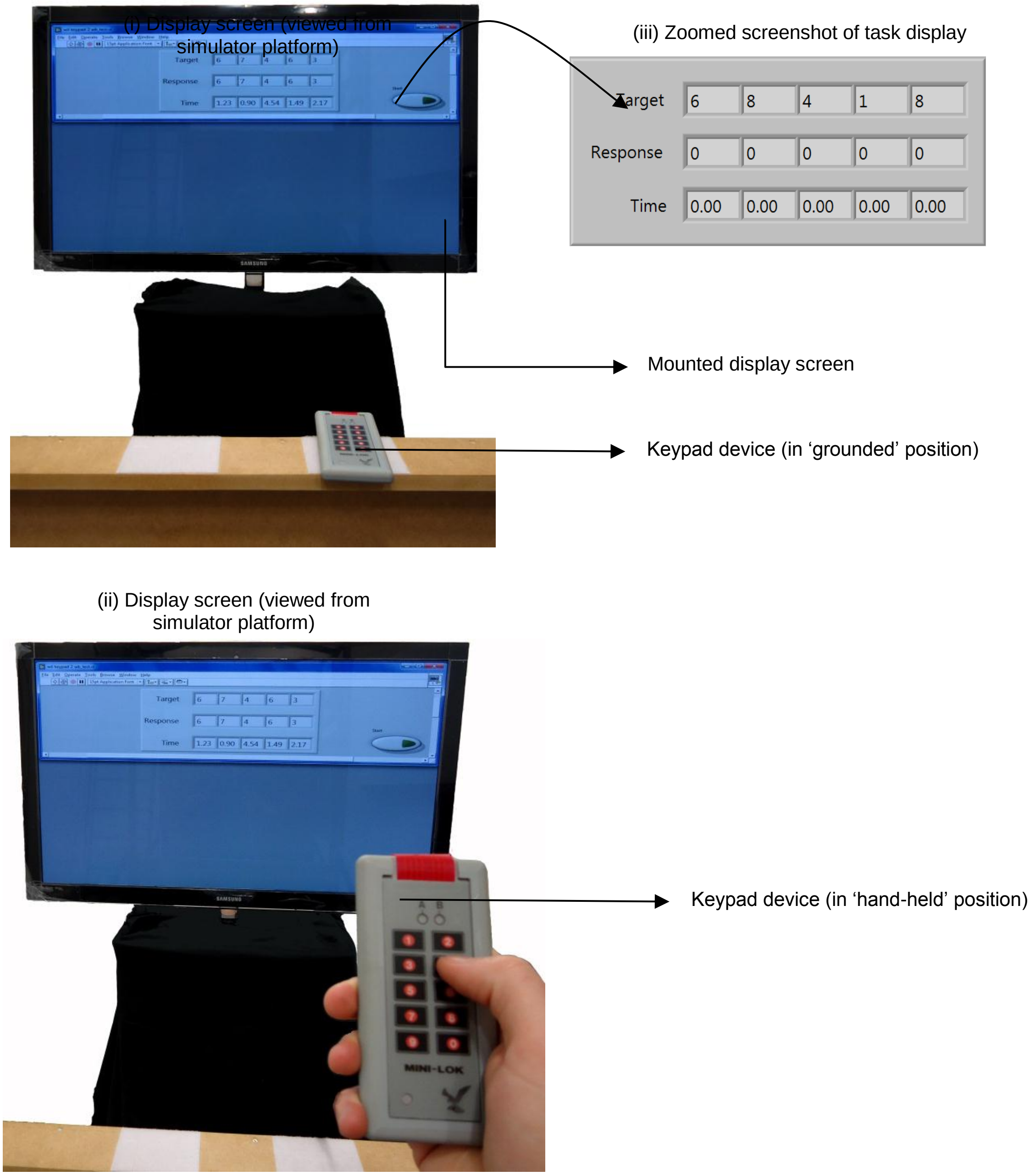


Figure 8.4 View from the simulator platform, showing the display screen positioned in front of the participant with the device in: i) a 'grounded position' (attached to the frame), ii) a 'hand-held' position. A zoomed screenshot of the task display (iii) illustrates the target and response numbers, as well as the response time

Participants were instructed to use their dominant hand and respond 'as accurately and as quickly as possible' by pressing the corresponding number to the 'target' number on the keypad. A correct input response was required before the subsequent 'target' number could be selected. The response time (RT) taken to correctly register the corresponding 'target' number and selection errors caused by pressing incorrect numbers on the keypad were automatically recorded by the LabVIEW program. The response time for each selection was displayed on the screen to provide the participants with immediate performance feedback. Once five correct responses were completed the display refreshed with a new cluster and this process was repeated five times (representing 25 'target' numbers) for each experimental condition.

8.3.5.2 Procedures and Design

The experimental protocol was conducted during a single laboratory testing session in the Environmental Ergonomics Research Centre, Loughborough University. The session commenced with anthropometric measurements followed by three familiarisation trials. These trials provided the participants with an opportunity to practice operating the keypad, as well as gain an understanding of the NASA-TLX ratings and weighting comparisons. Based on the measured anthropometric data, markers were placed on the motion platform to ensure the participants adopted the correct standing postures during the testing conditions. The image of the LabVIEW program on the screen was set at standing shoulder height to ensure the viewing angle between the participant and the screen remained the same for all postures.

Static (control) conditions with no vibration exposure were performed in the 'Free – Hand Held' and 'Free – Grounded' postures before and after the vibration conditions. Performance measures during static control conditions were not taken in the other hand-held postures based on pilot testing and the findings presented in Chapter 5. Manual control performance for discrete and continuous tasks showed no significant variation between stance orientations in control conditions (Chapter 5).

The control conditions served as a reference for subjective ratings and provided a baseline measure of performance. The order in which the control conditions were presented alternated between postures ('Free – Hand Held' and 'Free – Grounded') within each testing session and for each participant. The vibration conditions were randomised and counter-balanced for each participant based on posture and vibration magnitude using a Latin-square technique.

The simulator platform was controlled by a dedicated laboratory computer system, while a secondary laptop computer was used to run the LabVIEW software and testing program. The LabVIEW testing program was only started once the vibration platform had stabilised at the required magnitude (approximately 5seconds after initiating the motion file on the computer). Once the participant had completed the input task, the LabVIEW program stopped automatically, the vibration input ceased and the platform was returned to a 'neutral' position.

8.3.6 Data Analysis

Objective performance was evaluated using the mean response times taken to enter 'target' numbers and the accuracy of performance (based on incorrect inputs). The number of incorrect inputs was recorded and performance accuracy was calculated as a percentage of the total number of inputs (Equation 6.1, Section 6.3.6 Data Analysis).

Using the same method as in Chapter 6, the response times were divided into two classifications: the initial 'target' number response ($RT_{INITIAL}$) and the subsequent 'target' numbers response (RT_{SUB}). Figure 8.5 provides an example of the variation in mean response times for each of the 'target' numbers within the five digit sequence. The initial response time ($RT_{INITIAL}$) was located at position 1 and the subsequent response time (RT_{SUB}) was calculated as the mean of positions 2 – 5.

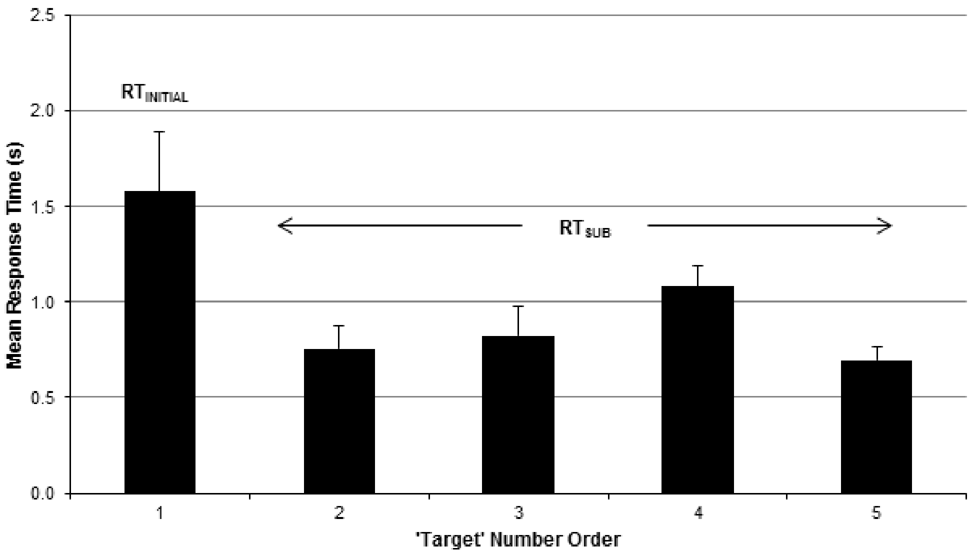


Figure 8.5 Mean response times taken to input a correct 'target' number, based on the order in which the number appeared in the five digit sequence (condition: no vibration (control), 'Free – Hand Held' posture)

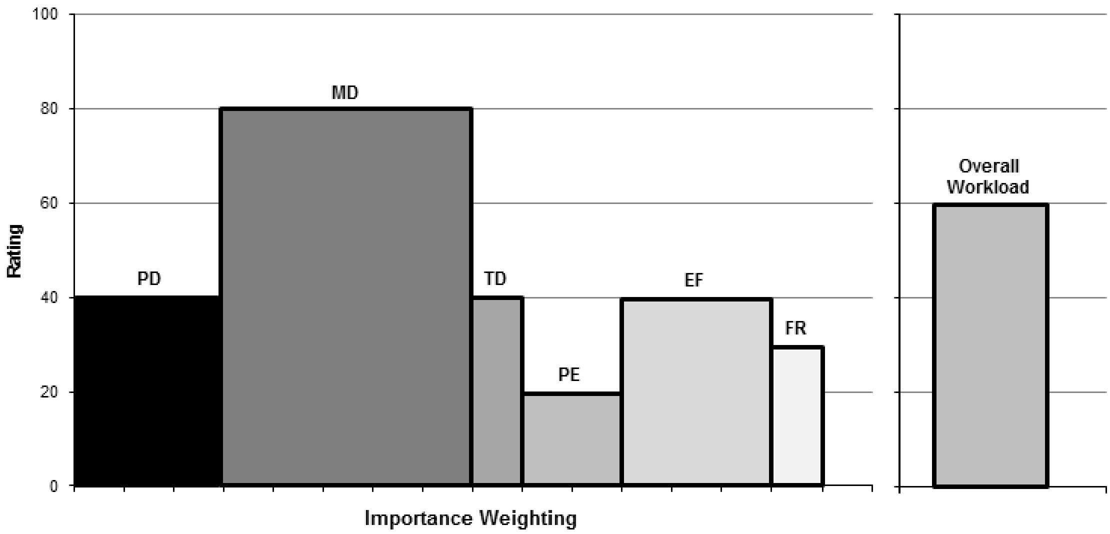


Figure 8.6 Graphical example of the composition of a weighted NASA-TLX workload score (overall workload = mean of weighted ratings)

The calculation of the overall NASA-TLX score was performed automatically by the COMBINE program (NASA-TLX software, version 2.0). The program used the raw ratings for the six sub-scales and applied the weightings, based on the pairwise comparison data. A graphical representation showing the composition of the weighted workload scores is shown in Figure 8.6. The height of the sub-scale bars represents the magnitude (rating) of each factor, while the width of the bars reflects the importance (weighting). The overall weighted workload score was calculated as the average area of the sub-scale bars.

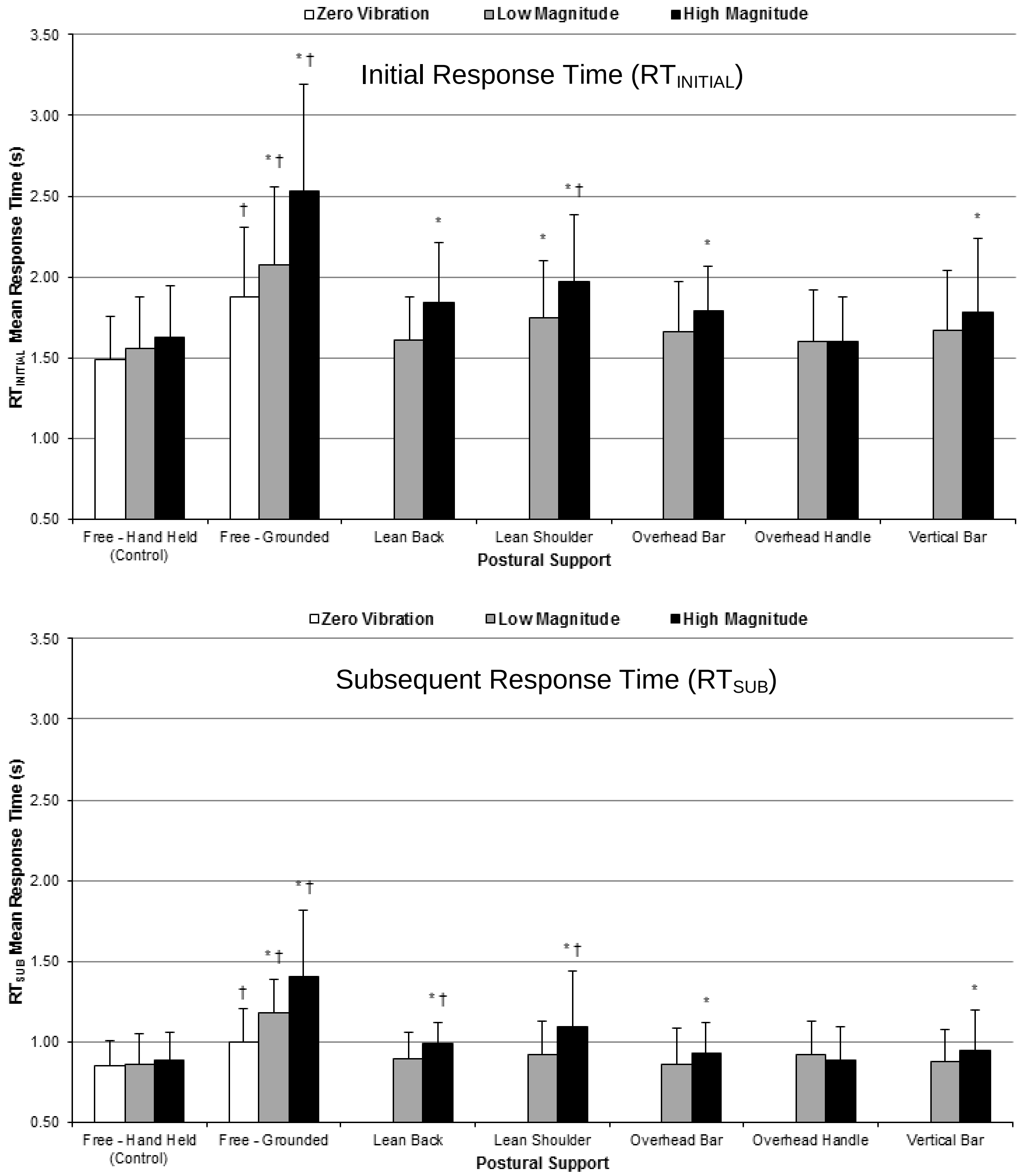
Before statistical analysis was performed, an outlier within the data set was first removed. Throughout the testing protocol for all experimental conditions, participant 14 consistently provided 'maximal' subjective workload ratings. Additionally, this participant repeatedly shifted posture during experimental conditions (including the control conditions). It was therefore decided to exclude this participant. Statistical analysis was conducted using *SPSS*® software (Version 15) and a repeated measures analysis of variance was used to determine whether vibration magnitude and posture significantly influenced objective performance and subjective workload.

8.4 RESULTS

8.4.1 Response Time and Performance Accuracy

The $RT_{INITIAL}$ showed significantly ($p < 0.05$) greater measures than the RT_{SUB} for each of the standing postural conditions tested (Figure 8.7). This would be expected as the $RT_{INITIAL}$ consisted of a cognitive processing (CP) time which was not necessarily present in the RT_{SUB}. Generally, the $RT_{INITIAL}$ and RT_{SUB} showed similar trends between each of the standing postures tested. With the exceptions of the 'Free – Hand Held' and 'Overhead Handle' postures, both the $RT_{INITIAL}$ and RT_{SUB} increased significantly with a corresponding increase in vibration magnitude (Figure 8.7). These effects were found in the low and high magnitude conditions for the 'Free – Grounded' ($p < 0.05$) posture ($RT_{INITIAL}$ and RT_{SUB}) and for the 'Lean Shoulder' ($p < 0.05$) posture (RT_{INITAL}). In the other postures the influence of vibration exposure on response times was significant ($p < 0.05$) in the high magnitude conditions (with the exception of the 'Overhead Handle' posture which showed no reduction in response time in either the low or high magnitude conditions).

Comparing the different types of support strategies to the 'Free – Hand Held' (control) posture; response times were significantly ($p < 0.05$) greater in the 'Free – Grounded' posture (RT_{INITAL} and RT_{SUB}). In the 'Lean Back' posture (RT_{SUB}) and the 'Lean Shoulder' posture ($RT_{INITIAL}$ and RT_{SUB}), these postural effects were significant ($p < 0.05$) in the high magnitude condition. There were no postural effects found for response times in the three hand-support strategies ('Overhead Bar', 'Overhead Handle' and 'Vertical Bar').

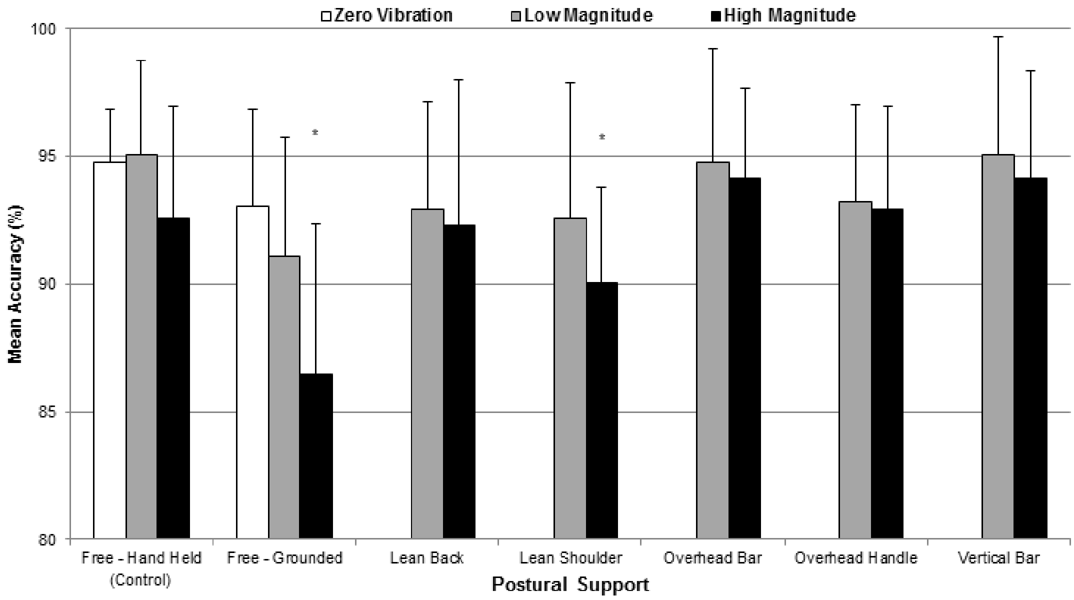


Where: ***** = significant (p < 0.05) effect of vibration magnitude, compared to the zero vibration conditions

† = significant (p < 0.05) effect of posture/support, compared to the 'Free – Hand Held' (control) posture

Figure 8.7 Mean response times (RT) for a keypad input task in different standing postures during exposure to multi-axis vibration

Overall, the accuracy of responses was consistent with the findings of previous studies (Card *et al*., 1978 and Hall *et al*., 1988) which reported performance accuracies between 87 – 95% for selection tasks using a mouse, text keys and touch screens. Performance accuracy (Figure 8.8) was significantly (p < 0.05) reduced during the high magnitude condition in the 'Free – Grounded' and 'Lean Shoulder' postures. There was no significant influence of posture/support strategies for each of the standing postures tested. However, trends could suggest the body-supported ('Lean Back' and 'Lean Shoulder') postures resulted in potentially greater interference with accuracy than the hand-supported postures.



Where: ***** = significant (p < 0.05) effect of vibration magnitude, compared to the zero vibration conditions

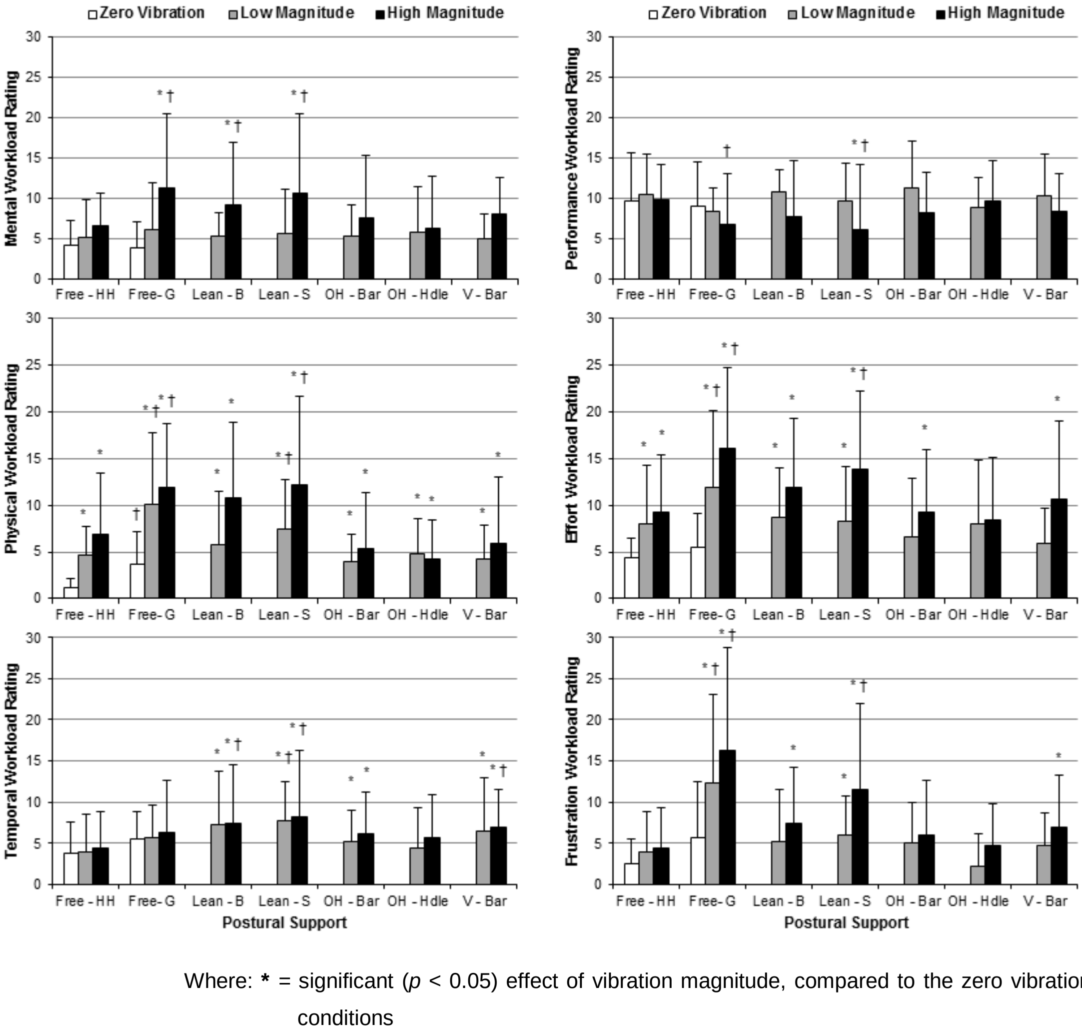
Figure 8.8 Mean performance accuracy for a keypad input task in different standing postures during exposure to multi-axis vibration

8.4.2 Subjective Workload

For each subscale of the NASA-TLX (Figure 8.9), increasing subjective workload scores were found to occur with corresponding increases in vibration magnitude (p < 0.05). Due to the high number of conditions when assessing each individual component of the NASA TLX subscales, a summary of the significant results is provided in Table 8.3.

These results show the greatest influence on subjective workload occurred in the 'Physical', 'Temporal' and 'Effort' subscales. The 'Mental' and 'Frustration' workload subscales showed significant effects in the 'Free – Grounded', 'Lean – Back' and 'Lean – Shoulder' postures. In situations where the 'Mental' workload increased, a corresponding increase in the ‘Frustration’ experienced by the participants was found. The ‘Effort’ required to perform the task consisted of a combined rating of both mental and physical workload. The extensive influence of vibration on the ‘Physical’ workload ratings could reflect a dominant factor in the overall ‘Effort’, where the greatest limitation on performance is based on the physical characteristics of working in a moving environment, rather than the mental demands of the task.

Overall, the hand-supported postures (‘Overhead Bar’, ‘Overhead Handle’ and ‘Vertical Bar’) tended to show lower workload ratings than the body-supported postures (‘Lean – Back’ and ‘Lean – Shoulder’).



Where: ***** = significant ($p < 0.05$) effect of vibration magnitude, compared to the zero vibration conditions

† = significant ($p < 0.05$) effect of posture/support, compared to the ‘Free – Hand Held’ (control) posture

Figure 8.9 Mean NASA-TLX subscale workload ratings, experienced by participants performing a keypad input task in different standing postures during exposure to multi-axis vibration

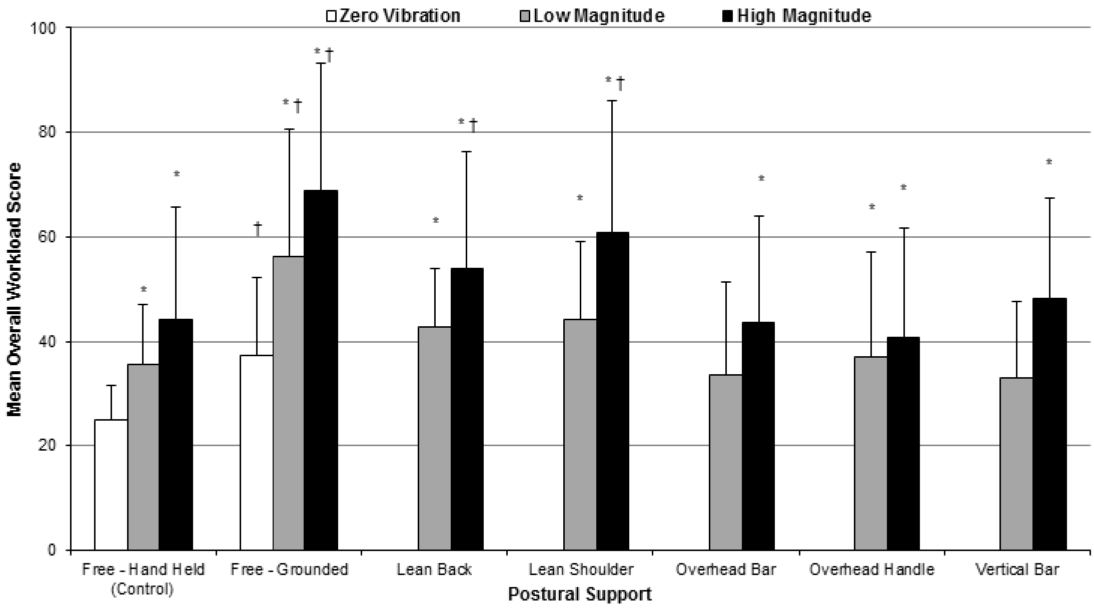
Table 8.3 Summary table showing the conditions during which vibration exposure (compared to the zero vibration condition) and postural support strategies (compared to the 'Free – Hand Held' posture) significantly increased subjective workload ratings

Subscale	**Free – Hand Held**		**Free – Grounded**		**Lean Back**		**Lean Shoulder**		**Overhead Bar**		**Overhead Handle**		**Vertical Bar**	
Vib. Mag. (ms^{-2} r.s.s., unweighted)	**0.519**	**1.039**	**0.519**	**1.039**	**0.519**	**1.039**	**0.519**	**1.039**	**0.519**	**1.039**	**0.519**	**1.039**	**0.519**	**1.039**
Mental				* †		* †		* †						
Physical	*	*	* †	* †	*	*	* †	* †	*	*	*	*	*	*
Temporal					*	* †	* †	* †	*	*			*	* †
Performance				†				* †						
Effort	*	*	* †	* †	*	*	*	* †						*
Frustration			* †	* †		*	*	* †						*
Overall	*	*	* †	* †		* †		* †		*	*	*		*

Where: ***** = significant ($p < 0.05$) effect of vibration magnitude, compared to the zero vibration conditions

† = significant ($p < 0.05$) effect of posture/support, compared to the 'Free – Hand Held' (control) posture

The overall workload score considered the importance of each subscale and the relative contribution to a combined expression of the workload experienced by participants. The results expressed in Figure 8.10 and Table 8.3 show that subjective workload increased significantly ($p < 0.05$) with increasing vibration magnitudes for all postures (except in the 'Overhead Bar' and 'Vertical Bar' postures at low magnitude). A comparison between the types of support strategies revealed the 'Lean Back' and 'Lean Shoulder' postures resulted in significantly higher ($p < 0.05$) workload demands than the 'Free – Hand Held' (control) posture (high magnitude condition). Participants consistently provided higher workload ratings in the 'Free – Grounded' posture ($p < 0.05$) than the 'Free – Hand Held' posture for all testing conditions ('zero vibration', 'low magnitude' and 'high magnitude' exposures). In addition, the hand-supported postures tended to show lower workload scores than the body-supported postures (similar to the trends found in Figure 8.9 with the NASA-TLX subscale ratings).



Where: ***** = significant ($p < 0.05$) effect of vibration magnitude, compared to the zero vibration conditions

† = significant ($p < 0.05$) effect of posture/support, compared to the 'Free – Hand Held' (control) posture

Figure 8.10 Mean overall workload demand experienced by participants performing a keypad input task in different standing postures during exposure to multi-axis vibration

8.5 DISCUSSION

This study was designed to investigate the influence of postural support strategies on manual control performance of a numerical serial input task and the associated perceived workload during WBV exposure in different standing postures. In all postures (with the exception of the 'Free – Grounded' condition) the keypad device was hand-held and therefore, the hand and the device would move in-phase. In the 'Free – Grounded' posture, the device was secured to a rigid frame mounted on the vibration platform. This meant there was a disassociation between the controlling hand and the keypad device, resulting in an out-of-phase movement.

In each testing condition, activity interference leading to degraded performance and increased subjective workloads would likely be due to a potential loss of stability, the transmission of vibration to the controlling hand and to the device, or cognitive effects.

8.5.1 Influence of Vibration and Mechanical Coupling

The majority of previous studies that have investigated the influence of WBV on task performance assess devices that were secured to the vibrating structure. The mechanical coupling between the device and the vibrating surface would increase the relative displacement between the hand and the device, potentially leading to greater activity interference and reduced accuracy (Paddan and Griffin, 1995). It could be hypothesised therefore that, conditions in which the relative displacement was minimised would improve performance measures.

This effect was demonstrated in the results presented in Chapter 5, investigating discrete and continuous manual control. In the discrete control task, the controlling hand was not in direct contact with the pegboard (minimal contact was made when participants inserted the pegs into the slots of the board). Consequently, the relative displacement during the continuous manual control task (where participants held onto the control) was less than during the discrete control task. Although workload measures increased during vibration exposure for both tasks, participants were able to maintain performance levels in the continuous control task (discrete manual control performance degraded progressively, with increasing vibration magnitude). It should be noted that the different characteristics of the tasks could act as an additional contributing factor to these results. In order to provide greater reliability and repeatability within such a comparison, the current study assessed the same task performed in various hand-held and grounded positions.

Further evidence concerning the influence of mechanical coupling on task performance and workload has been presented by Newell and Mansfield (2008); where the inclusion of armrests was found to improve performance measures for a reaction time task (Figure 5.8, Section 5.5.1 Manual Control Performance). In an upright seated posture without armrests, significantly longer reaction times and reduced performance accuracy were reported during vibration exposure than in a control condition without vibration. In the presence of armrest support, individuals were able to adapt to the vibration and maintain performance – the use of armrests ensured the hand/arm and the device moved in-phase, reducing the relative displacement of the hand which could result in performance degradation (Lewis and Griffin, 1978).

In the 'Free – Hand Held' posture, the only significant ($p < 0.05$) influence of vibration exposure resulted in an increase in the subjective workload experienced during the high magnitude condition. Objective performance measures revealed no significant effects on response time and performance accuracy in this posture, clearly demonstrating the compensatory ability of participants to overcome vibration exposure and maintain a similar level of performance as in the control (no vibration) condition. It is important to note that although participants were able to maintain performance, the task was rated as more demanding during vibration exposure than without vibration (Figure 8.10).

Considering the individual NASA-TLX subscales (Figure 8.9 and Table 8.3), the greatest influence of vibration exposure was found in the workload ratings associated with the physical demand and the overall effort expended to maintain performance levels. This would be expected as the motions to which the participants were exposed to would require an increased level of physical response (for example, increased muscle tension) to maintain stability. Additionally, the task was easily learnt and therefore the mental workload experienced by the individuals would be less likely to show a substantial influence due to vibration exposure. The conditions where mental workload was significantly increased were the 'Free – Grounded', 'Lean Back' and 'Lean Shoulder' postures (high magnitude). These effects could be due to the increased biomechanical response of the body in these postures (Chapter 7) that may influence the mental processing capabilities of the individuals. Time pressure, represented by the temporal demand, was found to significantly increase in the majority of postures (with the exception of the 'Overhead Handle' and the 'Free – Grounded'). The 'Free – Grounded' posture revealed increased workloads for all NASA-TLX subscales, except for the temporal demands which may suggest that participants prioritised completion of the task over the response time. Frustration tended to increase in the ‘Free – Grounded’ and the body support postures (‘Lean Back’ and ‘Lean Shoulder’) and these postures were also associated with the greatest decrements to performance. It could be suggested therefore, that the frustration experienced by the participants was due to the unsuccessful attempts to compensate for the influence of vibration and maintain performance. Where performance was not affected to the same extent (such as, the ‘Overhead Bar’ and ’Overhead Handle’), the decrease in performance did not correspond to an increase in frustration.

When the device was secured to the support framework, representing the ‘Free – Grounded’ posture, it was evident the demands of performing the task exceeded the ability of participants to cope with vibration exposure and consequently, performance was degraded (Figures 8.7 and 8.8). Response times (both $RT_{INITIAL}$ and RT_{SUB}) significantly increased in both the low and high magnitude conditions however, performance accuracy was only affected by high magnitude vibration. These results suggest that participants could have prioritised accuracy over speed at the expense of higher workload demands.

Differences in task performance and workload observed during vibration conditions between the ‘Free – Hand Held’ and ‘Free – Grounded’ postures could have been influenced by the mechanical coupling between the device and the driving-point of vibration. In the ‘Free – Grounded’ posture vibration was transmitted to the device through the rigid frame, while vibration at the hand was transmitted from the floor through the body. The different transmission pathways would result in an out-of-phase movement compared to the ‘Free – Hand Held’ posture where vibration at the device and the hand was transmitted through the body. In this condition, the device and controlling hand moved in unison (in-phase movements) and consequently there would be less relative motion between the position of the input finger/thumb and the keypad numbers, allowing for better performance during vibration exposure.

During the zero vibration conditions, response time performance was significantly poorer ($p < 0.05$) and workload substantially higher ($p < 0.05$) in the ‘Free – Grounded’ posture, than the ‘Free – Hand Held’ posture. Without the disturbance from vibration, a possible contributing factor could relate to the different movement times associated with the input fingers. Silfverberg *et al*. (2000) reported faster average movement times for the index finger, compared to the thumb. An important consideration with these results was that the study by Silfverberg *et al.* (2000) involved paired numbers and participants were not required to search for the correct number to enter. In the study presented in this chapter, there was an additional cognitive processing and visual scanning time in order to locate and enter the correct number on the device. Results shown in Figure 8.7 revealed an opposite trend to that proposed by Silvferberg *et al.* (2000), with slower response times associated with conditions where participants used the index finger ('Free-Grounded') rather than the thumb ('Free – Hand Held'). It could be suggested that during the experimental conditions, the influence of vibration exposure was a greater contributing factor to performance than variations in response times due to finger selection (Silfverberg *et al.*, 2000).

8.5.1.1 Performance Strategy

Using the same method described in Chapter 6, the response time results were divided into the mean time taken to input the initial number in the five digit sequence ($RT_{INITIAL}$) and the mean time taken to input the subsequent remaining four numbers (RT_{SUB}). The RT_{SUB} consisted of a visual scanning component (to locate the appropriate number on the keypad) and a physical manual control component (moving and pressing the selected button). In addition to these processes, the $RT_{INITIAL}$ further included a cognitive processing (CP) period where participants reviewed the set of 'target' numbers before inputting the corresponding number on the keypad ($RT_{INITIAL} = RT_{SUB} + CP$). The results in Figure 8.7 showed a significant influence of vibration exposure on both the $RT_{INITIAL}$ and the RT_{SUB} (generally limited to the high magnitude condition). This would suggest that vibration exposure caused disturbances not only in the processing of the new number sequences but also the physical capability to perform the task.

Similarly to the method presented in Chapter 6, the display screen and the keypad were separated in order to represent the different focus areas associated with mobile device usage during travelling (Holleis *et al.* 2007). The Participants alternated viewing between the keypad and the display (during the RT_{SUB}), after the initial number had been entered. Frequency distributions for the individual RT_{SUB} measures were calculated and are presented in Figures 8.11 (free-standing postures), Figure 8.12 (body-supported postures) and Figure 8.13 (hand-supported postures) for the low and high vibration conditions.

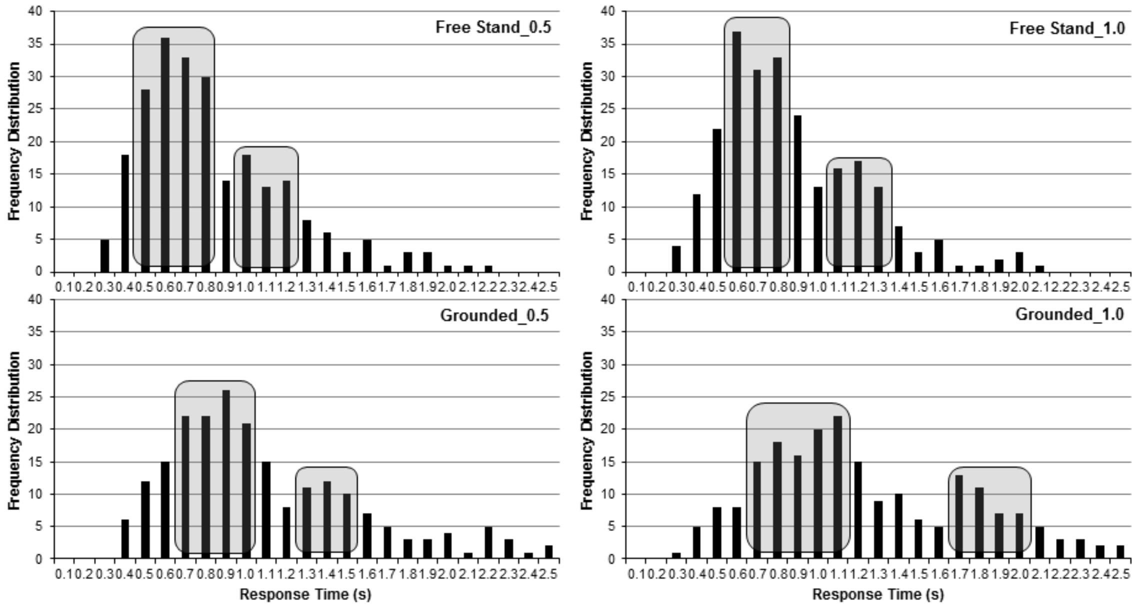


Figure 8.11 Frequency distributions of response times (RT_{SUB}) for correct inputs during the unsupported standing postures, highlighting the bimodal distribution (0.5 = low magnitude condition, 1.0 = high magnitude condition)

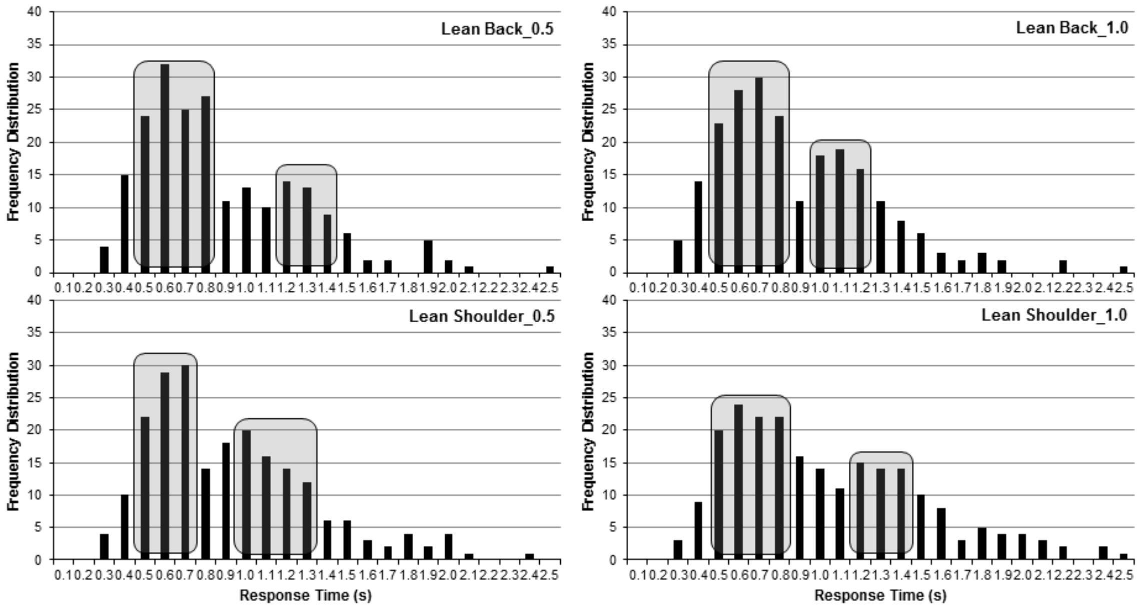


Figure 8.12 Frequency distributions of response times (RT_{SUB}) for correct inputs during the leaning supported standing postures highlighting the bimodal distribution (0.5 = low magnitude condition, 1.0 = high magnitude condition)

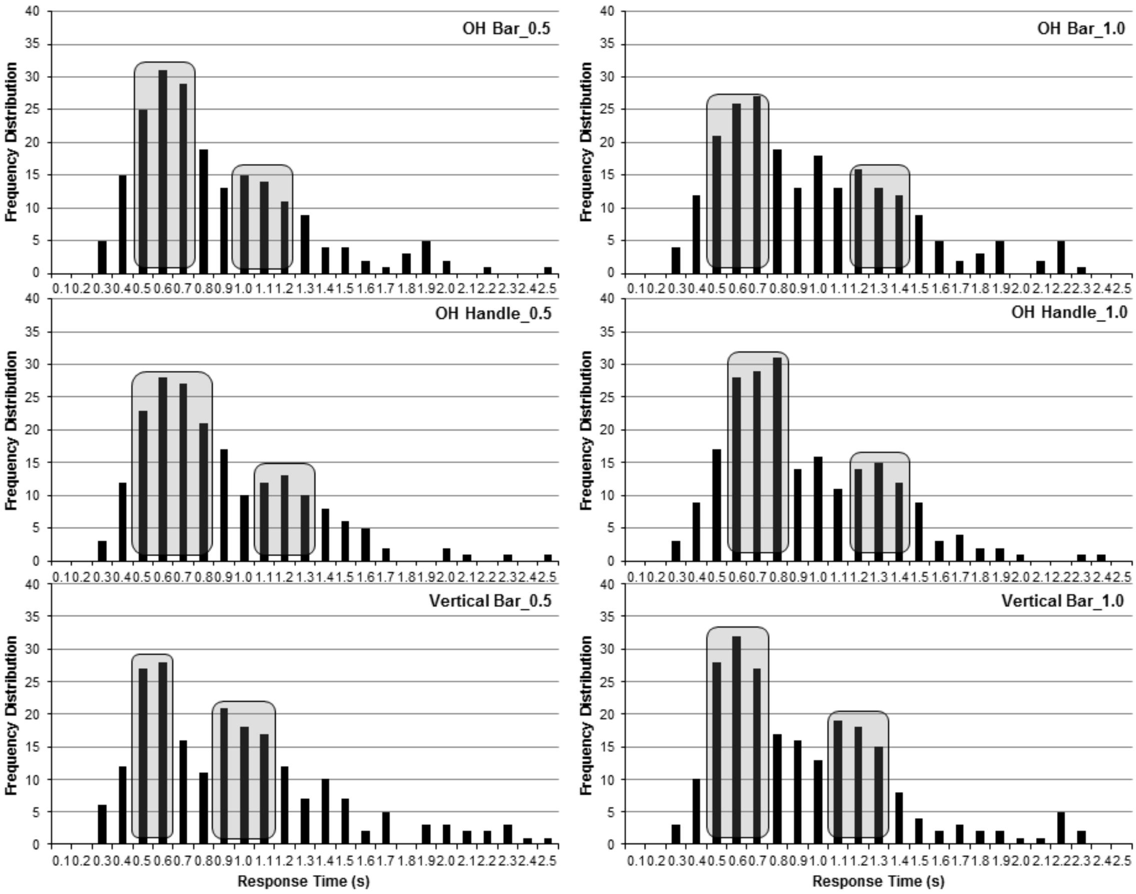


Figure 8.13 Frequency distributions of response times (RT_{SUB}) for correct inputs during the hand-supported standing postures highlighting the bimodal distribution (0.5 = low magnitude condition, 1.0 = high magnitude condition)

In each postural condition the frequency distributions for RT_{SUB} a bimodal distribution was found to occur (all frequency distributions met the requirements for normality). The response times demonstrated two locations where the frequency distribution increased, firstly between 0.4 – 0.8s and secondly, between 1.0 – 1.4s. Differences were found in the 'Free – Grounded' posture where RT_{SUB} increased between 0.5 – 0.9s and 1.2 – 1.9s. These results are comparable to those provided in Section 6.5.1 Performance Strategy (Attention Shift), Chapter 6. Based on the theory of an attention shift, reported by Holleis *et al.* (2007), it could be suggested that the first peak represented keypad inputs during the RT_{SUB} that were made with little scanning of the display and therefore provide a more accurate measure of manual control performance. The occurrence of a second peak would therefore correspond to the response times when participants scanned the display to confirm the 'target' numbers and the input on the keypad. The variations in response time and performance strategy could provide further insight into the effects of vibration exposure relating to the mechanisms responsible for activity interference. The use of eye tracking could be useful to quantify the extent to which participants split attention between the different locations.

8.5.2 Influence of Vibration and Postural Supports

In the context of transportation, people rarely stand freely (as in the case of the 'Free – Hand Held' and 'Free – Grounded' postures) due to the vibration experienced while travelling. Often standing passengers chose to utilise supports, such as leaning on walls or holding grab rails, to assist in maintaining stability during vibration exposure or to relieve muscles that fatigue when standing unsupported.

Considering the response time results in the study presented in this chapter (Figure 8.7), it is clear that the use of postural supports contributed to a general reduction in performance during vibration exposure, compared to the zero vibration condition. Increasing the magnitude of vibration exposure up to 1.039ms^{-2} r.s.s. resulted in a significant reduction in performance for all types of supports, with the exception of the 'Overhead Handle' that showed no influence on $RT_{INITIAL}$ or RT_{SUB} performance. Furthermore, response times during the 'Lean Back' and 'Lean Shoulder' postures were significantly ($p < 0.05$) higher than those in the 'Free – Hand Held' posture. It would seem the use of postural supports served to exacerbate the effects of vibration on performance, particularly in postures where the transmission of vibration to the controlling limb/hand would be greatest. A possible explanation could be that the benefits of improved stability by the use of a support were negated by the detrimental effects of vibration transmission through the support frame, resulting in degraded task performance.

An understanding of the dynamic interactions between the human body and supporting structures is essential in order to minimise the undesirable effects of vibration exposure (such as activity interference). Apparent mass and transmissibility frequency response functions have previously been used to represent the general dynamic response of the body at the driving-point (Matsumoto and Griffin, 2000) and remote locations (Mansfield, 2005 and Paddan, 1994; Paddan, 1995 and Paddan and Griffin, 1995), respectively. In seated postures, reduced reading performance during fore-and-aft vibration exposure has been attributed to the presence of a backrest which could affect the transmission of vibration to the head and arms (Lewis and Griffin, 1978 and Griffin and Hayward, 1994). Findings from Paddan and Griffin (1988) suggested that backrests in seated postures may affect the transmission of vibration through the body in three ways, namely: i) the addition of a vibration driving-point nearer the upper body, ii) altering the dynamic properties of the body and iii) changing the forces acting within the body.

In the study described in this chapter, the ‘Lean Back’ and ‘Lean Shoulder’ postures provided the nearest additional contact point for vibration transmission to the controlling limb/hand and possibly the most substantial postural change (compared to an upright, free standing posture) which could influence the dynamics of the body. The combination of these factors could account for the significant reduction in performance found in the leaning postures, compared to the ‘Free – Hand Held’ (control) posture. Considering the hand-supported postures, the ‘Overhead Bar’ and ‘Vertical Bar’ both consisted of a rigid bar that the participants held onto, whereas the ‘Overhead Handle’ was non-rigid. With little variation in body posture, it would be likely that transmission through the rigid bar supports would be greater (though not to the same extent as the leaning supports) than the non-rigid handle. Consequently, the rigid supports contributed to a significant reduction in performance compared to the zero vibration (hand-held) condition while there was no significant effect on performance when using the handle.

These results are supported by the biomechanical responses presented in Section 7.4, Chapter 7. Considering the influence of postural supports on apparent mass and transmissibility, the ‘Lean Back’ and ‘Lean Shoulder’ postures showed the greatest influence on the biomechanical responses of the body, followed by the ‘Overhead Bar’ and ‘Vertical Bar’ postures. The ‘Overhead Handle’ posture showed no significant influence on the biomechanical responses of the body, compared to the ‘Free Standing’ posture.

Performance accuracy (Figure 8.8) was largely unaffected by vibration exposure and the different types of postural supports. During high magnitude vibration the ‘Lean Shoulder’ posture demonstrated significantly reduced levels of accuracy compared to the control (zero vibration) condition. There was no significant influence of posture found between all supported postures and the ‘Free – Hand Held’ posture. Participants were therefore able to maintain accuracy despite vibration exposure, possibly at the expense of increased response time. The main contributing factors to the loss of accuracy in the ‘Lean Shoulder’ posture would be due to the proximity of the controlling limb/hand to the vibration source on the support and postural instability at the higher magnitude, particularly as the feet were positioned together in this posture (Table 8.4).

Numerous studies have shown a progressive increase in subjective workload with increasing magnitudes of vibration exposure (Newell and Mansfield, 2008 and Lin *et al.*, 2007). The results presented in Figures 8.9 and 8.10 illustrate similar vibration effects on workload demands experienced by participants during task performance. For each posture there was a significant increase in the overall workload during vibration exposure as compared to the 'Free – Hand Held' control condition. By assessing the individual subscales (Figure 8.9) of the NASA-TLX data, the specific factors that contribute to workload were identified. The results suggest the physical demands of working in a moving environment provided the greatest influence on the workload experienced by the participants.

Generally, these effects were observed at both the low and high magnitude conditions, with the exception of the 'Overhead Bar' and 'Vertical Bar' postures during low magnitude vibration. For the 'Lean Back' and 'Lean Shoulder' postures, overall workload demands were significantly higher than the 'Free – Hand Held' posture; with no significant postural influence on the workload experienced in the remaining hand-supported postures. Additionally, as the vibration magnitude increased, there was a greater increase in workload when using the rigid hand supports ('Overhead Bar' and 'Vertical Bar') than the handle support. Such variations could relate to the capacity of different supports to provide stability. Robert *et al.* (2007) assessed the head movements of standing passengers using various support strategies. Findings from this research showed that body supports (leaning backwards) provided greater initial stability than hand supports (vertical bar); however, during high magnitude motions the hand supports offered an improved capability to restore balance. In the current study, it could be suggested that at low magnitude vibration exposure, the body supports provided the greatest initial stability, followed by the rigid hand supports and finally the loose handle support giving the least amount of stability. As the vibration magnitude increases however, the ability to recover from a loss of balance would be reduced in the body-supported postures and transmission of vibration to the upper body and controlling limb/hand would be greater when using the body supports or rigid hand support; potentially resulting in higher workload demands in order to maintain performance. The loose handle in the 'Overhead Handle' support would therefore serve to attenuate the transmission of vibration as well as provide the necessary support to restore balance, consequently the degradation to performance could potentially be less than when using other support strategies.

Response times presented in Figure 8.7 support this notion as there were significant vibration effects in all tested standing postures (high magnitude condition), but no significant influence on response time or performance accuracy in the ‘Overhead Handle’ posture, compared to the ‘Free – Hand Held’ control posture.

8.5.3 Postural Instability

Using the same method as in Chapter 5, the researcher noted any loss of stability during each vibration condition that required the participants to make a postural adjustment (for example, any additional grasping onto the frame secured to the platform). In situations where postural adjustments were necessary to maintain stability, participants were required to return to the original posture as soon as possible.

Table 8.4 Postural instability of participants performing a serial manual control task during exposure to vibration ***** (represented by number of postural adjustments)

Vibration Axis	**Posture/Support Strategy**	**Total No. of Adjustments**
XYZ-axis	Free – Hand Held	10
	Free – Grounded	12
	Lean Back	5
	Lean Shoulder **	11
	Overhead Bar	3
	Overhead Handle	5
	Vertical Bar	6

Where: ***** = $1.039ms^{-2}$ r.s.s. multi-axis xyz-axis vibration
****** = reduced base of support due to postural orientation (feet positioned together, no separation)

Losses of balance occurred only in the high magnitude conditions (Table 8.4). The ‘Free – Hand Held’, ‘Free – Grounded’ and ‘Lean Shoulder’ postures were associated with the highest frequency of instability cases (8, 11 and 9 adjustments respectively). Generally, there were relatively few adjustments required in the hand-supported postures, possibly due to the improved ability to recover from a potential loss of balance as described by Robert *et al*., (2007).

Nawayseh and Griffin (2006) identified that loss of balance during horizontal vibration exposure was influenced by the base-of-support (BOS) in the direction of movement. In the current study, participants were exposed to random vibration stimuli in three simultaneous directions (x-, y- and z-axis) and the stance orientation was designed so that the BOS would be equal in the x- and y-axis directions; meaning that any benefits to stability would be as a result of the support strategy provided by the frame.

8.6 CONCLUSIONS

The aim of the study presented in this chapter was to investigate the influence of vibration exposure on manual control performance of a serial task and subjective workload, in a variety of standing postures.

H1: Serial manual control performance would decrease and subjective workload ratings would increase with increasing vibration magnitudes (based on the results obtained for manual control performance in Chapters 5 and 6).

Compared to the control (zero vibration) condition, response times significantly increased (indicating a lower performance level) with increasing vibration magnitudes. During the high magnitude conditions, response times significantly increased in all standing postures tested, with the exception of the 'Overhead Handle' posture. In all standing postures, subjective ratings of workload progressively increased with associated increases in vibration magnitude. Furthermore, the physical component of the overall workload ratings was found to be a main contributing factor.

H2: Serial manual control performance and subjective workload ratings would differ between the types of support strategies used by individuals. Supports which were found to influence the biomechanical response of the body (Chapter 7) were expected to show the greatest influence on task performance and workload.

The use of postural supports during vibration exposure showed little influence on performance accuracy, however significant effects were found for response times and workload (similar patterns of response were observed for both). The body-supported postures ('Lean Back' and 'Lean Shoulder'), particularly to the side ('Lean Shoulder') resulted in the greatest degradation to task performance as well as the highest workload demands. Performance and workload measures in hand-supported postures ('Overhead Bar', 'Overhead Handle' and 'Vertical Bar') were influenced by vibration to a lesser extent than in the body-supported postures. Previous studies (Lewis and Griffin, 1978) have shown reduced performance to be associated with the presence of a backrest that increased the transmission of vibration to the upper body. Based on the biomechanical responses of the body presented in Chapter 7, the effects of vibration on serial task performance and workload appear to relate to the biomechanical responses of the body in the same standing postures.

H3: Serial manual control performance and subjective workload ratings would be greater in the grounded condition compared to the hand-held conditions, due to differences in mechanical coupling between the hand and the control device.

Serial manual control performance, as measured by response times ($RT_{INITIAL}$ and RT_{SUB}) and accuracy, was substantially degraded in situations where there was direct mechanical coupling ('grounding') between the operating device and the vibrating structure (such as in the 'Free – Grounded' posture). When the device was hand-held however, the body served to attenuate the transmission of vibration to the device and controlling limb/hand, which consequently lead to less performance degradation and lower ratings of workload.

Additionally, there could be evidence of a trade-off between the need for stability and the transmission of vibration through the support. In order to improve performance in a moving environment while standing a balance needs to be found between these factors. Based on these findings, the use of an 'Overhead Handle' support for standing passengers would be recommended to minimise the influence of vibration on activity interference for mobile devices. This support showed no significant degradation to response times and performance accuracy compared to the 'Free – Hand Held' control posture, yet it still provided the necessary postural support required to maintain stability while exposed to whole-body vibration.

CHAPTER 9

GENERAL DISCUSSION

The overall aim of the thesis was to understand the influence of whole-body vibration (WBV) exposure and standing posture on manual control performance and the associated subjective workload experienced by individuals in these conditions. The results may be used to improve the representation of the response of the human body in standing exposures within current vibration standards (such as, ISO2631-1 (1997)). Previous studies have reported responses of free-standing individuals (for example, Subashi *et al.,* 2008), however, none have considered the influence of postural supports. Furthermore, the consequences of vibration exposure (such as, activity interference) have not been investigated in standing postures with the use of stability supports. The approach taken within this thesis was to assess these factors separately, through a series of laboratory studies and then provide an overall description of the human-environment system, describing the relationship between the human response to vibration and activity interference.

9.1 OVERALL SYSTEM CHARACTERISTICS

In order to understand the effect of vibration exposure on activity interference and the subjective workload experienced by standing rail passengers, the individual aspects of the human-environment interaction must be considered as a complete system (Figure 9.1). The separate components of this system have been divided into three categories and investigated in a series of field and laboratory experiments (Chapters 4 – 8). The first of these categories refers to the environmental context in which the individual is exposed to vibration. This could include, for example, the frequency, magnitude and direction of vibration, the posture adopted by the individual and the type of support strategies used to maintain stability. The second category considers to the biomechanical response of the human body exposed to such vibration, specifically the apparent mass and floor-to-hand transmissibility. The final category uses information obtained from the first two classifications to evaluate the consequences of vibration acting at the point of manual control (for example, degraded task performance and increased subjective workload).

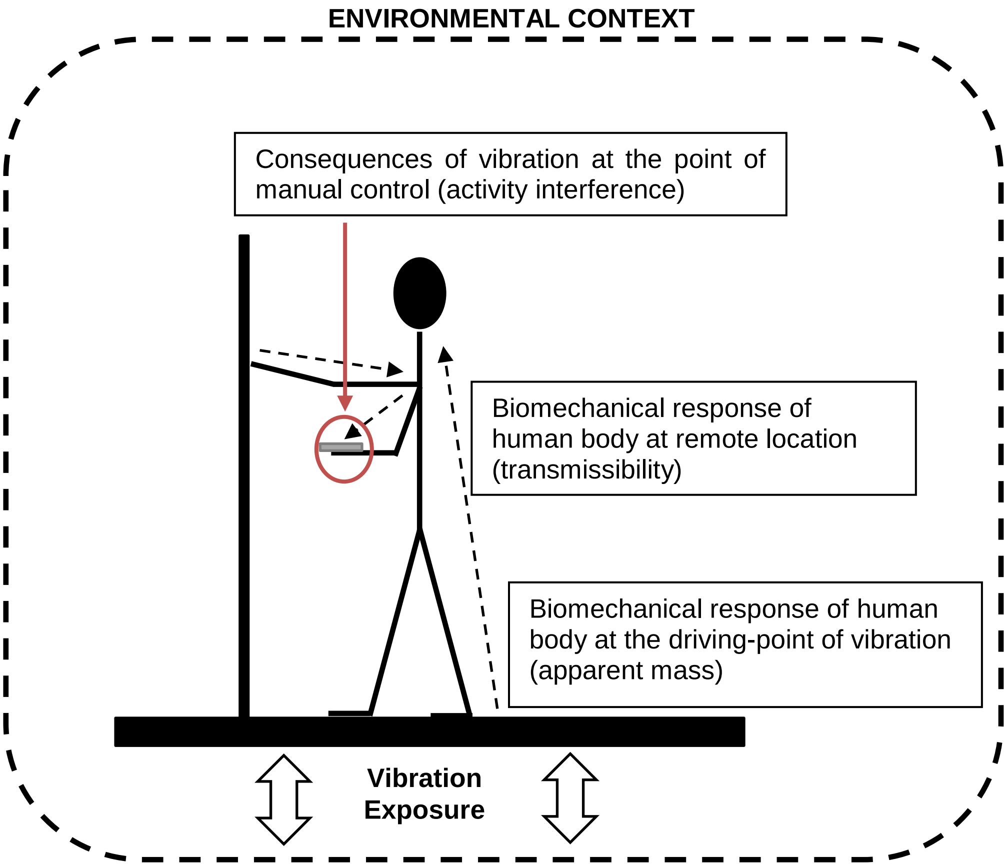


Figure 9.1 Diagrammatic representation of the overall system leading to vibration-induced activity interference in standing individuals (dashed lines represent transmission of vibration from driving-point to site of manual control)

9.1.1 Whole-Body Vibration Exposure on Trains

When considering WBV exposure the most applicable frequency range occurs between 1 – 20Hz, within which a resonance frequency exits where the effects on the human body will be maximised dependent upon the stimulus it receives (Mansfield, 2005). Previous studies have investigated the driving-point frequency response of the human body in the horizontal (x- and y-axis) and vertical (z-axis) directions, for seated and standing individuals. In normal seated postures (without a backrest), Fairley and Griffin (1990) reported two peaks in apparent mass during exposure to vibration in the x- and y-axis. The first peak showed a resonance frequency at about 0.7Hz for both fore-and-aft and lateral apparent mass, while the second resonance frequency was found around 2.5Hz and 2Hz (fore-and-aft and lateral directions respectively). In a standing posture, fore-and-aft apparent mass increased greatly as the frequency reduced from 1Hz – 0.125Hz (although no clear peak was observed). Matsumoto and Griffin (2011) proposed that the resonance frequency for fore-and-aft apparent mass could therefore occur at a frequency below 0.125Hz in standing individuals. During lateral vibration, Matsumoto and Griffin

(2011) reported a resonance frequency in apparent mass at about 0.5Hz. Considering vertical apparent mass, similar resonance frequencies have been reported for seated and standing postures (Matsumoto and Griffin, 1998). In both postures, the resonance frequency for vertical apparent mass was found within the region of 4 – 6 Hz, generally at about 5Hz (Coermann, 1962, Fairley and Griffin, 1989 and Matsumoto and Griffin, 1998). By bending at the knees, Coermann (1962) reported a decrease in resonance frequency to about 2Hz (Matsumoto and Griffin (1998) found similar results with a resonance frequency at 2.75 in a legs bent posture).

During a field study (Chapter 4) vibration measurements were recorded on the floor surface of underground trains. The PSD curves (Figure 4.5, Section 4.4.4 Vibration Measurement) showed peaks at about 0.5Hz (x-axis), 1.25Hz (y-axis) and about 2.25Hz (z-axis). In conditions where the frequency of vibration to which individuals are exposed corresponds to the most sensitive (resonance) frequencies of the human body, the influence of vibration would be maximized. These results correspond to the biomechanical responses reported by Fairley and Griffin (1990) for x- and y-axis vibration. This would be a particular concern for individuals exposed to horizontal motions as these would potentially compromise standing stability and would likely result in greater decrements to manual performance subjective workloads than at other frequencies. In the vertical direction however, the resonance frequency of the body tends to occur at a higher frequency (5Hz), compared to the peak frequency for the PSD z-axis curve (2.25Hz). This is not to say that performance would not be affected in this direction but rather that the effects could potentially be exacerbated if the frequency of vibration exposure had occurred at the resonance frequency of the human body.

Within a given vibration spectrum, motion-induced activity interference has been shown to progressively increase as the magnitude of vibration increases (above a certain threshold of effect). This relationship has been demonstrated by many researchers for x-, y- and z-axis vibrations (Lewis and Griffin, 1978). Some studies have shown only moderate performance decrements with increasing vibration magnitudes (for example, Newell and Mansfield, 2008), demonstrating the human ability to adapt to additional stressors to maintain a certain level of performance.

By calculating the relative manual control performance during vibration exposure as a percentage of the performance obtained during the control conditions (no vibration), different types of manual control tasks can be compared (Figures 9.2 and 9.3). The relative performance results for discrete and continuous manual control tasks (Chapter 5) are shown in Figure 9.2, while the relative performance results for a serial manual control task (Chapter 8) are expressed in Figure 9.3. Additionally, the range of r.m.s. and peak vibration magnitudes obtained during the field measurements (Chapter 4) have been included to demonstrate the exposures found on rail transportation, in relation to the vibration magnitudes used during laboratory investigations.

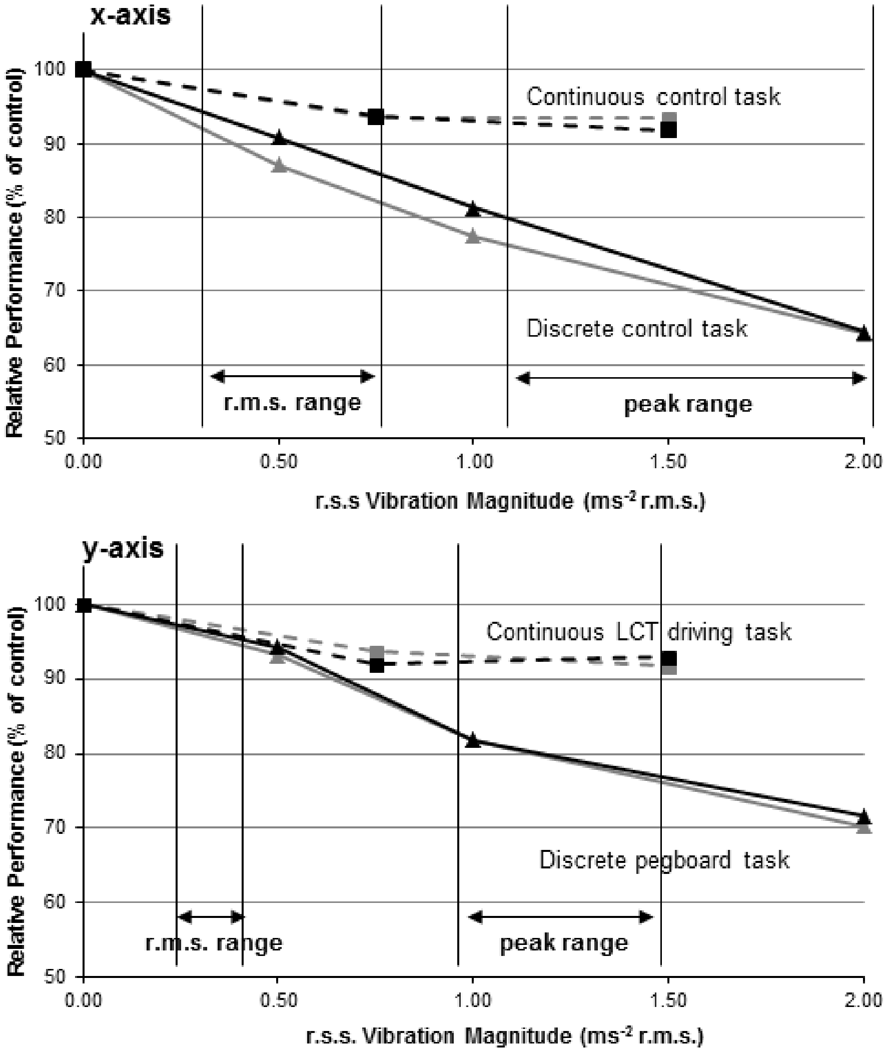


Figure 9.2 Relative performance measures as a percentage of static performance for discrete and continuous control tasks, during exposure to single-axis WBV in the x- and y-axis (black = lateral stance, grey = anterio-posterior stance)

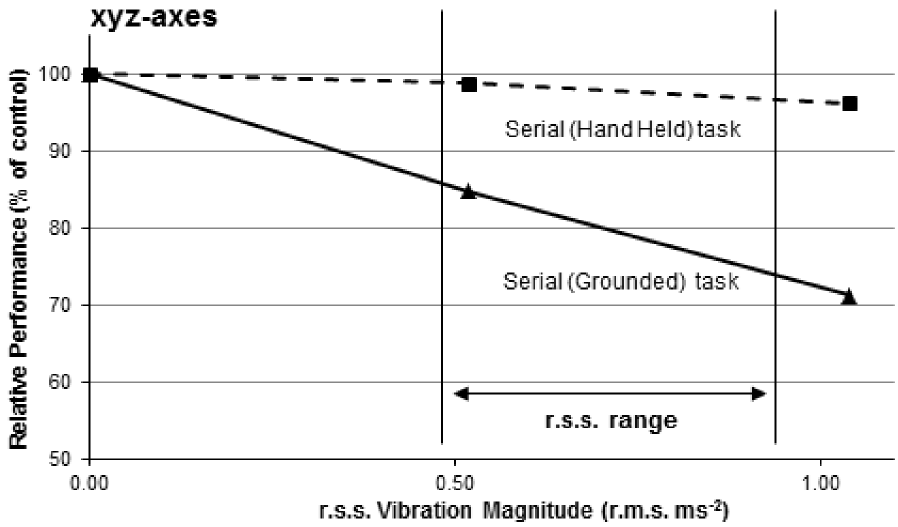


Figure 9.3 Relative performance measures as a percentage of static performance for a serial control task, during exposure to multi-axis WBV in the xyz-axes (black = lateral stance, grey = anterio-posterior stance)

Apart from the continuous control task where individuals were able to maintain a level of performance, decrements to performance were found to increase with increasing vibration magnitude (Figures 9.2 and 9.3). The discrete control task and the serial (grounded) control task showed the greatest degradation in performance, while the participants were able to adapt and maintain a consistent level of performance for the continuous control task and the serial (hand held) control task. These results indicate that although the vibration magnitudes to which individuals are exposed on public rail transportation were below the exposure action value (EAV) set by the HSE (UK), the ability for individuals to engage in activities requiring manual control, may still be compromised. A further consideration is the mechanical coupling between the individual and the device being operated. When performing the continuous and serial (hand held) manual control tasks, the hand and the device were coupled together which would reduce the relative displacement of the hand caused by vibration. In conditions without this coupling, such as discrete and serial (grounded) manual control task, the relative displacement between the hand and the device would increase, potentially resulting in greater performance degradation (Paddan and Griffin, 1993).

Lewis and Griffin (1978) reported that there was reasonable agreement that performance decrements were related to the transmission of vibration through the body. Reduced performance due to vertical (z-axis) vibration exposure has been positively correlated with transmission to the upper body and controlling limbs, with the greatest decrements (for continuous tracking tasks) occurring at frequencies between 4 – 5Hz (Buckhout, 1964) and 3 – 8Hz (McLeod and Griffin, 1989). During horizontal vibration (x- and y-axes) exposure, the greatest decrements to manual control performance occurred between 1 – 3Hz (Hornick, 1962 and Shoenberger, 1970). These studies have investigated seated postures and the influence of vibration on manual control performance, however similar frequency dependent effects were found in standing postures (Chapter 6). The study provided a comparison between the effects of vibration exposure on performance of a serial manual control hand held task in seated and standing postures. The results indicated that during horizontal motions (x- and y-axes), performance and subjective workloads were predominantly influenced at frequencies below 4Hz, whereas in the z-axis (vertical motion) these effects were found to occur up to 8Hz (Table 6.3, Chapter 6). It should be noted that the seated and standing postures were unsupported and therefore vibration was transmitted through the body from the floor. In reality, individuals often use walls and grab rails for support, potentially increasing the vibration transmission through the body.

There have been no published studies that have considered the influence of support strategies on the biomechanical response to vibration of standing individuals; nor have any studies investigated the effect of such supports on manual control performance in standing postures. Previous studies that focused on seated postures have shown a relationship between the biomechanical response of the human and activity interference, as evidenced by the resonance frequencies of the human body and the corresponding frequency dependence of performance degradation. By understanding the conditions and environments which influence the biomechanical responses in standing individuals, it could be possible to predict where performance decrements will likely occur.

9.1.2 Relationship between Apparent Mass and Transmissibility

By normalising the measured apparent mass to the static masses of the individual participants, the apparent mass and the transmissibility responses (Chapter 7) can be compared. Apparent mass is more frequently used as a method for characterising the ‘to-the-body’ biomechanical responses to WBV of the human body as it permits greater convenience for measurement and shows considerably less variability, compared to transmissibility data (Wang *et al*., 2008). Figures 9.4, 9.5 and 9.6 show the normalised apparent mass and floor-to-hand transmissibilities during x-, y- and z-axis vibration respectively.

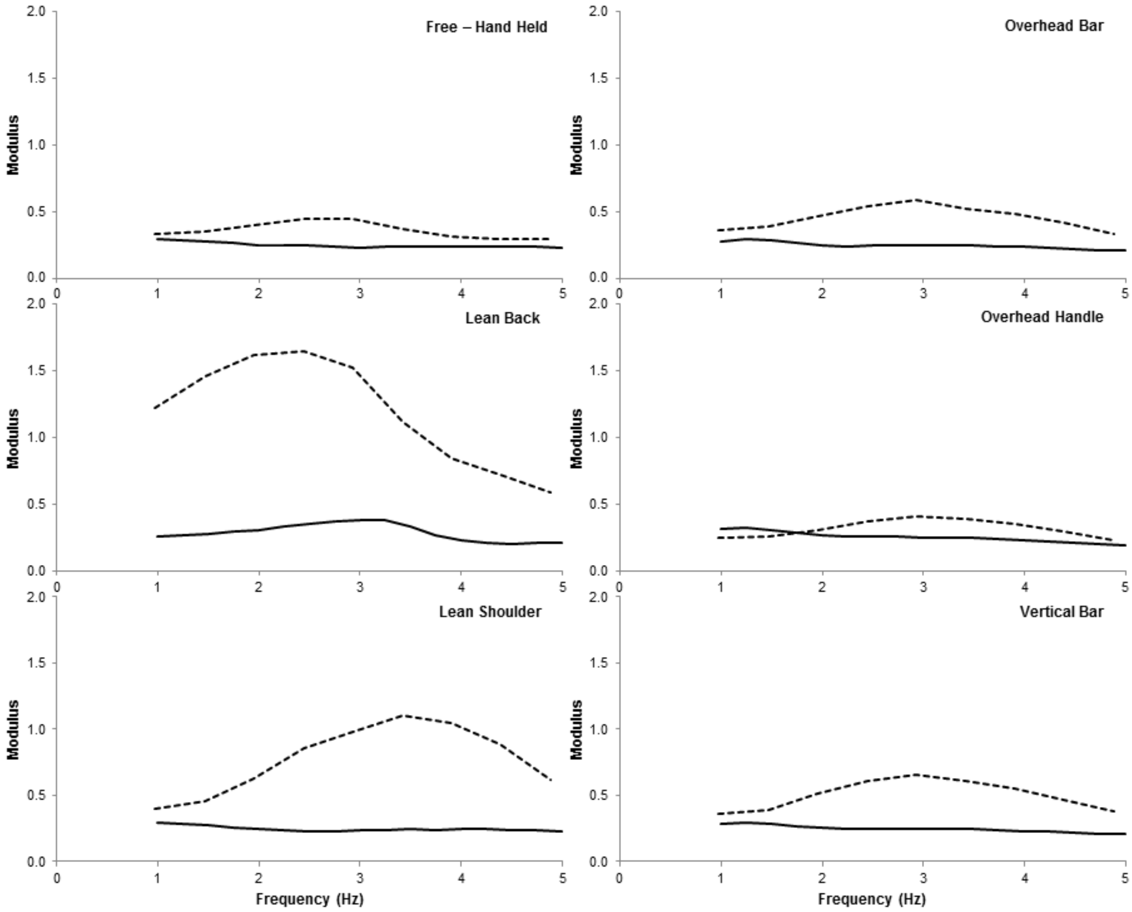


Figure 9.4 Comparison of normalised apparent mass and floor-to-hand transmissibility for 12 standing participants during x-axis vibration (solid lines = normalised apparent mass, dashed lines = floor-to-hand transmissibility)

In the horizontal (x- and y-axis) directions, variations were found in the resonance frequencies for apparent mass and transmissibility between the different postural conditions. During vertical (z-axis) vibration, the apparent mass and transmissibility responses exhibited similar resonance frequencies, regardless of the posture adopted. The normalised apparent mass responses indicated a biomechanical response in the body-supported postures (the ‘Lean Back’ (x-axis) and the ‘Lean Shoulder’ (y-axis)) however, no influence on apparent mass was observed in the hand-supported postures during horizontal motions (Figures 9.4 and 9.5). The floor-to-hand transmissibility responses showed a clear biomechanical influence in the ‘Lean Back’ and ‘Lean Shoulder’ conditions between 1 – 3Hz. Transmissibility responses in the ‘Overhead Bar’ and ‘Vertical Bar’ postures showed resonance frequencies, at about 3Hz (x-axis) and 2Hz (y-axis).

For both apparent mass and transmissibility responses, no distinct biomechanical influence was found in the ‘Free – Hand Held’ and ‘Overhead Handle’ postures during fore-and-aft and lateral vibration. Vertical normalised apparent mass and floor-to-hand transmissibility showed comparable responses (in terms of resonance frequency) however, the biomechanical responses were emphasised in the transmissibility responses compared to the normalised apparent mass (Figure 9.6). These results suggest that the overall biomechanical response of the body cannot be fully explained or understood by a single biomechanical measurement of either apparent mass or transmissibility, but should instead be represented by both biomechanical components.

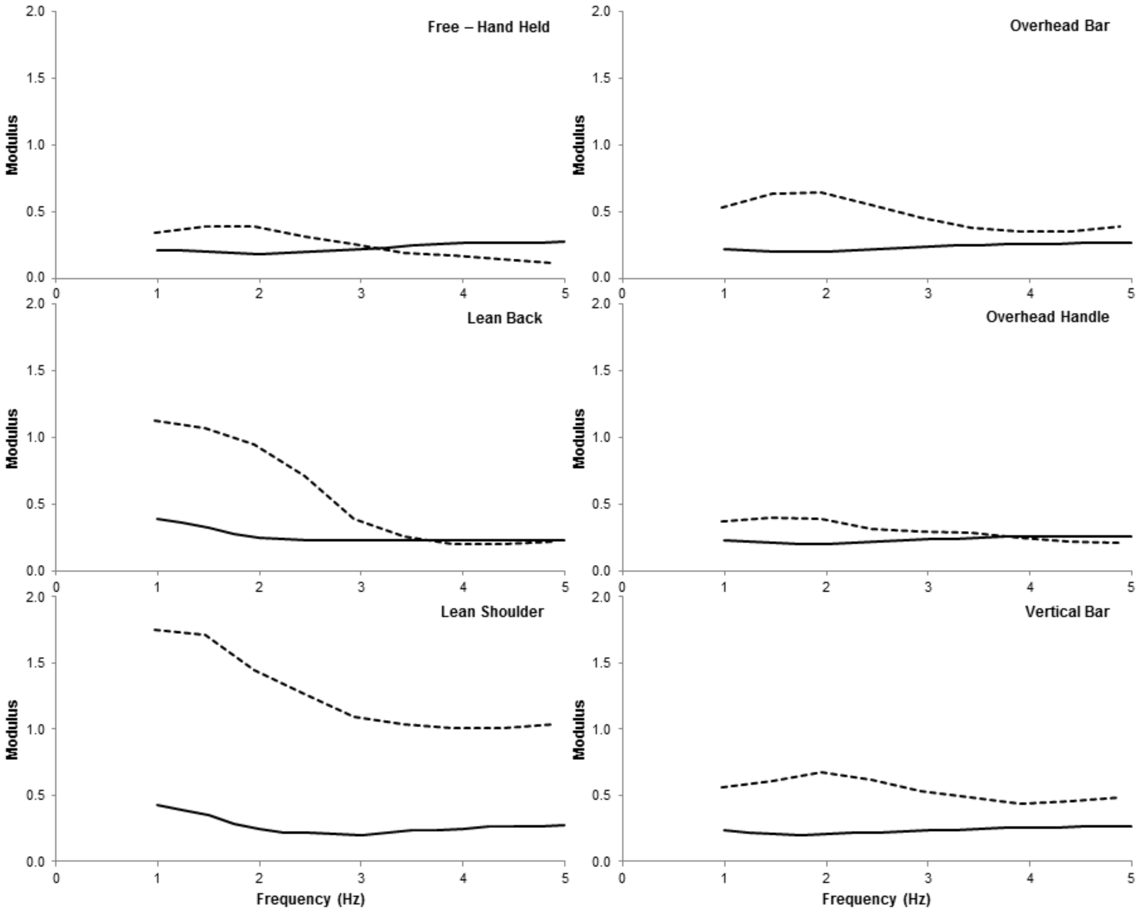


Figure 9.5 Comparison of normalised apparent mass and floor-to-hand transmissibility for 12 standing participants during y-axis vibration (solid lines = normalised apparent mass, dashed lines = floor-to-hand transmissibility)

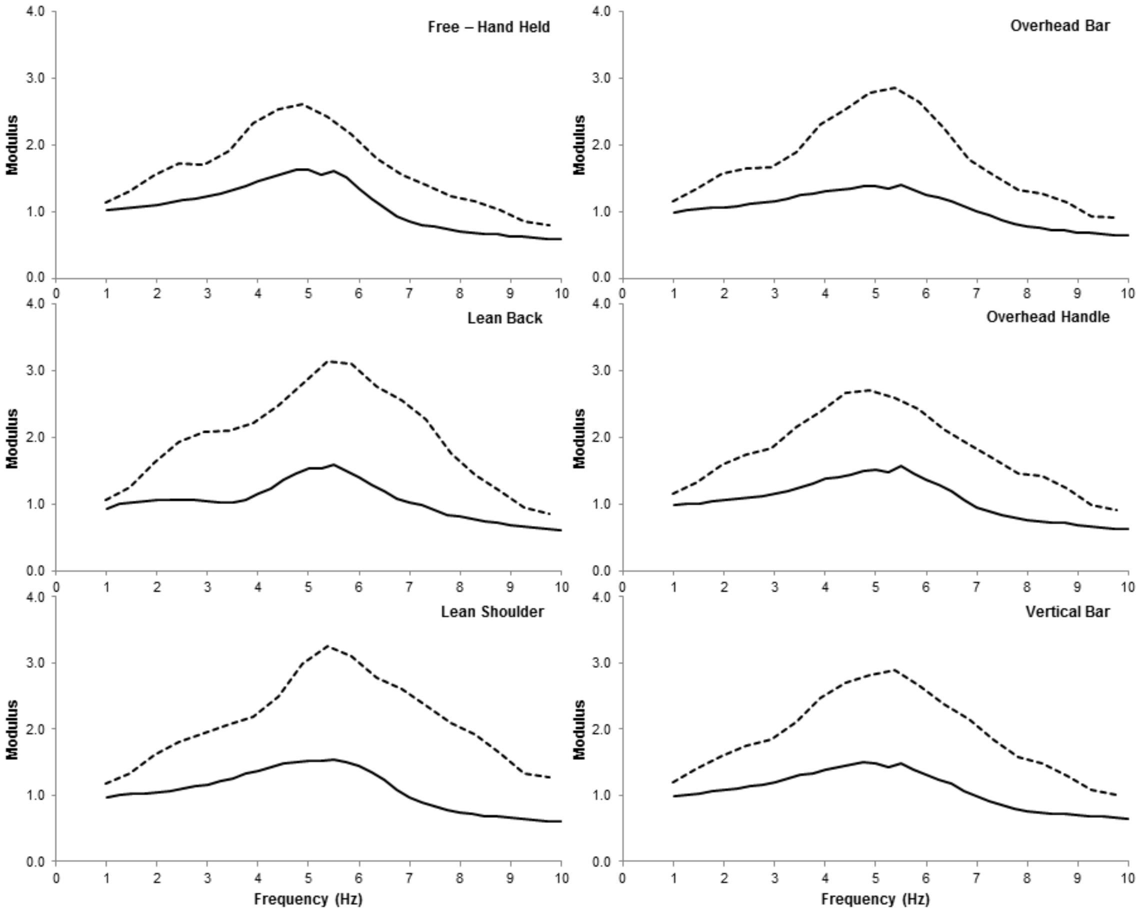


Figure 9.6 Comparison of normalised apparent mass and floor-to-hand transmissibility for 12 standing participants during z-axis vibration (solid lines = normalised apparent mass, dashed lines = floor-to-hand transmissibility)

9.1.3 Prediction of Vibration-Induced Activity Interference

Using measurements of the biomechanical response to vibration in various standing postures (Chapter 7), it could be possible to relate the biomechanical responses of body to manual control performance. The objective was not to develop a complex biomechanical model to represent the individual postures with masses, springs and dampers, but rather to evaluate the use of biomechanical responses as a method for identifying specific conditions where performance would likely be degraded.

Activity interference due to vibration exposure has previous been attributed to the transmission of vibration to the upper body and limbs (Lewis and Griffin, 1978). The floor-to-hand transmissibilities obtained during x-, y- and z-axis vibration (Chapter 7) are presented in Table 9.1, with the corresponding peak ratios for transmissibility to the hand. These ratios were calculated by comparing the transmissibility at the resonance frequency to that at 1Hz. The magnitude of the peak ratio therefore provides an indication of the vibration transmitted to the hand at the resonance frequency. Using this information, the likelihood of activity interference could be inferred.

Table 9.1 Peak ratios of the median transmissibilities and activity interference for a serial control task in the x-, y- and z-axis for standing individuals

Transmissibility						
X-Axis						
Posture	**Free Standing**	**Lean**		**Overhead Bar**	**Overhead Handle**	**Vertical Bar**
		Back	**Shoulder**			
1Hz	0.31	**1.22**	0.40	0.35	0.24	0.37
Resonance	0.46	1.64	1.1	0.62	0.38	0.66
Ratio	1.48	1.35	2.75	1.77	1.58	1.78
Y-Axis						
1Hz	0.35	**1.12**	**1.74**	0.53	0.37	0.56
Resonance	0.39	____	____	0.64	0.39	0.67
Ratio	1.11	____	____	1.21	1.05	1.20
Z-Axis						
1Hz	1.14	1.09	1.16	1.15	1.17	1.18
Resonance	2.61	3.13	3.25	2.86	2.71	2.92
Ratio	2.29	2.87	2.80	2.49	2.32	2.47
Activity Interference (mean RT_{SUB} for manual control serial task)						
Control	0.85	0.85	0.85	0.85	0.85	0.85
High Mag. *	0.88	0.99	1.10	0.93	0.87	0.94
Performance Degradation (%)	3.53	16.47	29.41	9.41	2.35	10.59

Where: * = 1.039ms^{-2} r.s.s. vibration magnitude

[green] = **minimal** influence (not significant) of supports on transmissibility and performance (compared to Free Standing posture)

[orange] = **moderate** influence (significant) of supports on transmissibility and performance

[red] = **substantial influence (significant) of** supports on transmissibility and performance

Ratios for all the supported standing postures were compared to the unsupported ('Free Standing') condition and for purposes of clarity, these have been colour coded to indicate the degree to which transmissibility was affected in each posture. The green colour coding indicates a minimal influence on transmissibility, the orange code shows a moderate effect and the red coding highlights conditions with the greatest influence on transmissibility (Table 9.1). The numbers represented in bold at 1Hz are considerably higher than the transmissibility responses for the other postures and consequently the ratios associated with these conditions were reduced (despite showing the greatest transmissibility at resonance). Additionally, in the y-axis, the 'Lean Back' and 'Lean Shoulder' postures showed no clear resonance frequency (peak transmissibility could lie below 1Hz and therefore outside the frequency range tested). No peak ratios are included for these conditions.

Performance decrements for a serial control task are included in Table 9.1, based on the response time taken to complete four numerical inputs (RT_{SUB}) using a hand held keypad (Chapter 8). The percentage degradation follows the same colour coding scheme used for the transmissibility responses and clearly demonstrates a similar trend in relation to the different standing postures. The postures responsible for the greatest degradation in performance are also associated with the greatest transmissibility of vibration to the hand.

Additional factors to consider are the base-of-support (BOS) and the associated influence on postural stability. In the body-supported postures, the 'Lean Back' and 'Lean Shoulder' postures demonstrated similar levels of vibration transmitted to the hand, yet the 'Lean Shoulder' posture showed a significantly greater influence on task performance. The smaller BOS in the 'Lean Shoulder' posture compared to the 'Lean Back' posture lead to greater instability (Chapter 8, Table 8.4) which could contribute to the greater activity interference demonstrated in the 'Lean Shoulder' condition.

9.1.3.1 Human Adaptability to Vibration Exposure

The ability for humans to adapt to additional stressors and maintain performance has been widely acknowledged (Hancock and Warm, 1989 and Hockey, 1997). Through the series of experimental investigations presented in Chapters 5 – 8, the influence of vibration exposure on objective measurements of performance have yielded varying results. When performing a discrete manual control task, individuals were unable to maintain performance even at relatively low magnitudes of vibration (Chapter 5). Individuals performing a serial control task showed variable adaption capabilities dependent on postural conditions (Chapter 8) and vibration frequency (Chapter 6). No performance degradation was found when performing a continuous control task, individuals were therefore able to adapt and maintain performance even with increasing vibration magnitudes (Chapter 5). A consistent trend throughout all these investigations however, was the subjective workload experienced by the individuals when performing these tasks. In all conditions, an increase in vibration magnitude corresponded to increased ratings of workload.

Figure 9.7 illustrates the relationship between objective performance and subjective workload, using the principles outlined in the 'extended-U' hypothesis (Hancock and Warm, 1989) and the compensatory control model by Hockey (1997).

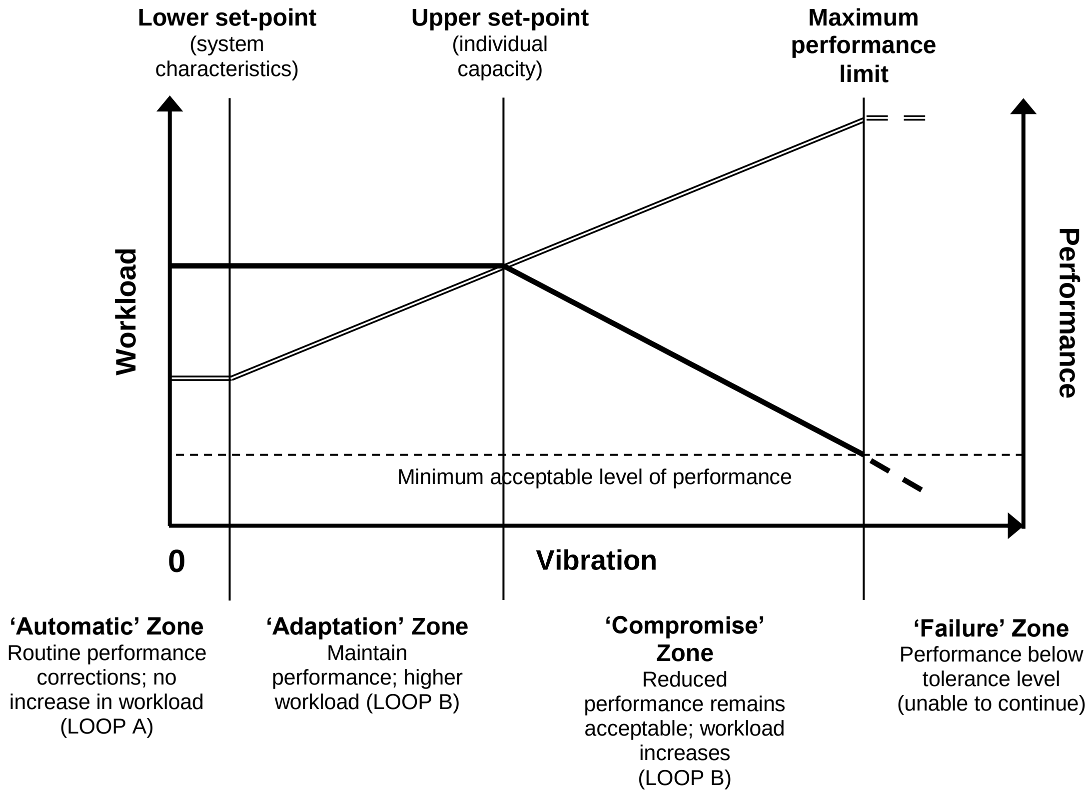


Figure 9.7 Performance-Workload Model illustrating the relationship between objective task performance and subjective workload during exposure to vibration (bold line = performance; double line = workload)

In the performance-workload model shown in Figure 9.7, the four 'zones' of performance and workload have been developed based on the loops described in the compensatory control model (Hockey, 1997). The 'automatic' zone represents 'loop A' where there is no additional increase in workload and performance remains constant. Performance levels within this zone are limited by the lower set-point based on the characteristics of the system (for example, the physical ability of the individual to perform routine corrections and the capabilities of the device to accommodate for minor adjustments). As the vibration (stress) increases there is an 'adaptation' zone in which performance is unaffected however, there is a corresponding increase in the workload experienced by the individuals ('loop B'). The capacity of the individual to adapt determines the upper set-point and limitation on this 'adaptation' zone.

A continued increase in vibration would result in performance degradation and a further rise in workload ('compromise' zone). In this situation the individual could re-evaluate the performance criteria and objectives – by lowering the acceptable level of performance, the overall tasks may continue to be completed although there will likely be an increase in other performance factors such as accuracy. For example, an individual would still be able to type an email on a mobile device however there would potentially be an increase in the number of misspelt words. The final zone is the 'failure' zone, where performance continues to degrade below a minimum acceptable level and tasks can no longer be completed.

None of the tasks investigated in Chapters 5, 6 and 8 were performed within the automatic zone (subjective workload increased in all test conditions). By adapting to the increased vibration when performing the continuous manual control task (Chapter 5), individuals performed within the adaptation zone. For the discrete control task, performance progressively degraded with increases in vibration (Chapter 5) and therefore individuals were operating in the compromise zone (in some cases, potentially into the failure zone). The serial control task showed variable effects of vibration on performance, depending on the frequency of the vibration and the postures adopted by individuals (Chapters 6 and 8). In the body-supported postures ('Lean Back' and 'Lean Shoulder') performance was located in the compromise zone, while vibration exposure in the 'Overhead Handle' posture showed little influence on performance and would therefore be within the adaptation zone. The remaining 'Overhead Bar' and 'Vertical Bar' conditions possibly demonstrate a cross-over point, moving from the adaption zone into the compromise zone.

Overall it could be suggested that the use of biomechanical responses (transmissibility) of the human body to vibration exposure provides useful information for identifying conditions within a moving environment that could lead to activity interference.

9.2 LIMITATIONS AND FUTURE WORK

A number of limitations associated with the studies presented in this thesis have arisen and following these, future work issues have been identified that should be considered in order to develop a greater understanding of the human response to whole-body vibration.

9.2.1 Context

This thesis investigated only one environmental context, that being underground rail transport; yet there are many other environments in which people are exposed to vibration and experience activity interference in standing postures. The selection of rail transportation was based on the ease of access to participants and gaining approval from regulating authorities for the field investigation. Within the time frame of this research, it would not have been feasible to consider multiple modes of transport. Nevertheless, by expanding the research to include other types of environments (such as, air and sea transport) in future studies, the 'real world' applicability of the findings could be enhanced. Furthermore, other environments would contain different vibration characteristics (for example, rotational axes) in which activity interference could be assessed.

9.2.2 Methods

9.2.2.1 Sampling Approach

During the laboratory studies, the participants primarily consisted of students or research staff. The inclusion criteria for participation in the studies were delimited to create a fairly homogenous group in order to minimise the influence of additional, extraneous factors (for example, age). The sample sizes were consistent with previous research studies and were mainly restricted due to time constraints. A greater number of participants would however, increase the statistical power of the studies and improve the validity of the findings to be generalised to larger populations. Future work could also investigate factors such as age, visual acuity and manual dexterity across different population groups.

9.2.2.2 Quantitative vs. Qualitative Techniques

This thesis relied predominantly on quantitative, rather than qualitative approaches (such as, in-depth interviews and focus groups) for data collection. The key difference between quantitative and qualitative methods refers to the degree of flexibility of each approach. Generally, quantitative methods are fairly inflexible, with strictly defined parameters. This was a particularly important consideration in this thesis, given the high number of variables that needed to be controlled (for example, vibration characteristics). Quantitative methods seek to confirm hypotheses about phenomena and predict causal relationships, whereas qualitative methods seek to explore phenomena and describe relationships (Mack *et al.*, 2005). The advantage of this inflexibility is that it allows for meaningful comparison of responses across participants and between different studies.

Qualitative methods however, are typically more flexible and allow greater spontaneity and adaptation of the interaction between the researcher and the study participant. For example, qualitative methods ask mostly 'open-ended' questions that enable participants to respond in their own words, rather than forcing participants to choose from fixed responses, as would be the case with quantitative methods.

Although these approaches involve distinct research techniques, the objectives of quantitative and qualitative research are not mutually exclusive. When used alongside quantitative methods, qualitative research can help to interpret and better understand the implications of quantitative data. It is therefore recommended that future research considers the potential added value that could be gained from qualitative data (for example, understanding why people adopt certain standing behaviours during vibration exposure).

9.2.2.3 Manual Control Performance Assessment

The manual control tasks presented in this research were relatively simple to perform in order that participants could be trained quickly. The Lafayette Purdue Pegboard used to assess discrete manual control (Tiffin, 1948) and the Lane Change Task (LCT) simulator software used to evaluate continuous manual control performance (Chapter 5) have been used in previous studies to identify the influence of vibration on manual control performance (Harbluk *et al.,* 2007). Previous studies have tended to use 'real-world' devices to assess serial manual control however; this could introduce the risk of personal preference creating a biased response depending on the type of device investigated. Consequently, a generic keypad and mounting was developed for the investigating serial manual control performance (Chapters 6 and 8).

In order to compare the use of a generic device to 'real-world' devices from previous studies reported in the literature, the numerical input response times ($RT_{INITIAL}$ and

RT_{SUB}) were converted into words per minute (Equations 9.1 and 9.2). This comparison is presented in Figure 9.8.

Soukoreff and MacKenzie (1995) developed a theoretical model to predict the upper and lower boundaries of text-entry rates using a stylus and hand held soft keyboard. Traditionally, sets containing five characters have been used to represent one word, from which the words per minute (wpm) can be calculated in order to compare text-entry speeds of different devices. The upper boundary (fastest entry speed) represented the movement time between key presses (Fitts, 1954), while the Hick-Hyman Law was used to include a visual scan time as well as movement time for the lower boundary. The Hick-Hyman Law has been established in numerous choice reaction tasks (for example, pressing buttons in response to lights) and considers the overall response time to consist of a movement time and visual scan time (Hick, 1952 and Hyman, 1953).

In Chapters 6 and 8, the serial numerical input task performed by participants consisted of a five number sequence. The time taken to input the first number ($RT_{INITIAL}$) comprised of three components: i) movement time, ii) visual scan time and ii) cognitive processing time. The time to enter the remaining four subsequent numbers (RT_{SUB}) demonstrated a pattern of response with two peak response times: the first consisted of movement time ($RT_{SUB\ –\ MOVEMENT}$ between 0.4 – 0.7s), whereas the second included a visual scan time as well as ($RT_{SUB\ –\ MOVEMENT\ AND\ VISUAL\ SCAN}$ between 0.9 – 1.1s).

$$Lower\ Boundary\ (wpm) = \frac{60}{\mathrm{RT_{INITIAL}} + 4 \times \mathrm{RT_{SUB\ (MOVEMENT\ AND\ VISUAL\ SCAN)}}} \quad \text{Equation 9.1}$$

$$Upper\ Boundary\ (wpm) = \frac{60}{5 \times \mathrm{RT_{SUB\ (MOVEMENT)}}} \quad \text{Equation 9.2}$$

The results showed the lower boundary range produced keypad entry speeds between 10 – 12wpm, and the upper boundary range between 20 – 35wpm (Figure 9.8). These response speeds were found to be reasonably consistent with the text entry speeds reported in previous studies based on the use of ‘real’ devices. The use of the generic keypad to evaluate serial manual control of a hand-held device is therefore representative of the performance expectations of individuals using mobile devices a ‘real-world’ context.

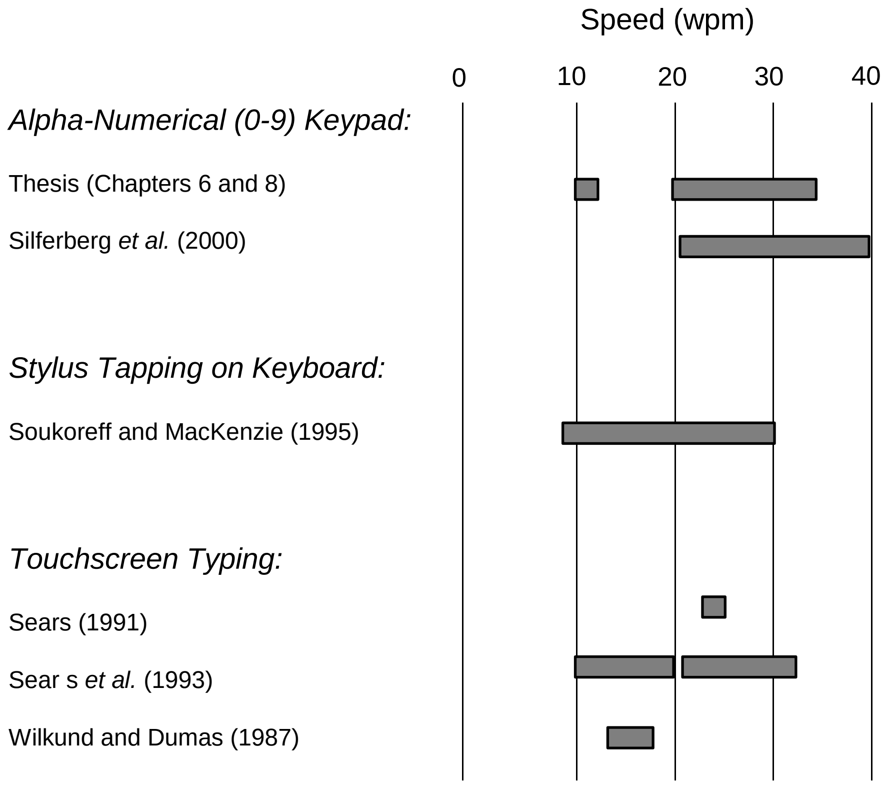


Figure 9.8 Performance comparisons for a generic alpha-numeric keypad and several other text-entry methods.

By allowing individuals use current technologies and devices that would typically be found in a 'real-world' context (as opposed to generic models), the external validity of the results could be improved. This could include further evaluation of the attention shift between the display and the keypad (demonstrated in Chapters 6 and 8) to identify the influence of vibration of specific components of manual control.

9.2.2.4 Workload Assessment

During the study conducted at JNIOSH (Kawasaki, Japan), only the semantic rating scale was used to evaluate subjective workload. This was due to difficulties in explaining the instructions for using the magnitude estimation technique to participants in a foreign language. The semantic rating scale was simpler to translate and explain and ensured reliable results could be obtained. For the final study (Chapter 8), the NASA Task Load Index (TLX) was used instead of the semantic scale and magnitude estimation methods. Although this limited the ability to compare subjective responses between the different studies, the NASA TLX method provided a more comprehensive understanding of the influences on workload (for example, the individual mental and physical components of workload).

These methods of determining the subjective workload ratings have been used extensively in previous studies (for example, Corbridge and Griffin, 1991 and Newell and Mansfield, 2008), however the techniques all relied on the perceptions of workload, given by the individual. Difficulties may occur when an individual provides a subjective rating based on what is thought to be an expected outcome rather than a true expression of the workload experienced. Additional methods to assess workload of the participant should be considered (for example, performance of a secondary task or physiological measures).

9.2.3 Human Response to Vibration

9.2.3.1 Biomechanical Response

Due to noise within the system, the biomechanical responses of apparent mass transmissibility could only be reported for single-axis vibration exposures. These types of motions are not commonly found in 'real-world' environments and future work should investigate the response of the standing human body to multi-axis (simultaneous x-, -y- and z-axes) exposures. Investigating combinations of these axes and with different types of postural supports could help future studies gain a better understanding of the mechanisms responsible for the biomechanical response of the body to vibration.

9.2.3.2 Stability

Standing stability was found to be compromised in certain conditions, generally associated with high vibration magnitudes. Understanding the level of stability provided by different supports, could provide additional insight into the selection of specific postural supports. This should be conducted using objective balance assessments as well as subjective perceptions of stability in different conditions.

9.2.3.3 Cultural Differences

Certain cultural differences may have influenced the study presented in Chapter 6, which was conducted at JNIOSH (Kawasaki, Japan). Using a keypad device to assess serial control performance, the Japanese participants tended to prioritise response time over accuracy. In comparison, using the same device, the UK participants (Chapter 8) focused on accuracy at the expense of response time. Future studies could investigate the influence of vibration exposure between different populations on additional factors, such as, discomfort. This information could then be used to develop vibration standards that better represent specific populations.

CHAPTER 10

GENERAL CONCLUSIONS

The research presented in this thesis was designed to enhance the knowledge of two key topic areas relating to the human response to whole-body vibration (WBV) that have not previously been investigated. These areas included: i) the vibration-induced activity interference in manual control tasks experienced by standing individuals, and ii) the influence of postural supports on the biomechanical response of the standing human body to vibration.

The following points outline the main conclusions of the thesis and summarise the key findings:

Classify the behaviour of standing rail passengers, relating to the types of devices operated, the support strategies used and postures adopted during travel time.

The use of mobile devices by standing rail passengers followed recent market trends and future forecasts. Devices offering high levels of functionality (such as, 'smart-phones') were most commonly used, with a 'touch-screen' interface.

The standing postures identified by the Rail Safety and Standards Board, UK (RSSB, 2009) were confirmed by the observations presented in Chapter 4. Additionally, an interaction effect was found in the use of upper body supports (such as, hand rails) and lower body orientations (foot placement) in order to maintain stability. In a bi-pedal stance there was greater lower body stability and consequently passengers tended to use hand supports. Alternatively, when passengers adopted a uni-pedal (single weight-bearing) stance the lower body stability would be comprised and therefore, body supports were generally used as these offered greater stability to the individual by increasing the contact area between the body and the support. This could have implications for the interior design of train carriages and the positioning of supports for train passengers. For example, in areas where the floor space is restricted (such as, passageways) passengers would likely have a reduced base-of-support at the feet. Appropriate upper body (hand) supports should be provided in these situations to compensate for any potential loss in lower body stability.

Quantify the vibration exposures typically experienced by passengers in public rail transportation systems.

The vibration magnitudes found on the underground trains were similar those reported in the literature for a variety of rail transport systems. Although magnitudes did not exceed the exposure action value (EAV) set by HSE in the UK, activity interference would be expected to occur at these magnitudes. Based on the magnitudes obtained in the x-, y- and z-axes, horizontal motions would be expected to produce the greatest effect on task performance. In addition, horizontal motions could influence the stability of standing passengers. By increasing the damping of horizontal vibrations, the design of train carriages could be improved and reduce the activity interference associated with the use of mobile devices by standing passengers.

Evaluate the influence of WBV vibration exposure on the objective performance of manual control tasks and the associated subjective workloads.

Manual control performance of a discrete control task showed progressive degradation with increasing vibration magnitudes, whereas continuous manual control performance showed no adverse effects to vibration exposure. Manual control performance of a serial task showed variable effects of vibration exposure. In an unsupported ('Free – Hand Held') posture, performance of a serial control task was unaffected by increasing vibration magnitudes however, in presence of postural supports, performance degradation was found to depend on the type of support used. This clearly demonstrates a need to improve the damping of postural supports found on trains.

Conditions in which the control device and the hand were in contact with each other (mechanical coupling) were found to reduce activity interference, compared to conditions in which the device and the hand were separated (as in the discrete control task). This could be attributed to the increased relative motion between the device and the hand which resulted in out-of-phase (disassociated) movements.

These results could have further implications in areas such as human-computer interaction or user interface design. Interactions with mobile devices that require a high degree of precision, (for example, pressing 'buttons' on a smartphone) would likely result in greater performance decrements than those where the method of interaction is more continuous. Such features could include the use pattern recognition or intelligent dictionaries (similar to predictive text) for text entry tasks that would reduce the number of discrete components associated with the task, consequently reducing activity interference. Additionally, as evidenced In the performance results presented in Chapters 6 and 8, task components that required greater cognitive processing ($RT_{INITIAL}$) were influenced by vibration exposure to a greater extent than those with less processing involvement (RT_{SUB}). These results could have implications for the design of more intuitive mobile technologies (for example, reduced number of sub-menu classifications).

Performance and workload responses were found to demonstrate frequency-dependent effects with the greatest levels of performance degradation (based on performance accuracy) associated with frequencies below 2Hz (x- and y-axes) and above 4Hz (z-axis). These results showed similar trends to the reported biomechanical responses of the standing human body and were closely matched to the frequency weighting curves proposed in ISO2631-1 (1997).

The subjective workload experienced by the participants in the vibration conditions increased progressively with increasing vibration magnitudes. The ability to adapt and compensate for vibration exposure in order to maintain manual control performance therefore occurred at the expense of workload.

It is recommended that postural supports should therefore provide sufficient damping of vibrations below 2Hz (x- and y-axes) and above 4Hz (z-axis) as these are the most sensitive frequencies for manual control performance in standing individuals and are associated with rail transport systems.

Quantify the biomechanical responses of the human body to WBV in a variety of standing postures.

The biomechanical responses (apparent mass and transmissibility) were found to be similar to those reported in previous studies (for example, Matsumoto and Griffin, 2000). It was evident from the combined apparent mass and transmissibility responses that the body-supported postures (‘Lean Back’ and ‘Lean Shoulder’) were responsible for the greatest influence in biomechanical responses, followed by the rigid hand-supports (‘Overhead Bar’ and ‘Vertical Bar’). The biomechanical responses obtained in the ‘Overhead Handle’ posture were generally consistent with those found in the ‘Free – Hand Held’ posture. In order to reduce the detrimental effects associated with the response of the human body to vibration, it is recommended that the damping of rigid supports for standing rail passengers be increased. Such changes may include the provision of additional cushioning for leaning (body) supports or the substitution of rigid overhead bars (hand supports) for more flexible handles.

Evaluate the use of biomechanical responses to WBV as a predictive measure for activity interference in manual control tasks and judgments of subjective workload.

The conditions in which manual control performance was degraded were found to correspond to the conditions which demonstrated the greatest influence on the biomechanical responses of the body. The body-supported postures ('Lean Back' and 'Lean Shoulder') particularly the 'Lean Shoulder' posture resulted in the greatest degradation to task performance. Performance in rigid hand-supported postures ('Overhead Bar' and 'Vertical Bar') was influenced by vibration to a lesser extent than in the body-supported postures, with performance in the 'Overhead Handle' posture the least affected.

Measurements of biomechanical responses of the human body to vibration in different postures could therefore be used as a basis for predicting the likelihood of activity interference. Additionally, the results from Chapter 5, demonstrate that performance and workload responses during multi-axis vibration exposure could be reasonably predicted using the r.s.s. summation method to combine the responses obtained during single-axis vibration exposures.

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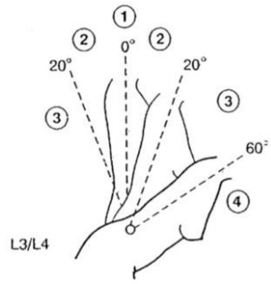
APPENDIX A1

REBA (Rapid Entire Body Assessment) body part diagrams used to develop the observation sheet in Chapter 4 (Hignett and McAtamney, 2000)

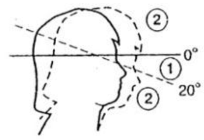
Trunk

Movement	Score	Change score:
Upright	1	+1 if twisting or side flexed
0°–20° flexion 0°–20° extension	2	
20°–60° flexion >20° extension	3	
>60° flexion	4	



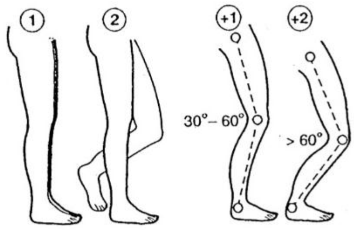
Neck

Movement	Score	Change score:
0°–20° flexion	1	+1 if twisting or side flexed
>20° flexion or in extension	2	



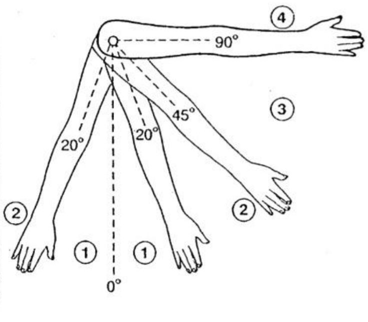
Legs

Position	Score	Change score:
Bilateral weight bearing, walking or sitting	1	+1 if knee(s) between 30° and 60° flexion
Unilateral weight bearing Feather weight bearing or an unstable posture	2	+2 if knee(s) are >60° flexion (n.b. Not for sitting)



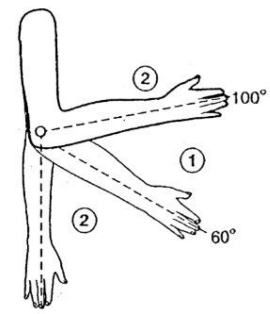
Upper arms

Position	Score	Change score:
20° extension to 20° flexion	1	+1 if arm is: • abducted • rotated
>20° extension 20°–45° flexion	2	+1 if shoulder is raised
45°–90° flexion	3	–1 if leaning, supporting weight of arm or if posture is gravity assisted
>90° flexion	4	



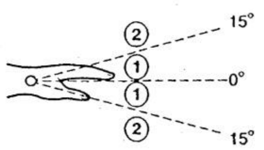
Lower arms

Movement	Score
60°–100° flexion	1
<60° flexion or >100° flexion	2



Wrists

Movement	Score	Change score:
0°–15° flexion/ extension	1	+1 if wrist is deviated or twisted
>15° flexion/ extension	2	



APPENDIX A2

Observation sheet used during field study (Chapter 4)

INFORMATION

Date & Time	
Location	
Mode of Transport	
Position (doorway, centre)	
Capacity (%)	
Sex and Approx. Age	
Extra	

Upper Body

Trunk		Arms	
		For Support (left/right)	
Upright		< Shoulder Hgt	
Bent (Flexion)		Shoulder Hgt	
Twisted		> Shoulder Hgt	
Bent and Twisted			
		Active on Task	
		Single Hand	
		Both Hands	

Lower Body

Legs		Foot Position	
Bi-lateral Weight Bearing		Fore-Aft (gap between feet)	
Uni-lateral Weight Bearing			
		Lateral	
Weight Bearing Leg		Split Stance (like F-A but no gap)	
Knees Locked			
Kness Unlocked (≤ 30°)		Other (define)	
Knees Bent (> 30°)			

SUPPORT STRATEGIES

Type		Available	Used
Overhead Spring (dangling) Support			
Overhead Hand Rail			
Vertical Hand Rail			
Padded Back/Buttock Support			
Leaning on Wall	Single Shoulder		
	Both Shoulders		
	Back		
None			
Other (define)			

TASK

Type		Interface	
Reading (book, paper)			
Writing		Interface	
Music Player		Keypad	
Non-Verbal Mobile Phone		Touchscreen	
Model (iPhone, B.Berry)		Stylus Pen	
		Other (define)	
Other (define)			

Time on Task	

NOTES

* loss of stability	
* task interference	
* postural changes	
* observational time	

APPENDIX A3

Participant health screen form listing contra-indications for participation

PARTICIPANT HEALTH SCREEN

Name:_______________________________

Date_____/_____/_____

It is important that volunteers participating in research studies are currently in good health and have had no significant medical problems in the past. This is to ensure (i) their own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes. Please complete this brief questionnaire to confirm fitness to participate:

*** Indicate either 'yes' or 'no'**

1. **At present**, do you have any health problem for which you are:

a) on medication, prescribed or otherwise……………………………….	Yes	No
b) attending your general practitioner…………………………………….	Yes	No
c) on a hospital waiting list…………………………………………………	Yes	No

2. **In the past two years**, have you had any illness which required you to:

a) consult your GP…………………………………………………………	Yes	No
b) attend a hospital outpatient department………………………………	Yes	No
c) be admitted to hospital………………………………………………….	Yes	No

3. **Have you ever** had any of the following:

a) convulsions/epilepsy…………………………………………………….	Yes	No
b) asthma or respiratory disease………………………………………….	Yes	No
c) diabetes…………………………………………………………………...	Yes	No
d) blood disorder……………………………………………………………	Yes	No
e) head injury………………………………………………………………..	Yes	No
f) digestive problems or disease of gastro-intestinal tract……………...	Yes	No
g) disease of genito-urinary system………………………………………	Yes	No
h) heart problems of disease of cardiovascular system……………….	Yes	No
i) problems with bones or joints…………………………………………..	Yes	No
j) disturbance of vision or retinal detachment…………………………..	Yes	No
k) disturbance of balance or coordination……………………………….	Yes	No
l) ear/hearing problems……………………………………………………	Yes	No
m) thyroid problems………………………………………………………..	Yes	No
n) kidney or liver problems………………………………………………..	Yes	No
o) back pain…………………………………………………………………	Yes	No

4. Do you use any prosthetic device?
(not including dentures, external hearing aids and spectacles)…………………….. Yes No

5. If **YES** to any questions, please describe briefly if you wish:……………………………………………..
……
....

6. **For female participants:** could you be pregnant?...

APPENDIX A4

Information to participants form (example taken from Chapter 8)

INFORMATION TO PARTICIPANTS

Influence of whole-body vibration and postural support on serial manual control performance

1. Background Information

Rapid development of technology coupled with the accelerating move towards the use of mobile equipment, such as laptops, personal digital assistants (PDAs) or smart-phones, has provided individuals with the ability to engage in meaningful activities in novel and previously unanticipated ways (Perry *et al*., 2001). Many people choose to work while travelling (e.g. rail transport systems) and the vibration to which passengers are exposed has been shown to affect the performance of such activities (Mansfield, 2005). Survey data collected by Khan and Sundström (2007) indicated that 60% of passengers experienced moderate difficulties in task performance while travelling. The majority of research has focused on seated postures; however there are situations where standing people are exposed to whole-body vibration (WBV) (e.g. during peak travel when there is limited seat availability).

2. Purpose:

The current study has been designed to compare different methods of support for standing individuals exposed to WBV. Performance measurements using a hand-held device and the associated subjective workload will be used to identify variations between each type of support.

3. Criteria:

Healthy male and female individuals between the ages of 18 and 45years. Participants should be regular users of a mobile phone or other hand-held device (eg. PDA or smartphone) and must have no illness or ailment that may harm the participant or hinder the results of the study.

4. Experimental Procedure

You will need to complete a general health screening questionnaire as well as an informed consent form to confirm that you give your consent to participate in the experiment and that you understand the given instructions.

4.1 Preparation

After anthropometric measurements of stature and mass have been collected, you will be fitted with a safety harness and asked to stand inside a metal frame, mounted to a vibration simulator platform. You will be asked to stand in a comfortable upright posture with your feet shoulder width apart and knees locked. When the area surrounding the simulator is clear of personnel, the simulator will be started and will rise approximately 15cm to its neutral position. You will then have an opportunity to familiarize yourself with the test equipment (hand-held keypad) and practice giving subjective ratings of workload. When you and the experimenter are confident that you understand the requirements of the experiment, testing shall begin.

4.2 Experiment

Following the familiarization trials, there will be two control conditions (no vibration stimuli) to provide a 'reference' level for performance and subjective ratings. Following this condition, a series of vibration stimuli (based on measurements taken from various modes of transport) will be presented during which different stability supports will be utilized in a range of standing postures. During each condition you will be asked to complete a simple numerical input task using a hand-held keypad (the task to be explained in detail during the testing session). Each test condition will last approximately 30 seconds and between each condition you will be asked to provide subjective ratings of workload. The use of these scales will be explained to you by the experimenter before the experiment commences.

4.3 Dismount

After the experiment the platform will lower approximately 15cm to its settled position. It is important that you do not step off the platform or release the safety harness until told that it is safe to do so by the experimenter – the system remains pressurized for some time after any sounds coming from the pump have stopped. The safety harness will then be released and you will be allowed to dismount.

4.4 Questions/Comments

When the experiment is over you can ask any further questions that you may have or make additional comments about your experience.

5. Withdrawal and Confidentiality

You are free to withdraw from the experiment at any time. Should you decide to withdraw, please inform the experimenter who will stop the equipment and you can follow the dismount procedure. You do not have to give any reason for withdrawal and you can request that data collected not be used for analysis.

If you do take part in the research all information collected will be kept strictly confidential. All references to participants in the report and any subsequent publications/presentations will be anonymous. The information will be kept in a secure location, remain the property of Loughborough University and be destroyed 5 years after publication.

If you have any questions, please do not hesitate to ask the researcher.

APPENDIX A5

Informed consent form (example taken from Chapter 8)

INFORMED CONSENT FORM

TITLE: **Influence of whole-body vibration and postural support on serial manual control performance**

INVESTIGATORS: **William Baker and Dr. Neil Mansfield**

SITE: **Environmental Ergonomics Research Centre**

Please tick the box

I confirm that I have read and understood the information sheet. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason and without my professional or legal rights being affected. ☐

I understand that the discussion will be confidential and I agree to maintain the confidentiality of the views of the other participants. ☐

I understand that the data (including audio-recordings) will not be available to me after the study? ☐

I agree to take part in the above study

Signature (Participant)……………………………………………………… Date…………..……

NAME (BLOCK CAPITALS)……………………………………………………………….

I have explained the study to the above participant and they have indicated their willingness to take part

Signature (Researcher)………………………………………………………. Date…………..……

NAME (BLOCK CAPITALS)……………………………………………………………….

APPENDIX A6

Frequency distributions of response times for a serial manual control task in seated and standing postures, showing bimodal distribution of response

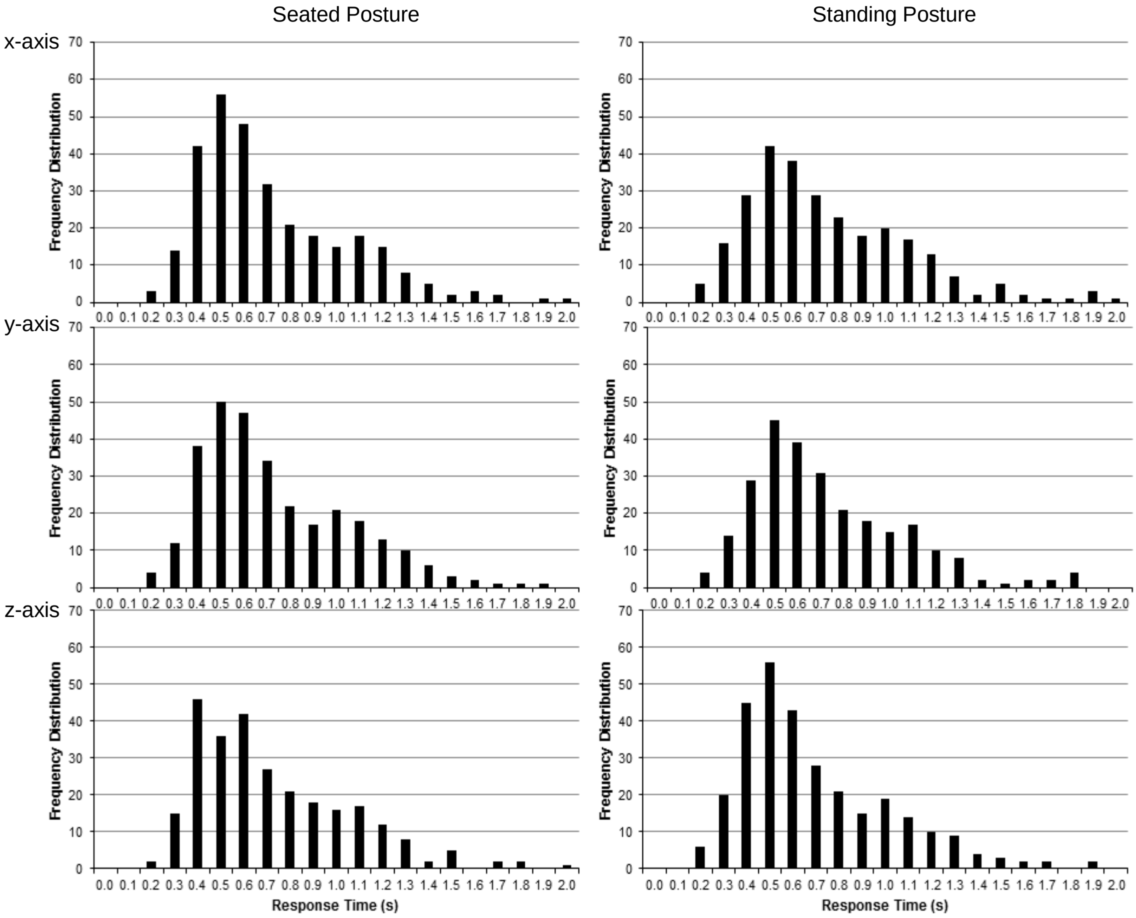


Figure A6.1 Frequency distributions of response times (RT_{SUB}) for correct inputs during vibration exposure at 1Hz for seated and standing individuals

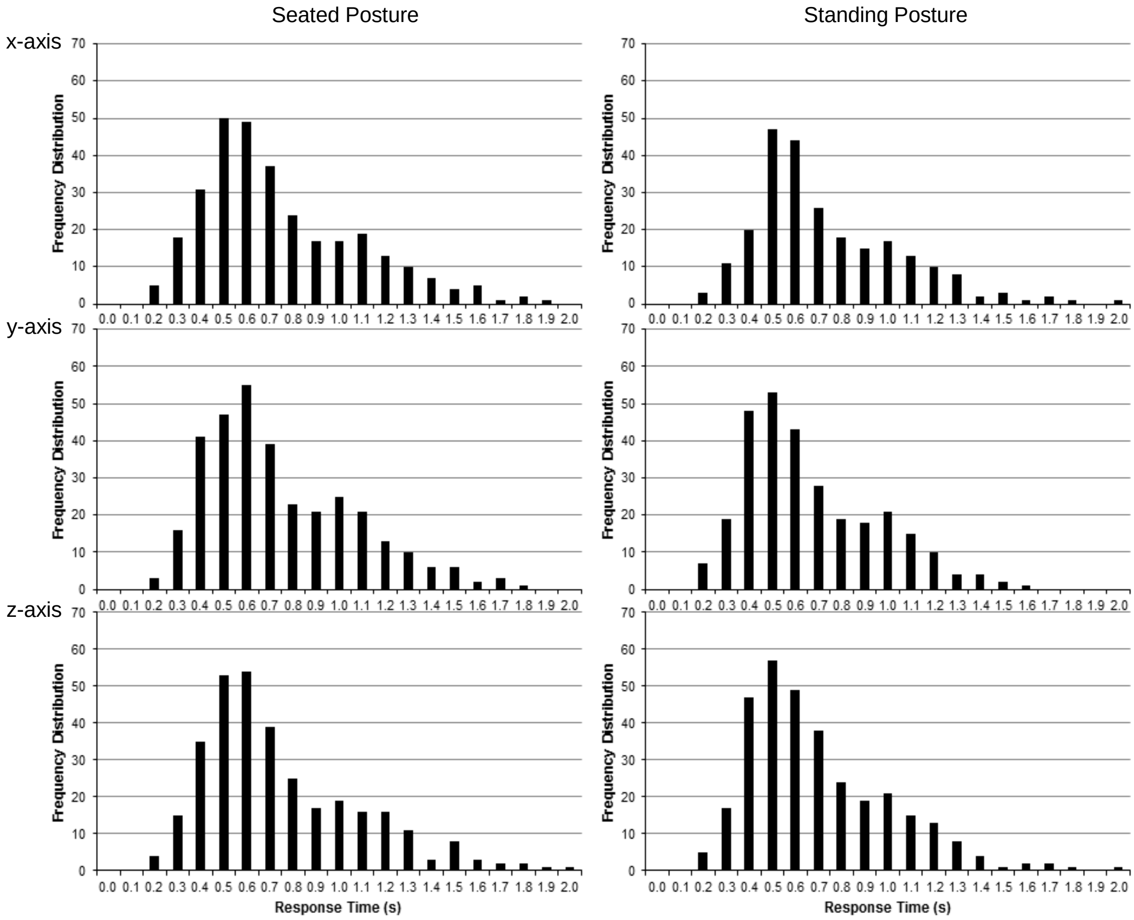


Figure A6.2 Frequency distributions of response times (RT_{SUB}) for correct inputs during vibration exposure at 2Hz for seated and standing individuals

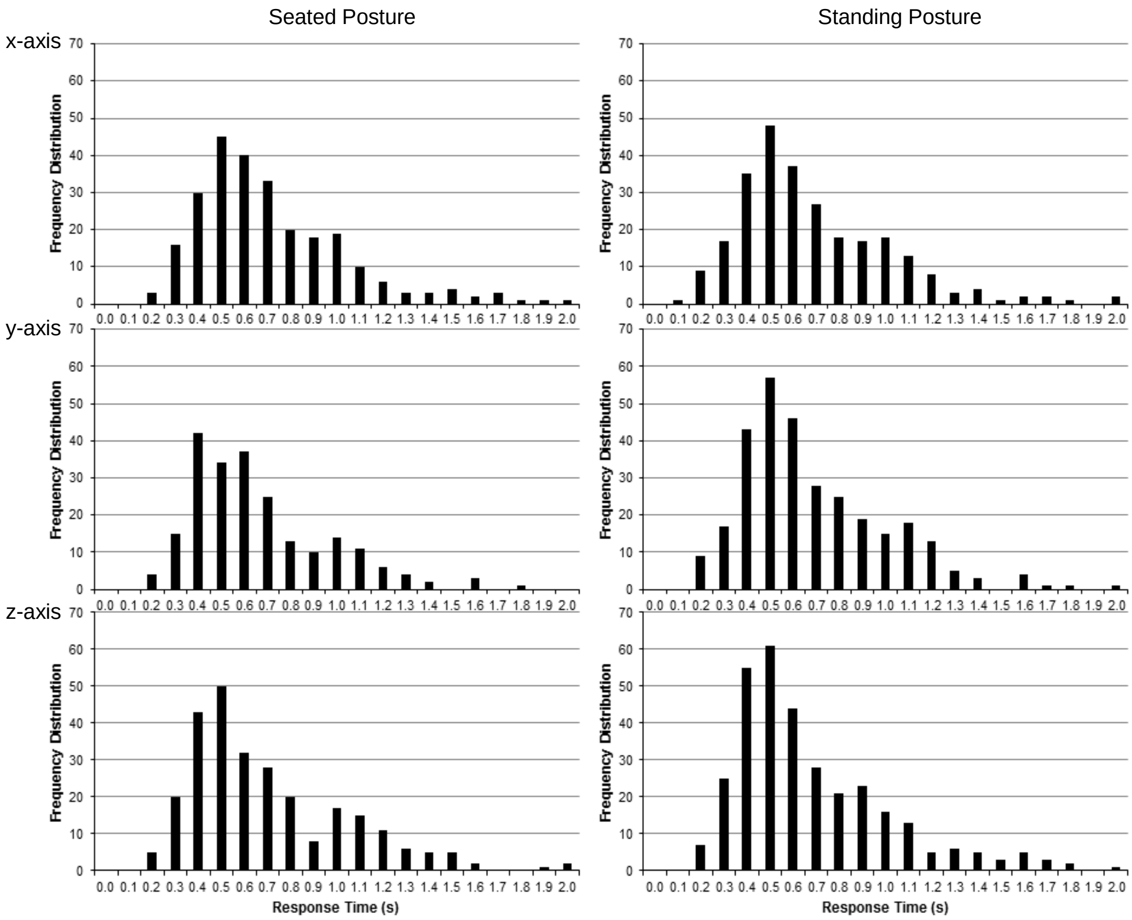


Figure A6.3 Frequency distributions of response times (RT_{SUB}) for correct inputs during vibration exposure at 4Hz for seated and standing individuals

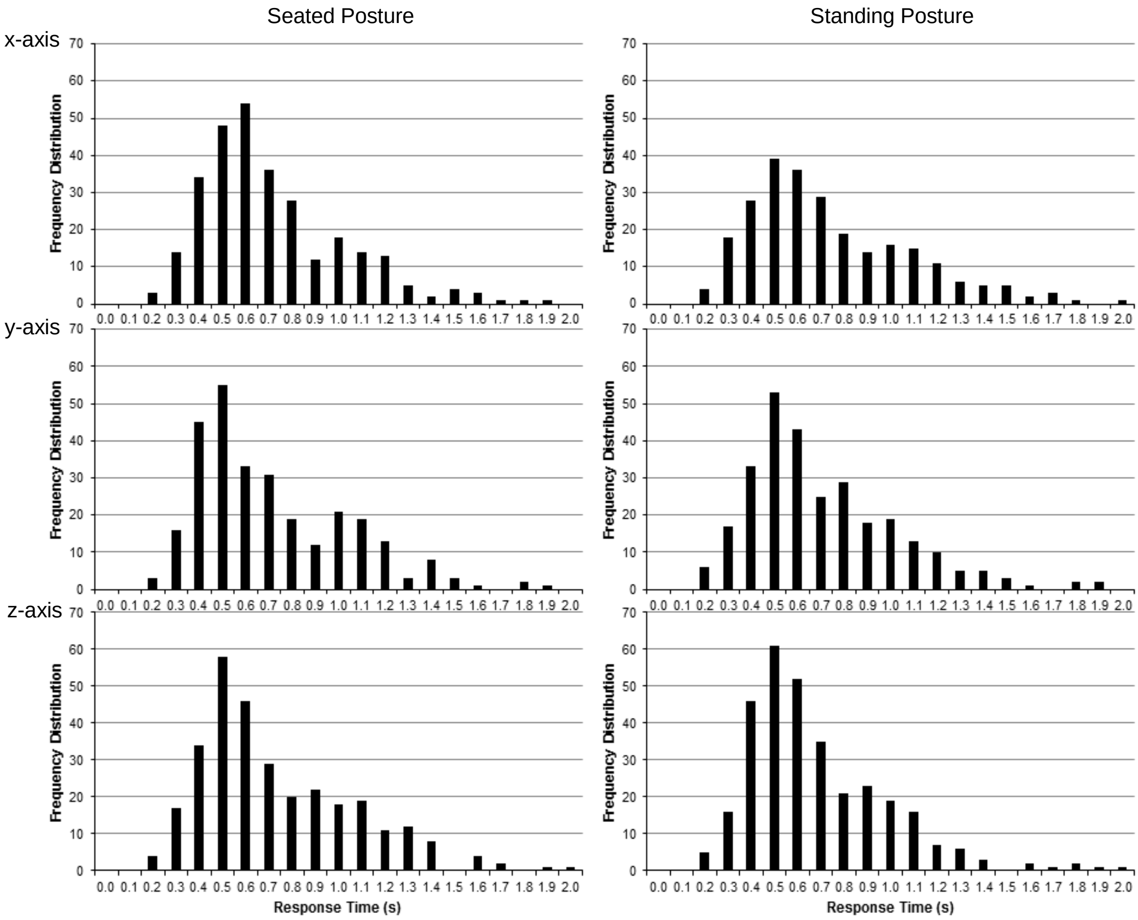


Figure A6.4 Frequency distributions of response times (RT_{SUB}) for correct inputs during vibration exposure at 8Hz for seated and standing individuals