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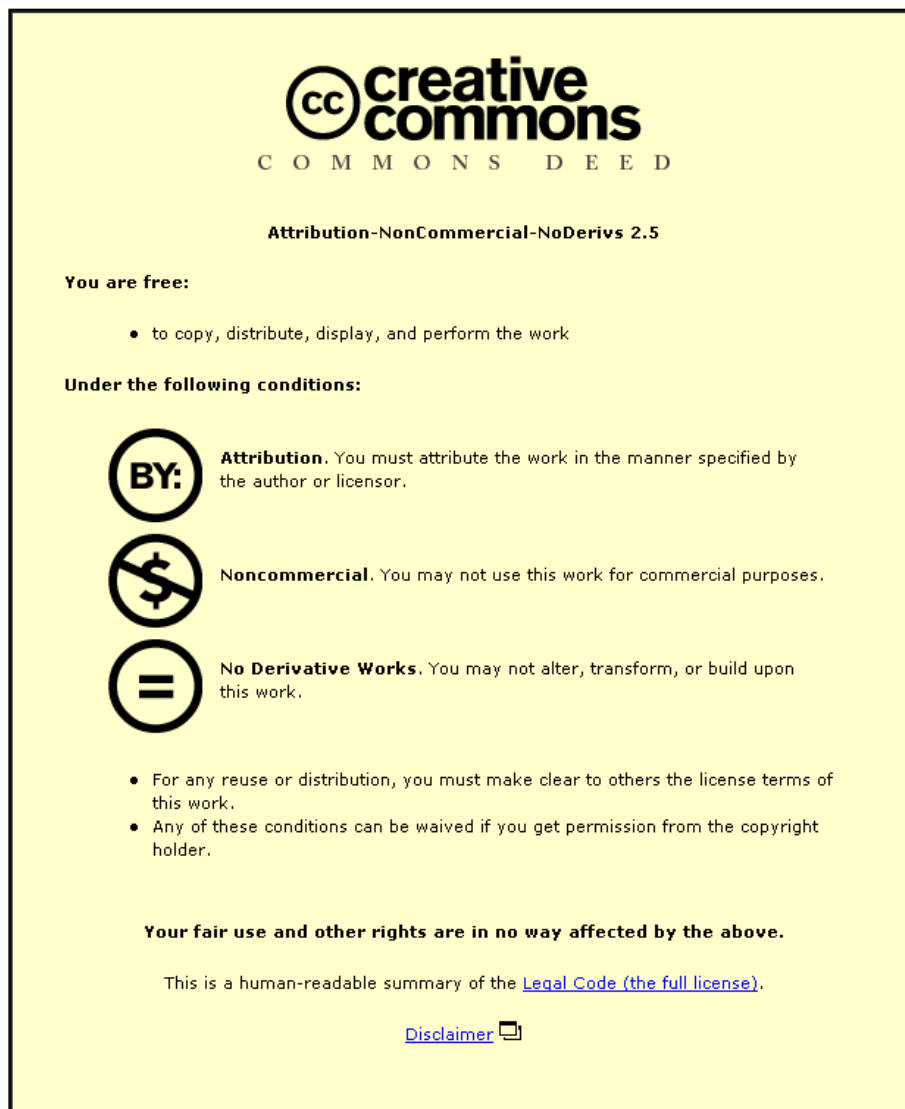
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Variability in humans, machines and tasks on whole-body vibration exposures and effects

By

Geraldine Newell

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy of Loughborough University
November 2007

Abstract

Doctor of Philosophy

Variability in humans, machines and tasks on whole-body vibration exposures and effects

Geraldine Newell

There are many factors that can influence the effectiveness of any risk management strategy, in the case of whole-body vibration exposure many problems are faced with the quantification of risk, measurement of risk and subsequent risk reduction. The quantification of vibration effects is equally as complex as the quantification of vibration itself. Exposure to whole-body vibration (WBV) causes a distribution of motions and forces within the human body and to complicate matters the transmission of vibration to the body is also dependent on body posture. To-date there has been little attempt to accurately reflect many of the typical postures and vibration environments experienced by operators of earthmoving machines in a laboratory setting. The overall aim of the thesis was to determine the variability between humans, machines and task environments in order to provide knowledge to inform improvements in methods of risk management for whole-body vibration exposure. The field measurement phase of the research focused on characterising features of whole-body vibration exposure among operators of earthmoving machines throughout a range of industry sectors. Some of the biggest industries; coal mining, quarries, and construction were targeted to obtain data on the types of machines for which very little was previously available. Research was carried out under real operating conditions to investigate the nature of occupational exposure to whole-body vibration and to determine the causes of variability between measurements. The laboratory phase of the research simulated the conditions of the 'real working environment' observed in the field study in order to examine how twisted non-neutral postures could influence the biomechanical, performance and workload responses of humans.

The machines with the greatest vibration emission were generally those that spent most of their time tracking. The worst machine for vibration exposure was a challenger 85D tracked tractor towing a 'hex' attachment. Operators of this machine would exceed the EU Physical Agents Exposure Limit Value in about 2.5 hours. The next most severe earthmoving machines were bulldozers and tracked loaders and with long working hours typically observed in industry some of these machines would also exceed the ELV in a working day. The influence of variability between work cycles was found to be a particular problem for the bulldozer and excavator machines, variation between work cycles exceeded the 25% variance limit criteria. If these machines were targeted for a WBV health risk assessment then the measurement durations will need to take account of this variation in the extrapolation to an 8-hour exposure. The operators of these tracked machines were also found to adopt non-neutral twisted postures during reversing manoeuvres. The twisted posture adopted by the bulldozer and tracked loader operators was recreated in the laboratory. Findings demonstrated that operators are likely to be putting their necks in a vulnerable position in the twisted posture due to the large increase in rotational movement at the head during exposure to vibration. Decrements in reaction time performance and increases in workload were also found while individuals were sat in a twisted posture and exposed to vibration.

Acknowledgments

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Table of Contents

Tables

XI

Figures

Abbreviations

σ	Standard Deviation
0	Degrees
~	Approximately
AT	Articulated Trucks
BD	Bulldozer
BS	British Standards
CL	Challenger (Tracked Tractor)
CP	Compactor
DT	Dump Trucks
EAV	Exposure Action Value
ELV	Exposure Limit Value
EX	Excavator
GPS	Global Positioning System
HSC	Health and Safety Commission
HSE	Health and Safety Executive
m/s^2	metres per second squared
MG	Motor Grader
MH	Material Handler
PA(V)D	Physical Agents (Vibration) Directive
PSD	Power Spectral Density
R	Rollers

r.m.s.	Root mean square
SSL	Skid Steer Loader
TL	Tracked Loader
TPNA	Twisted Posture No Armrests
TPWA	Twisted Posture With Armrests
UPNA	Upright Posture No Armrests
UPWA	Upright Posture With Armrests
VDV	Vibration Dose Value
WBV	Whole-body vibration
WL	Wheel Loader
x-axis	Fore-and-aft axis
y-axis	Lateral axis
z-axis	Vertical axis
VMRT	Visual Motor Reaction Time
NASA TLX	NASA Task Load IndeX

Chapter 1

1.1 General Introduction

Risk management is fundamental to all places of work and is especially important for work environments that expose employees to multiple occupational hazards. Earthmoving machinery operators are often faced with a variety of ergonomic risk factors within their working environment. It is thought that earthmoving and agricultural machines are responsible for some of the most common, prolonged and severe occupational whole-body vibration (WBV) among civilians (Griffin, 1990).

Epidemiological studies have investigated professional operators of earthmoving machines and have found increased risks for musculoskeletal symptoms and disorders in the lower back, neck and shoulders (Boshuizen *et al.*, 1990; Wickström *et al.*, 1994; Bovenzi and Betta, 1994; Bovenzi and Hulshof, 1998, 1999; Rehn *et al.*, 2002; Rehn, 2004). Associations have also been found with many other types of vehicles including taxi drivers (Chen *et al.*, 2004; Justinova, 2005) and rally car drivers (Mansfield and Marshall, 2001). Many studies have also reported increased discomfort due to whole-body vibration exposure (Parsons *et al.*,1982; Parsons and Griffin, 1982; Corbridge, 1987; BS6841, 1987; ISO2631-1, 1997).

'*Work related low back disorders, covering both low back pain and low back injuries, are a significant and increasing problem in Europe*' (European Agency, 2000). Back pain is the leading cause of all reported work-related disorders in Europe. The European survey of working conditions revealed that 30% of European workers suffer from back pain. (Op De Beeck and Hermans, 2000).

It is believed that over long periods of exposure to vibration pathological mechanisms may cause degenerative changes to the inter-vertebral discs, resulting in pain and suffering to the exposed operator (Bovenzi and Hulshof, 1998; Stayner, 2001). However, it is far from obvious what type of damage will occur and what mechanisms are involved in the damage process (Griffin, 1998). There is still no established dose-response relationship (Bovenzi and Hulshof, 1998), and the association has been correlated more closely to the occupation rather than the vibration exposure itself (Stayner, 2001). For this reason the Physical Agents (Vibration) Directive has specifically required minimisation of risks to take into account "*the design and layout of workplaces and work stations*" amongst other factors. It is therefore important to consider the combination of occupational risks during evaluations of vehicle operators

to ensure a holistic approach is adopted. When making an assessment of the work environment it is essential that the entire task be considered, other risk factors like poor posture, prolonged sitting, manual handling and working in the cold are often found in whole-body vibration environments (Mansfield, 2005).

There are many factors that can influence the effectiveness of any risk management strategy, in the case of whole-body vibration exposure many problems are faced with the quantification of risk, measurement of risk and subsequent risk reduction. Different standards and methodologies have been used to evaluate whole-body vibration in operational conditions. The formation of such standards has caused some controversy over placing health limits in ISO 2631-1 (1997) that cannot be supported by a dose-response relationship. Health limits have only been added to the statute book since the implementation of the European Physical Agents (Vibration) Directive (2002) into UK law under the Control of Vibration at Work Regulations (HMSO, 2005). The directive can help to guide actions and provide justification for such actions; however, it can also conceal understanding and the assumptions embedded within standards, such that the minimization of the risks of injury from exposures to vibration could be compromised (Griffin, 2006).

Each week about 1.3 million drivers in Great Britain are exposed above the action value of the Directive, mainly off-road operators or drivers of mobile machinery (Brereton and Nelson, 2005). However, the first priority for industry is to take action to reduce an estimated 20,000 exposures above the exposure limit value by 2010, in some cases by 2014, using the risk management principles applied in the Physical Agents (Vibration) Directive (Brereton and Nelson, 2004).

Measurements of whole-body vibration can provide important information for risk management strategies of workers exposed to vibration. Unfortunately the complex nature of whole-body vibration makes it almost impossible to create generic values for whole-body vibration emission values of working machines. Under real operating conditions the constantly varying conditions of the ground surface and the wide variety of tasks that are carried out by machines means that the operating conditions vary from site to site and from day to day (BS EN 14253, 2003). Many variables can also influence the extrapolation of a vibration measurement to a daily dose measure. It is important to quantify the variation inherent to whole-body vibration exposure to help understand how this variation will affect health risk assessments.

The sensations caused by WBV can include discomfort or annoyance; it can also affect human performance and present a health risk. The quantification of vibration effects is equally as complex as the quantification of vibration itself. Exposure to WBV causes a distribution of motions and forces within the human body. It is believed that large biological variations exist between individuals with respect to whole-body vibration effects and to add to this complication the transmission of vibration to the body is also dependent on body posture (CR 12349, 1996). To-date there has been little attempt to accurately reflect many of the typical postures and vibration environments experienced by earthmoving machinery operators in a laboratory setting. Therefore current application of biomechanical models to the real world operating conditions is limited. Developments are needed to aid understanding of the variability of working postures on the interactions and causative effects associated with whole-body vibration exposure.

1.2   Aims of the thesis

The overall aim of the thesis was to determine the variability between humans, machines and task environments in order to provide knowledge to inform improvements in methods of risk management for whole-body vibration exposure. The field measurement phase of the research focused on characterising features of whole-body vibration exposure among earthmoving machinery operators throughout a range of industry sectors and types of machines for which very little data was previously available. Research was carried out under real operating conditions to investigate the nature of occupational exposure to whole-body vibration and to determine the causes of variability between measurements. The laboratory phase of the research simulated the conditions of the 'real working environment' in order to examine how postural confounding factors influence human dynamic characteristics, performance and workload during exposure to the conditions observed in the workplace. Figure 1.1 outlines the schematic of the approach.

The specific aims of the thesis are:

- Quantification of whole-body vibration in large range of earthmoving machines in a variety of environments and performing a variety of tasks

- Develop understanding of the postural requirements of the types of tasks and machines the operators are using

- Determine and understand variability between work cycles for earthmoving machines

3

- Evaluate seat-to-head transmissibilities using conditions observed in the field trials to understand the response to vibration in a variety of postures

- Evaluate performance and workload measures for a variety of occupational postures while exposed to multi-axis vibration
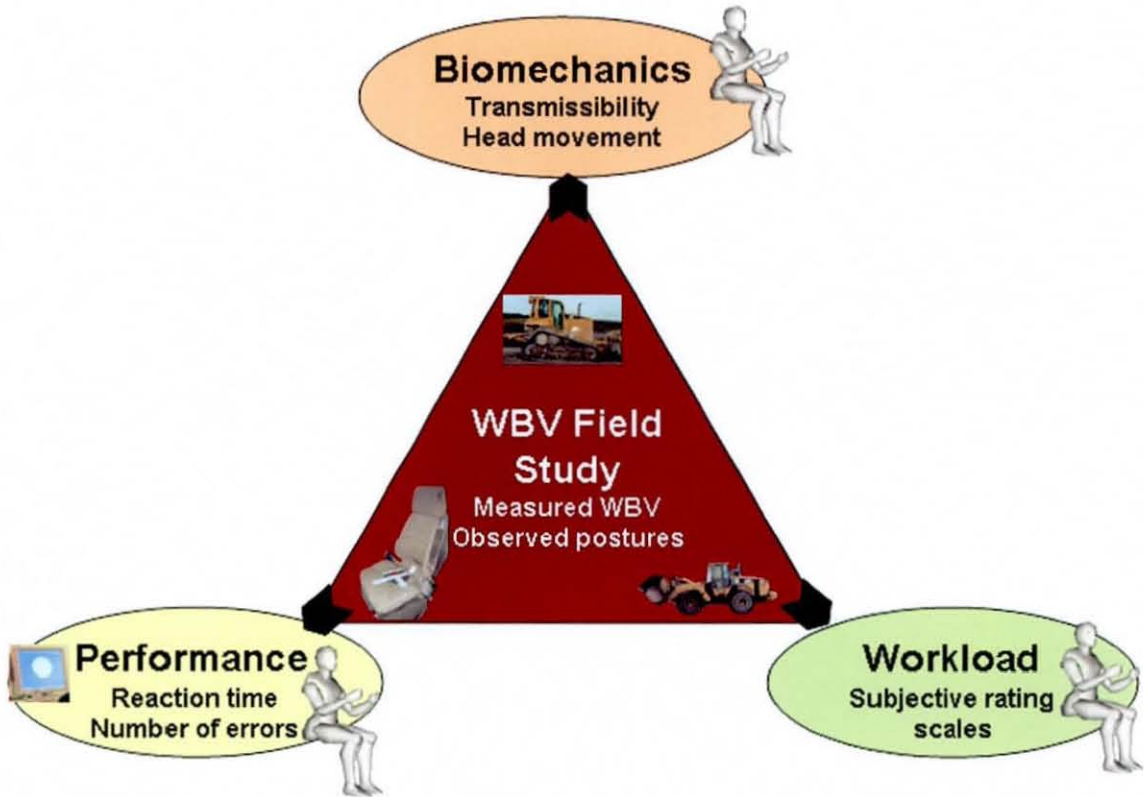
Figure 1.1 Factors considered for the assessment of risk exposures on the human response to vibration

1.3 Thesis structure

The thesis is divided into 11 chapters. An outline of the chapters is provided in

Figure 1.2.
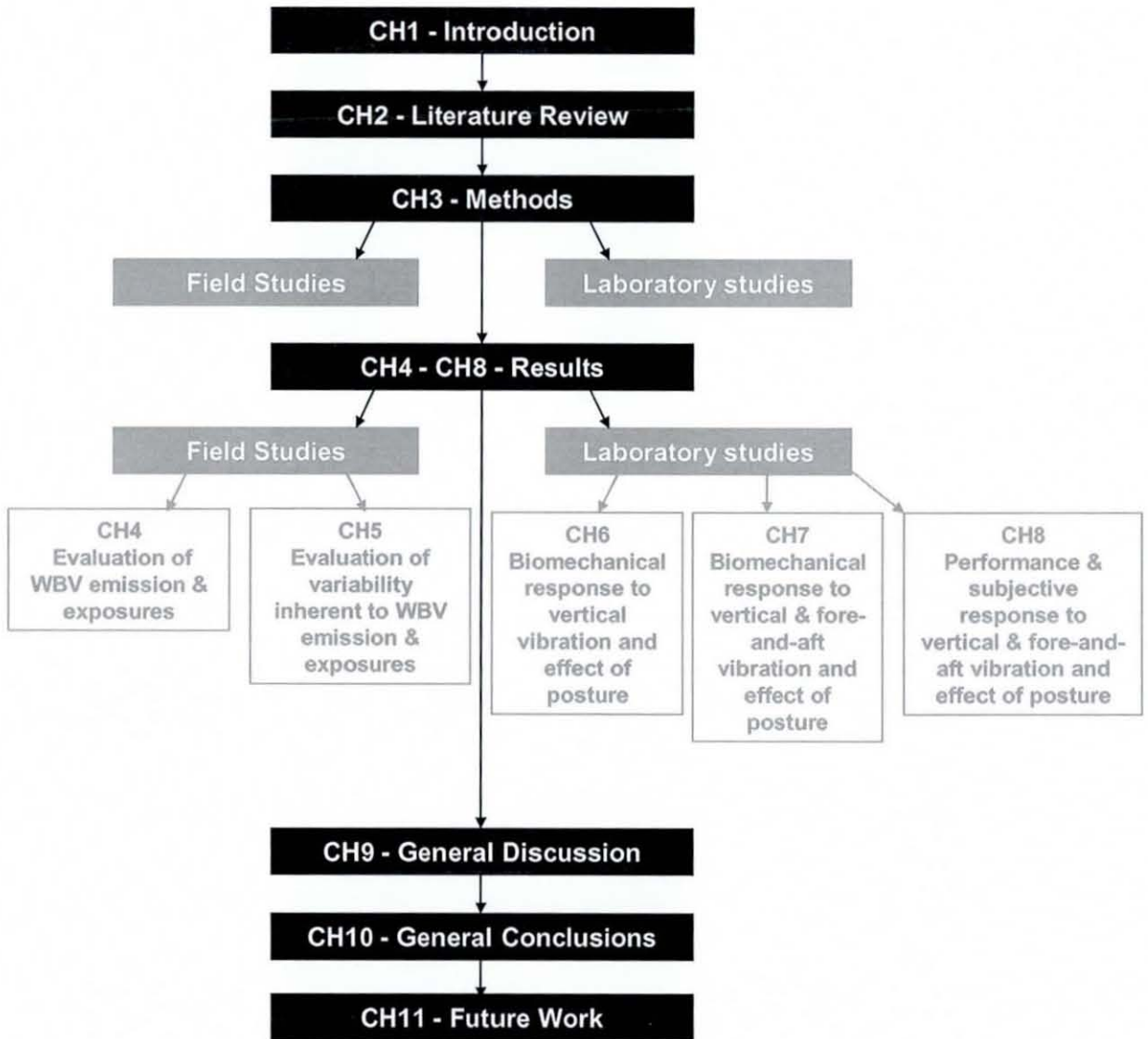
Figure 1.2 Outline of thesis structure.

Chapter 2 - Literature Review

2.1 Introduction

This literature review provides an overview of the methods that have been used to assess whole-body vibration exposure over the past 20 years and identifies the potential problems with their application (Section 2.2). It also discusses the measurement studies both on- and off-road that have been performed to determine how much vibration drivers are exposed to during their daily work (Section 2.3); followed by a discussion of the factors that can influence the variation between the measurement exposures (Section 2.4). The final section presents the current state of knowledge regarding the human responses to whole-body vibration at work, it identifies where further developments are needed, and outlines the physiological, biomechanical, and psychological responses to whole-body vibration, including the different ways of assessing the responses.

2.2 History of legislation for the measurement and assessment of whole-body vibration

Before the implementation of the Physical Agents (Vibration) Directive (2002) four European Union countries had defined back disorders due to whole-body vibration (WBV) exposure as an occupational disease. At the time, depending on whether the back problems occurred in Belgium, Germany, Netherlands or France could largely influence the compensation claim. The countries adopted different diagnostic criteria and pre-conditions with respect to the WBV exposure (CR 12349, 1997; Hulshof *et al.*, 2002).

The viewpoints expressed in different European countries resulted in the creation of a variety of guidelines in relation to whole-body vibration exposure. For example, German guidelines considered a daily reference exposure for an 8-hour period of 0.8 m/s² (vertical weighted r.m.s) and a lower limit of 0.6 m/s² for cases where there was evidence of shock type vibration or poor body posture (Schwarze *et al.*, 1998).

Everything changed with the full adoption of the Physical Agents (Vibration) Directive (PA(V)D), which came into force in July 2005, with harmonization of the legal framework across Europe. The standards that have provided the foundation for the Directive and the changes that have taken place throughout Europe will be discussed throughout the following sub-sections.

6

2.2.1 International Standard Organization 2631-1 (1985)

International Standard 2631 "Guide for the evaluation of human exposure to whole-body vibration" was first published in 1974 (ISO 2631, 1974) and republished in 1978 (ISO 2631, 1978) with editorial changes. The standard was subsequently republished in 1985 under a new title "Evaluation of human exposure to whole-body vibration –part 1: general requirements" (ISO 2631-1, 1985). The standard was based on root-mean-square (r.m.s.) acceleration and two frequency weightings defined from 1-80 Hz by straight lines on a logarithimic graph of acceleration versus frequency. The health hazard assessment method was based on 3 translational axes; fore-and-aft (x-axis), lateral (y-axis) and vertical (z-axis), with the coordinate system originating at the heart. The standard brought with it a host of complexities including time-dependency, and ambiguous evaluation procedures. The time-dependency relates to a method of defining a fatigued-decreased proficiency boundary (from 1 min to 24 hrs), with three sets of limits, even though the method had not been supported by research. The standard failed to define a precise analysis method and therefore application of the procedure could be performed in different ways depending on the judgement of the individual applying the methods (Griffin, 1990; Griffin, 1998a).

2.2.2 British Standard 6841 (1987)

In Britain the perceived failure of ISO 2631 (1985) to tackle some major issues relating to whole-body vibration exposure prompted the adoption of the British Standard (BS 6841) in 1987 (Griffin, 2004). The standard covers methods and guidance for the evaluation of vibration and repeated shock with respect to health effects, within the frequency range 0.5-80 Hz. It is applicable to all forms of multi-axis, multi-frequency, random, stationary and non-stationary vibration. It identifies the four principal effects of vibration: degraded health, impaired activities, impaired comfort and motion sickness. The frequency weightings used in this standard include W_b for vertical seat, W_c for backrest fore-aft and W_d for horizontal vibration on the seat. The frequency weightings at the seat are described in more detail in the following section.

The r.m.s method is described in BS 6841, yet the standard specifies vibration dose value (VDV) as the primary method for vibration exposures. Calculations of these methods are presented in the methods section of this thesis (Chapter 3).The VDV method gives a better indication of the presence of high acceleration events (shocks) compared with the r.m.s. method. Due to the nature of the averaging process with the r.m.s. the presence of shocks will be smoothed out over time. The VDV was adopted

7

on the assumption that shock events may be more harmful to health and overall comfort compared to continuous vibration exposure with lower magnitudes. It states, *"Sufficiently high vibration dose values will cause severe discomfort, pain and injury"*. The standard considers a vibration dose value of 15 m/s$^{1.75}$ and above to be a level of concern that will usually cause severe discomfort.

The standard's guide for health hazards only refers to the use of VDV when considering the evaluation and assessment of vibration exposure. This has meant that VDV values need to be estimated in certain cases where measurements are limited to r.m.s., this method is referred to as eVDV. However, if the crest factor is above 6.0 then ideally the vibration dose value (VDV) would be used as the motion may contain occasional shocks and also if the vibration magnitude varies or if it is intermittent. The r.m.s. would not be a good indicator in these cases for the estimation of VDV. For example, Lewis and Griffin (1998) found a difference of more than 250% between the estimated safe daily WBV exposure durations of three severe machines when the r.m.s. method was used compared with the VDV.

2.2.3 International Standard Organization 2631-1 (1997)

The updated version of International Standard ISO 2631 (1985) was produced in 1997 with differences to frequency weightings and criteria (Mansfield, 2005). ISO 2631-1 (1997) defines a variety of methods for the measurement of periodic, random and transient whole-body vibration (sinusoidal or complex). The standard considers vibration within the frequency ranges from 0.5 Hz to 80 Hz for health, comfort and perception.

The basicentric axes in ISO 2631 are defined according to the orientation of the body with respect to gravity. The standard specifies that vibration measurements should be made in accordance with a coordinate system originating at a point from which the vibration is considered to enter the human body, as presented in Figure 2.1. In the case of driving the interfaces between the human body and the vibration source are the surface the feet is in contact with and the point of contact between the buttocks / back and the surface of the seat.

Frequency weightings are used for each axis of vibration to account for the varying effect it has at different frequencies on human tissue, as the body has a non-linear response to frequency. The weightings have a higher value attributed to frequencies

with greater sensitivity and a low value to attenuate the frequencies where the human tissue is less sensitive (Griffin, 1990).

The resonant frequency of the human body ranges from 2 Hz for lower limbs, 4-8 Hz for trunk and shoulders; and from 50-200 Hz for the hand (Chaffin and Andersson, 1991). Most importantly the resonant frequency for the human spine in the vertical direction (i.e. spinal compression) is centred around 3-5 Hz, where it is assumed that the potential for injury is the highest (e.g. Paddan and Griffin, 1988a; Fairley and Griffin, 1989; Kitazaki, 1994; Mansfield and Griffin, 2000; Rakheja et al., 2002).
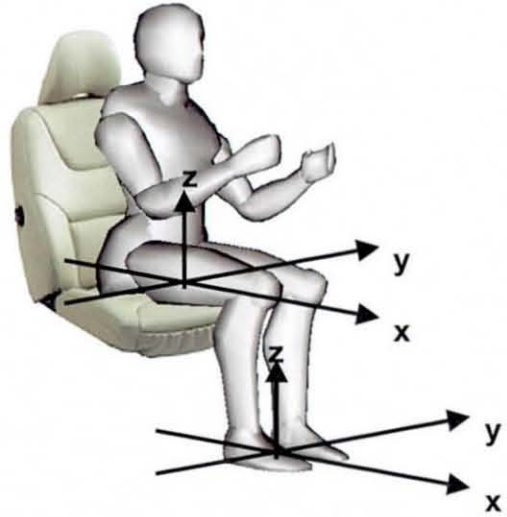
Figure 2.1 The principal basicentric coordinate system for the seated person, ISO 2631-1 (1997).

The weighting used in ISO 2631-1 (1997) for fore-aft (x-axis) and lateral (y-axis) vibrations is W_d, and for vertical (z-axis) the weighting is W_k, this is illustrated in Figure 2.2. The British Standard 6841 employs the frequency weighting W_b for vertical vibration as outlined in Figure 2.2. This gives more weight to frequencies between 0.5 and 2 Hz and to increase the importance of vibration frequencies above 8 Hz (Griffin, 1990). The differences between the two frequency weightings W_b and W_k have been explained further in a review by Griffin (1998a): '*It is not possible to provide technical explanation as to why ISO 2631-1 (1997) has a weighting with the shape of W_k since no evidence was presented as to why W_k was preferred to W_b, or any other shape*', he continues to add '*the differences are relatively small compared with W_b weighting, the maximum differences give W_b 20% less weight than Wk at low frequencies and give W_k about 25% greater weight than W_b at the highest frequencies*'. Some consider that from a technical stand point there appears to be more of a consensus for the W_b frequency weighting as it appears to reflect both the biomechanical (e.g. transmission to the spine, apparent mass) and subjective responses (e.g. perception sensitivity, comfort) more accurately than W_k (Griffin, 1998a), although this is not a universal view. Regardless of the differences the two frequency weightings have been found to produce similar vibration magnitudes for 100 different vehicles tested by Paddan and Griffin (2001; 2002).

9
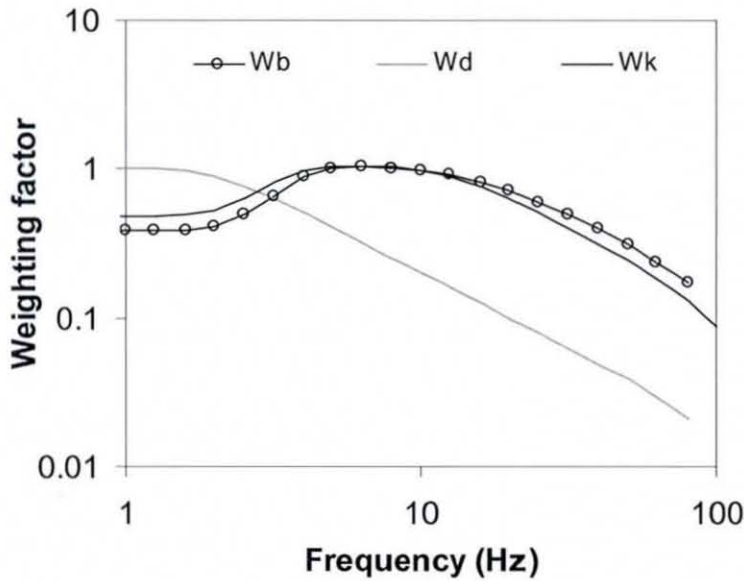
Figure 2.2 Frequency weightings used in BS6841 (1987) and ISO2631 (1997).

The fact that W_k has 20% more weight at lower frequencies below 5 Hz will alter the apparent efficiency of suspension seats because they typically have a resonance in this range. Many off-road machines have the greatest energy around the lower frequencies (e.g. Village and Morrison, 1989) and these types of machines are often associated with back disorders (e.g. Teschke *et al.*, 1999; Hartman *et al.*, 2005). For this reason it may appear beneficial to increase the importance of vibration at these frequencies as this gives more incentive to implement control measures, although the purpose of the weighting is to support the relative importance of the different frequencies. Therefore, the overall importance of any specific environment depends on the assessment method used, this varies between the British and the International standard (Griffin, 1998a)

According to ISO 2631-1, once the frequency weightings have been applied a multiplying factor of 1.4 is used on the horizontal axes of vibration, yet not the vertical axis of vibration. This in effect, could increase the chances of horizontal vibration being evaluated as having magnitudes of greater severity than vertical vibration. Similarly to the frequency weightings the multiplication factors will evidently increase the severity of many off-road machines because they frequently operate in environments that promote significant horizontal motions (Paddan *et al.*, 1999; Cann *et al.*, 2003; Mansfield, 2003; Scarlett and Stayner, 2005a,b). There is much controversy surrounding the application of these weighting factors within the guidelines of the updated International standard (ISO2631-1, 1997). BS6841 (1987) specifically adopted changes to the frequency weightings from ISO 2631 (1985) to eliminate the need for multiplying factors for the horizontal vibration. This in effect, means the frequency-

weighted vibration evaluations reported according to ISO 2631-1 (1997) should have 40% greater horizontal vibration magnitudes when compared to the BS6841 (1987) method. The reason for these multiplying factors has been outlined by Griffin (1990):

"When making comparisons or combining the weighted values in the horizontal axes with the weighted values in the vertical a correction factor of 1.4 is required since the 4-8 Hz limits for z-axis vibration are 1.4 times higher than the corresponding horizontal axes limits in the range 1-2 Hz. This is where the multiplying factors come into affect." p.419

Most of the guidance for ISO2631 (1997) was based on research from seated individuals exposed to vertical vibration. At the time, knowledge about human responses to the horizontal axes was 'limited', therefore the standard was agreed upon without sufficient understanding of the responses to the fore-and-aft and lateral directions of vibration (Griffin, 1998a).

Measurement calculations for crest factors less than 9.0, according to ISO 2631 (1997), should use the frequency-weighted r.m.s. acceleration to evaluate the effects of vibration on health. The measurements should be made separately for each translational axis of motion, so that the overall assessment can be carried out according to the worst axis of vibration. Guidelines for the effect of vibration on health are highlighted in ISO 2631 informative appendix B. The lower and upper limits correspond to vibration dose values of 8.5 and 17 $m/s^{1.75}$, respectively.

The crest factor is used to determine the terrain quality of a particular route, i.e. the roughness. Commonly reported crest factors for travelling on urban roads range from 3-6 (Griffin, 1990). Higher crest factors can be found in a variety of machines and operations, this is particularly true for mining environments where severe shocks have been observed in earthmoving machines, with crest factors greater than 10 (Robinson *et al.,* 1997). If the crest factor is less than 9.0 then the root-mean-square value method is recommended by ISO 2631. According to a current draft amendment to ISO 2631 (2007) "Experience has shown that the crest factor can increase with measurement duration for stationary signals, as the probability of measuring a larger peak is greater"; implying that the use of crest factor can be unreliable.

2.2.4 European Physical Agents (Vibration) Directive (2002/44/EC)

The implementation of the Physical Agents (Vibration) Directive has provided a legislative framework to minimise health risks from vibration and to limit workers'

exposure, for the first time throughout Europe. Some welcome the Directive, as it has standardised the measurement techniques used, in accordance with ISO2631-1 (1997). Others do not agree with the Directive because the defined exposure limits have not been derived from a dose-response relationship. The nature of the dose-response relationship between back pain and whole-body vibration has still not been established. This suggests that the action and limit values set out in the Directive may be inaccurate, as the boundaries for health effects cannot be defined.

The Physical Agents (Vibration) Directive was published in the Official Journal of the European Communities in 2002. The directive outlines minimum requirements for member states to enforce laws concerning exposure to whole-body and hand-transmitted vibration. This Directive has now come into force in the UK and other member states; in the UK both hand-arm and whole-body vibration exposure limits have been incorporated into the 'Control of Vibration at Work Regulations' (HMSO, 2005). A possible delay of enforcing the limit values could mean that equipment already in use by 2007 may need not comply until 2010. Derogations have been set for the agricultural and forestry industries so they are allowed an additional four years, resulting in compliance with the limit value from 2014.

The Directive specifies that where there is likely to be a risk from vibration exposure, the employers are required to:

- Eliminate the risks from mechanical vibration at their source or reduce them to a minimum
- Reduce exposure to a minimum by limiting duration and intensity
- Choose work equipment of appropriate ergonomic design that can produce the least amount of vibration for the task
- Ensure appropriate maintenance programmes for work equipment, workplace and workplace systems
- Assess exposure levels
- Assess the design and layout of workplaces, work stations and rest facilities
- Provide adequate information and training on correct and safe work practices
- Provide clothing to protect employees from cold and damp
- Carry out a programme of measures to reduce exposure and provide appropriate health surveillance when exposure reaches the exposure action value
- Ensure that any worker should not be exposed above the exposure limit value

The daily exposure action and limit value in the Directive have been standardised to an eight-hour period. Both the limit and action values pertain to the highest vibration of the three orthogonal axes, identified as either weighted A(8) or vibration dose value. The first method A(8) or m/s² A(8) is normalised to 8 hours. This method produces a cumulative exposure using an r.m.s. acceleration value adjusted to represent an 8 hour working day.

The exposure values for Directive 89/391/EEC (2002) are as follows:

- Daily exposure limit value: 1.15 m/s^2 A(8) or 21 m/s$^{1.75}$ VDV
- Daily exposure action value: 0.5 m/s^2 A(8) or 9.1 m/s$^{1.75}$ VDV

Member states were given the option to implement r.m.s., VDV or a combination of the two methods for the action and limit values. In the UK, after much deliberation it was decided that both the action and limit value would be implemented using the A(8) method. The Health and Safety Executive (HSE) estimate that around 50,000 assessments of whole-body vibration (WBV) will be required in the United Kingdom. This figure is based on the assumption that 1 in 20 workers will be assessed from the 1.3 million that are exposed above the WBV exposure action value of the PAVD (0.5 m/s² A(8) (Coles, 2002; Brereton and Nelson, 2003).

If workers' exposure to whole-body vibration is to be assessed, then it must be done in accordance with ISO 2631 as outlined in Part B of the Directive's annex. This also includes the multiplying factors of 1.0 for the vertical (z-axis), and 1.4 for the horizontal axes (x- and y-axes).

Now that ISO2631-1 (1997) has been enforced by the Directive the number of individuals using the International standard has more than likely increased. Mansfield (2005) suggests *'the complexity, confusing approach, and content of ISO2631 will not improve with an increased user population. Indeed, considering that the majority of this extended user group will be new to the field, scope for increasing the confusion is substantial.'* (pg155).

2.2.5 Machinery Safety Directive (1998)

The Machinery Safety Directive of the European Community (89/392/EEC) requires that machinery suppliers reduce vibration exposures for the operators to the 'lowest level', and requires specification of vibration emission values when the frequency weighted acceleration value exceeds 0.5 m/s^2 r.m.s. Griffin (2004) postulates that if

whole-body vibration is evaluated in the same way for the Machinery Safety Directive and the Physical Agents (Vibration) Directive then the stated vibration emission value will correspond to the r.m.s. eight-hour exposure action level in the PAVD. Hence, if the machinery evaluation does not produce a vibration magnitude greater than 0.5 m/s^2 r.m.s. then it would not exceed the action value unless either exposures lasted longer than eight hours. However, the declared vibration magnitudes by machinery suppliers may not be representative of the vibration exposure during machinery use, depending on the method used to collect the data.

Two generic test methods have been produced to support the EU Machinery Directive, including European Standard EN 1032 (2003) to test mobile machinery, and European Standard EN 13059 (2002) to test industrial trucks. The standards are designed so that anyone using the methods can obtain comparable and reliable data for declaration of emission values under the Machinery Directive. The standards cannot, however, help to derive whole-body vibration exposures experienced in every day work tasks. Nor can they provide accurate emission values for 'real' working environments; this area of understanding is still limited. However more recently there has been publication of a technical report providing guidelines for assessment of exposure to whole-body vibration of earth-moving machines. The technical report provides example of exposures for many machines, and it was partly developed from the data reported later in this thesis.

2.2.6 Summary of legislation

The standards cannot provide a probability or severity of any disorders pertaining to whole-body vibration, nor can they provide exposure durations that will create specific disorders in a certain percentage of the exposed population. It has been questioned whether the current legislation *'provides a fair reflection of the state of knowledge among the medical, engineering or scientific community at the end of the 20th century'* (Griffin, 1998).

The International standard specified by PA(V)D (ISO 2631-1 1997), provides a variety of interpretations of the vibration data and variety of methods the guidance can often be confusing and potentially misleading. When the thesis was formulated EN14253 (2003) was available to provide some guidance for collecting vibration emission data in real working environments. Since then there have been improvements made to the standard with a revised version published in 2006, including a new annex based on

work produced for this thesis looking at measurement 'artefacts' (presented in Appendix A1)

It is of significant importance to gather representative data for each machine in true working conditions to ensure the stated vibration magnitudes give an accurate figure for what the operator is actually exposed to during daily operations. Consideration of the machines used outside of their designed application should also be of interest to machine suppliers and the buyers of the machines. If the incorrect machine is chosen for a particular task and it is too small or unsuitable for the task the operator could be exposed to higher vibration magnitudes than have been stated by the supplier.

Griffin (1990) summarises the importance of striving for clear defined methods; *"Where there are no agreed 'rules' for measurement or evaluation, information cannot be communicated to others: the satisfactory reporting of vibration conditions is dependent on an understanding of the rules. The definition of both unambiguous means of measurement and useful methods of evaluation are, therefore, essential for progress."* (p.453)

Research is needed in this area to further the knowledge of the issues that arise with vibration measurements, in addition to gathering representative data that can be amalgamated into a WBV database of hazardous machines. This database could prove as a useful tool to guide employers towards their most problematic machines so they can conduct a more thorough risk assessment. The following section outlines previous studies that have investigated vibration exposures in a variety of settings. This information can serve as a starting point for the characterization of whole-body vibration exposures in industry.

2.3 Whole-body Vibration Exposures in Vehicles

2.3.1 Comparison between on-road and off-road vehicles

A meta-analysis was performed to bring together the knowledge from a range of different exposure studies. Literature was reviewed from a number of sources covering peer reviewed journals relevant to this area of discipline from online sources including HSE, Science Direct, Web of Science, and PubMed. Conference proceedings and local human vibration literature collection in the Department of Human Sciences at Loughborough University were also reviewed. The meta-analysis provides an overview of the vibration profiles that have been evaluated for a range of on- and off-road vehicles. Table 2.1 presents the quartile ranges for all the vibration measurements that

have been reviewed for the meta-analysis, quartiles were used to prevent the overall data being skewed by the nature of extreme values present in some of the studies. Off-road vehicles exceeded all the quartile values for the horizontal axes compared with the on-road vehicles.

The same cannot be said for the vertical axis, the maximum r.m.s magnitude for the vertical direction was found in an on-road vehicle. The vehicle was a 4-ton garbage truck measured by Maeda and Morioka (1998) in Japan. The vehicle at the time was travelling on a rough road with a full load of garbage. Additional vibration measurements of the same truck were made, and regardless of the measurement condition the vibration magnitude was exceptionally high, including when the vehicle was idling. The authors mentioned the suspension mechanism as a possible cause of the high vibration exposure. All three trucks investigated had similar high exposures; these anomalies can be observed in Figure 2.3 (machine samples 121-131). However one concern with the study is the lack of measurement sampling time. Each sample was only taken for 30 seconds; this could reduce the validity of the data captured, for a discussion of acceptable measurement times please refer to section 0. If the study is excluded from the meta-analysis then the off-road vehicles would exhibit the maximum amount of vibration in all three axes, and even with inclusion of the study the upper quartiles are still consistently higher for the off-road machines. The maximum r.m.s magnitude from all the measurements occurred in the fore-and-aft direction for a tractor operator harrowing in Finland (Sorainen *et al.*, 2006). If the operator of this machine was exposed for 8-hours their exposure would be over 4 times greater than the limit value of the PA(V)D, 1.15 m/s² A(8).

Table 2.1 Quartiles ranges from meta-analysis of on- and off-road machinery vibration

Quartiles	On-road (246 measurements) (m/s² r.m.s)			Off-road (194 measurements) (m/s² r.m.s)		
	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
Median	0.21	0.22	0.40	0.50	0.50	0.56
Lower	0.15	0.16	0.23	0.34	0.30	0.34
Upper	0.3	0.32	0.58	0.72	0.73	0.80
Maximum	1.67	1.98	2.45	4.96	2.62	1.80

Data taken from; Cann *et al.* (2003); Eger *et al.* (unpublished); Fairlamb & Hayward (2005); Funakoshi *et al.* (2004); Gould (2002); Holmes & Paddan (2004); Maeda & Morioka (1998); Mansfield & Atkinson (2003); Okunribido *et al.* (2005); Paddan (2004); Paddan *et al.* (1999); Scarlett & Stayner (2005a; 2005b); Sorainen *et al.* (2006); Stayner & Scarlett (2003); Toward *et al.* (2005); Vibration database (NIWL, 2003).

The only time off-road vehicles exhibit negligible vibration in all directions is while the vehicles are idling (machine numbers 72-82, highlighted in Figure 2.3). It is clear that overall profiles demonstrate that operators driving off-road vehicles will be exposed to greater magnitudes of vibration, particularly in the horizontal directions, when compared with drivers of on-road vehicles. This is mainly due to the nature of the working environment; the road surface has a big influence on the vibration characteristics. On-road vehicles will generally be operating on smoother roads and will therefore only experience similar conditions if the operator is driving the machine over a poorly maintained road with potholes and irregular surfaces. Off-road machines are adapted to working on mixed terrain conditions and can be responsible for shaping the rough terrain (e.g. scrapers, graders, dozers, rollers, excavators). Another concern with off-road machines is they tend to expose operators to lower frequencies which coincide with the most sensitive frequencies of the body. Table 2.2 gives an indication of the comfort level experienced for each of the vehicles reviewed here and indicates where the Machinery Safety Directive and the Physical Agents (Vibration) Directive limit thresholds come, in relation to this. It is clear that operators of off-road vehicles could be experiencing discomfort during their daily work, in addition to having an increased risk to their health.
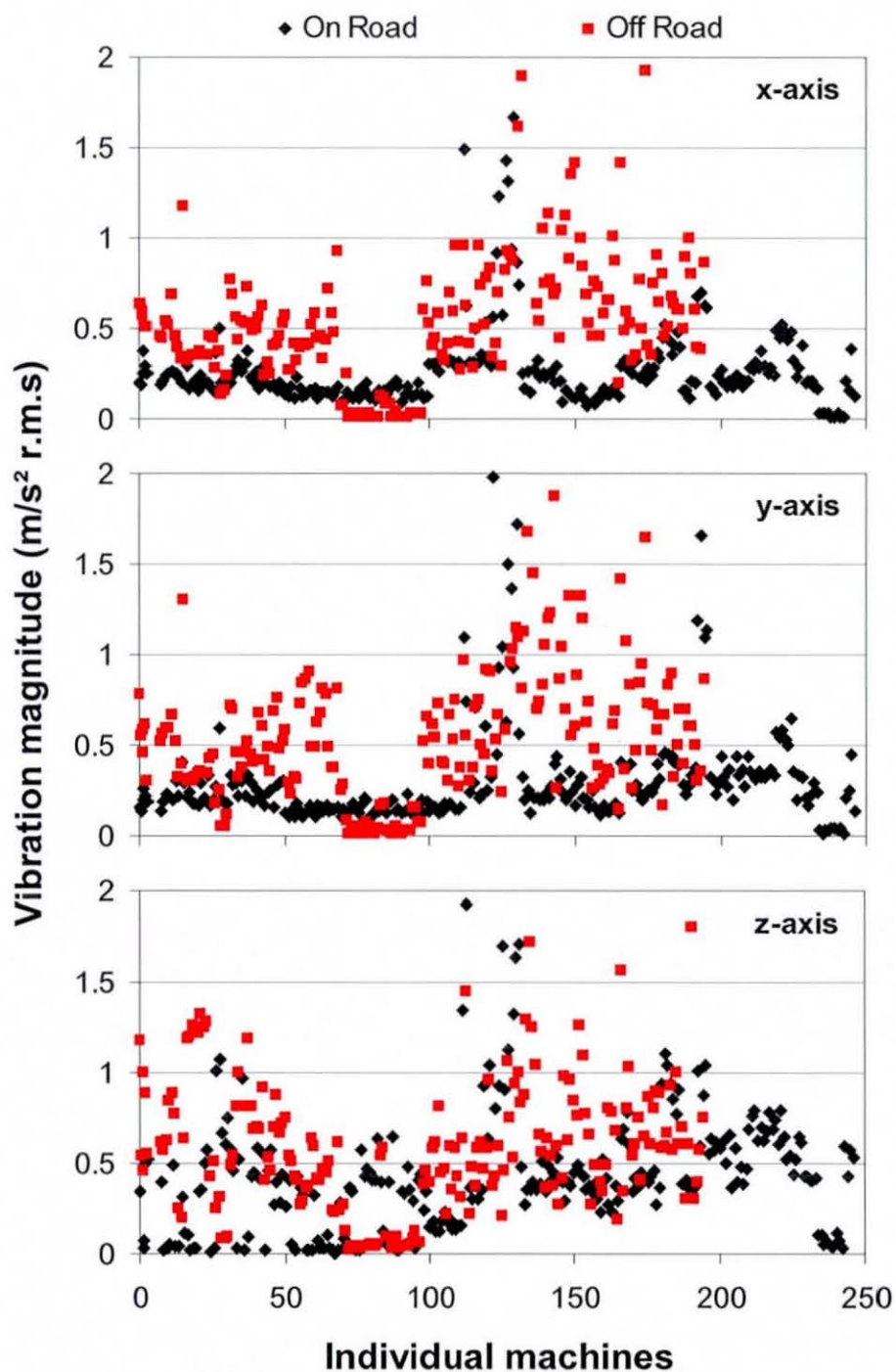
Figure 2.3 Vibration magnitudes experienced in a large range of vehicles. On-road vehicles include buses, lorries, cars, HGVs, vans, ambulances, garbage trucks and milk floats. Off-road vehicles include tractors, landrover, dozers, dumper trucks, excavators, mobile cranes, forklift, telescopic handler, wheel loaders, ATVs, skid steer loaders, scrapers and rollers. Data taken from studies by Cann *et al.* (2004); Eger *et al.* (no date); Fairlamb & Hayward (2005); Funakoshi *et al.* (2004); Gould (2002); Holmes & Paddan (2004); Maeda & Morioka (1998); Mansfield & Atkinson (2003); Okunribido *et al.* (2005); Paddan (2004); Paddan *et al.* (1999); Scarlett & Stayner (2005a; 2005b); Sorainen *et al.* (2006); Stayner & Scarlett (2003); Toward *et al.* (2005); Vibration database (Umea, Sweden, 2003).

Table 2.2 Scale of discomfort outlined in BS6841 (1987) & ISO 2631-1 (1997), with reference to the Machinery Safety Directive and Physical Agents (Vibration) Directive limits.

Vibration Magnitude	Comfort level	Physical Agents (Vibration) Directive	Machinery Safety Directive
Less than 0.315 m/s^2	Not uncomfortable	/////////	/////////
0.315-0.63 m/s^2	A little uncomfortable	Action value	Values to be
0.5-1.0 m/s^2	Fairly uncomfortable	category ($0.5 m/s^2$)	specified when ($>0.5 m/s^2$)
0.8-1.6 m/s^2	Uncomfortable	Limit value	
1.25-2.5 m/s^2	Very uncomfortable	threshold	
Greater than 2.0 m/s^2	Extremely uncomfortable	($1.15 m/s^2$)	

Griffin (1990) suggests that *"agricultural and earth-moving machinery are responsible for some of the most common, prolonged and severe occupational vibration exposures among civilians."* (p.431). The meta-analysis supports this statement, most of the off-road vehicles fall within the increased risk category for vibration exposure and they can mainly be classified as agricultural or earthmoving machines. The scope of this thesis will be to address the gaps in knowledge in relation to earthmoving machines, for three reasons; (1) they can expose operators to severe vibration, (2) there are many of these types of machines used in industry so the knowledge gained has the potential for wider application and therefore reduction of the number of exposed operators, and (3) there were few or no reported emission values in the literature for many of these machine types when this research was being completed. The following machines fall within the category of earthmoving machines as specified in ISO 6165 (2002):

-1   Backhoe loader   -7   Pipelayer
-2   Dumper   -8   Roller
-3   Excavator   -9   Scraper
-4   Grader   -10   Bulldozer
-5   Landfill compactor   -11   Trencher
-6   Loader

2.3.2 Whole-body vibration database

A centralised database created by the National Institute for Working Life (2003) was reviewed for this chapter. Table 2.3 presents the data extracted from the database on a variety of earthmoving machinery in comparable task environments to those found in the United Kingdom.

The database was created from research reports in a variety of working conditions, with the vibration magnitudes presented being specific to each situation. Although this database proves to be a good starting point for accessible knowledge on vibration magnitudes there are many problems associated with it. Firstly it was produced in Sweden where the types of machines used and type of operations can vary considerably from other places in Europe or further a field (e.g. the most common use for wheel loaders is snow clearing). Secondly there are no details presented on the driver of each vehicle, the seat type is only specified in some cases, along with the age of the vehicle and there is no mention of the speed the vehicle was travelling (if applicable). In addition to this only a small selection of the data specifies the frequency content of the vibration. Some of the terminology used to describe the type of vehicle can also be confusing, for example, a bulldozer has been described as "band excavator". This makes it difficult to compare the data with other research in this area.

Table 2.3. Summary of vibration exposures reported on NIWL database (2003).

Publication, Date & measurement	Vehicle Type	Exposure Values (m/s² r.m.s.)			Task
		X	Y	Z	
Centralised European database for whole-body vibration (2003) National Institute for Working Life, North Umea, Sweden

All measurements from the database were made in accordance with ISO 2631 (1997) | Loader - CAT 930 | 0.6 | 0.5 | 1.0 | Loading and distribution in gravel pits. |
	Loader – Yale 7500	0.6	0.7	0.6	Loading of broken rock in a rock pit.
	Loader – CAT 966C	0.5	0.4	0.7	Loading sand in a gravel pit.
	Loader – Hanomag 55D	0.9	0.7	0.3	Working in a quarry on the clay excavation.
	Band Excavator – CAT D6 (i.e. bulldozer)	1.0	0.6	0.6	All three excavators were working in a quarry on clay excavation.
	Band Excavator - Iveco Allis FD14	0.8	0.6	1.8	
	Band Excavator – Hanomag D600	0.6	0.5	0.3	
	Tractor excavator – Volvo BM616-B	0.4	0.3	0.4	Digging of cable trench, travelling on an asphalt surface.
	Tractor excavator – Hymas 474 C-4	0.2	0.2	0.2	Pole setting.
	Road Grader – CAT 14	0.2	0.2	0.6	Road grading on a gravel road surface
	Road Grader – CAT D5B, Band (Known as Dozer Crawler)	0.3	0.2	0.1	Grading and shovelling clay over the clay surface.

2.3.3 Surveys of whole-body vibration in earthmoving machines

Numerous studies have investigated whole-body vibration exposures in commercial, industrial and off-road machines. The following section discusses the various different vibration exposure surveys and highlights the similarities and the differences between the methodologies and findings of the studies.

21

Boulanger *et al.* (1978) conducted measurements in a working quarry on a small selection of machines. The maximum r.m.s. values of the weighted accelerations from a one-third octave analysis were presented in the x-, y-, z-axes for a mechanical scraper (0.45, 0.4 and 1.2 m/s²), bulldozer without suspension seat (0.55, 0.5 and 0.6 m/s²) and bulldozer with suspension seat (0.55, 0.5 and 0.25 m/s²). The vertical vibration magnitude experienced in the mechanical scraper should be of concern as it exceeds all vibration exposure limits currently in place when multiplication factors are applied. It could be argued that due to the age of this study the results could no longer be valid with the advancement in machine design and working conditions over the past 25 years, in addition to the methods used to calculate the vibration values. However a recent study by Cann *et al.* (2003) found comparable data for mechanical scrapers with vertical vibration magnitudes ranging from 1.3 –2.0 m/s² r.m.s. for the 4 measured machines (as presented in Table 2.4).

Mansfield (2003) assessed the impact of the Physical Agents (Vibration) Directive on the quarrying industry for WBV and the demolition industry for hand-transmitted vibration. The author measured vibration exposures for 13 quarrying vehicles working in a variety of quarries including rock, sand and gravel. The frequency weighted accelerations are presented in Figure 2.2, for all three axes of translational vibration. The worst axis of vibration for the loaders was either the lateral or the fore-and-aft, while the articulated dump trucks had the highest vibration magnitudes in the lateral direction. The remaining vehicles, including the off-highway dump trucks, telescopic handlers and bulldozers had the vertical axis of vibration dominating the operators' exposure. Mansfield (2003) concluded that the quarrying industry would only exceed the action value set out by PA(V)D. Therefore, health surveillance may need to be implemented as a way of monitoring the drivers exposed to vibration and other risk factors. As long as the workers are not going to be exposed to those vibration levels for longer than 40 hours a week then they will not exceed the limit value of the Directive.

Cann *et al.* (2003) explored the WBV exposure levels of heavy equipment operators in the construction industry. The vehicles tested ranged from smaller machines like skid steer loaders, wheeled loaders and graders to the larger machines, including dump trucks and bulldozers. Measurements were conducted in accordance with ISO 2631 (1997) although calculations were performed using BS 6841 (1987) weighting factors. The sampling frame for the measurements lasted for a 20-minute period. Both the r.m.s. and VDV were calculated in order to get a better measure for jolting or repeated

shocks. The dominant axis for each machine was either in the vertical or the horizontal axis, as follows:

The vertical (z-axis) was dominant in the following machines:	The horizontal (x-axis) was dominant in the following machines:
Graders	Bulldozers
Skid steer loaders	Excavators
Backhoes	Crawler loaders
Vibratory compactors	Compactors
Wheel loaders	
Dump trucks	
Scrapers	

It is not surprising to find a large discrepancy between the worst axis of vibration for the dump trucks and wheel loaders measured in Mansfield (2003) and those measured in Cann et al. (2003). This could be due to a number of factors including different types of terrain, operator driving style, speed of vehicle, job tasks performed. Unfortunately these specific details have not been published in either study, Mansfield (2003) identified that the dump trucks were working in a rock quarry while the wheel loaders worked in either a rock or sand and gravel quarry. Cann et al. (2003) made reference to the ground conditions, with the dump truck travelling on a soft ground, while the wheel loaders were working on a pavement area.

Although both studies conducted the measurements according to ISO 2631 (1997), Cann et al. (2003) used the frequency weightings and multiplying factors from BS 6841 (1987), this would result in lower horizontal vibration magnitudes than if the analysis had been performed using the ISO multiplying factors. Only the worst axis of vibration has been presented for each machine, this prevents the opportunity of applying the multiplying factors to the vibration magnitudes in the horizontal axes.

Table 2.4. Summary of vibration exposures reported by Mansfield (2003) and Cann *et al.* (2003).

Machine	Mansfield (2003)			Cann et al. (2003)	
	x-axis m/s^2 r.m.s.	y-axis m/s^2 r.m.s.	z-axis m/s^2 r.m.s.	Worst axis m/s^2 r.m.s.	Worst axis $m/s^{1.75}$ VDV
Articulated Dump Truck	0.65 ± 0.21 (0.46 – 0.87)	0.82 ± 0.14 (0.70 – 0.98)	0.61 ± 0.09 (0.54 – 0.71)	- -	- -
Rigid Dump Truck (Off-highway truck)	0.39 ± 0.02 (0.38 – 0.41)	0.41 ± 0.03 (0.38 – 0.43)	0.50 ± 0.11 (0.40 – 0.61)	1.21 ± 0.70 (0.7 – 1.7)	17.2 -
Track-type Tractor	0.98 -	0.91 -	1.10 -	0.92 ± 0.14 (0.6 – 1.1)	9.01 ± 2.60 (5.2 – 12.8)
Wheeled Loader	0.62 ± 0.15 (0.46 – 0.87)	0.58 ± 0.17 (0.32 – 0.74)	0.39 ± 0.12 (0.21 – 0.51)	1.16 ± 0.70 (0.7 – 1.7)	31.7 -
Crawler Loader	- -	- -	- -	1.01 ± 0.18 0.8 – 1.1	8.71 ± 1.91 6.6 – 10.4
Skid Steer Loader	- -	- -	- -	1.18 ± 0.63 (0.5 – 1.7)	9.64 ± 5.11 (4.3 – 14.5)
Scraper	- -	- -	- -	1.61 ± 0.30 (1.3 – 2.0)	14.9 ± 2.34 (12.2 – 17.9)
Grader	- -	- -	- -	0.55 ± 0.15 (0.4 – 0.7)	7.25 ± 2.67 (3.4 – 9.2)
Compactor	- -	- -	- -	0.91 ± 0.41 (0.5 – 1.3)	7.86 ± 3.45 (5.4 – 10.3)
Telescopic Handler	0.52	0.50	0.67	-	-

Values are mean ± standard deviation with the range in parentheses

A number of the studies mentioned previously looked at the vibration magnitudes experienced in excavators. One particular study conducted over 20 measurements on a range of excavators in a variety of working tasks and terrain (Gould, 2002). Due to

technical problems during the study only 19 exposure levels could be calculated from the measurements taken. These values are presented in Table 2.5 with the excavator vibration magnitudes recorded from other exposure studies.

Table 2.5. Meta-analysis of whole-body vibration in excavators

Study	Machine / Weight (in metric tons)	Task	Surface	x-axis	y-axis	z-axis
Gould (2002)*	ABS Compact / 4	Moving steel plates	Dry soil	1.42	1.42	1.56
(ISO Weightings)	Komatsu / 24	Earthmoving	Grass	0.49	0.36	0.34
	Komatsu / 17	Earthmoving	Asphalt	0.59	1.07	0.80
	Volvo / 29	Earthmoving	Wet soil/clay	0.53	0.83	1.03
	Kato / 12	Earthmoving	Rough gravel	0.32	0.26	0.54
	Hydrema / 15.2	Earthmoving	Fine gravel	0.35	0.47	0.60
	Komatsu / 7.5	Earthmoving	Wet soil	0.77	0.84	0.75
	Atlas / 13	Earthmoving/flattening	Asphalt	0.50	0.95	0.41
	Atlas / 14	Earthmoving/flattening	Asphalt	1.93	1.65	0.65
	Komatsu / 24	Moving rocks	Dry soil	0.41	0.73	0.86
	Caterpillar / 26.8	Moving rocks	Rock pile	0.35	0.47	0.60
	Komatsu / 21	Moving rocks	Rock pile	0.75	0.72	0.80
	Caterpillar / 26.2	Moving rocks	Rock pile	0.91	0.58	0.90
	Akerman / 20	Moving rocks	Dry soil/rock	0.65	0.67	0.89
	Volvo / 21	Flattening soil	Wet soil	0.80	0.17	0.58
	Komatsu / 29	Moving gravel/flattening	Fine gravel	0.46	0.67	0.59
Gould (2002)* cont...	Kobelco / 13.5	Moving gravel	Rough gravel	0.51	0.83	0.67
(ISO Weightings)	Kobelco / 13.5	Moving gravel	Rough gravel	0.68	0.90	0.93
	Komatsu / 24	Moving rocks and clay	Clay	0.64	0.32	0.57
Cann et al. (2003)** (BS Weightings)	Excavator x 14	Digging, earthmoving	Hard, soft or muddy	0.51 ± 0.28 (0.1 - 1.1)	~ ~	~ ~

Study	Machine / Weight (in metric tons)	Task	Surface	x-axis	y-axis	z-axis
Paddan & Griffin	Excavator	Digging soil	Soil	~	~	0.10
(2001)*	Excavator	Travelling 4 km/h	Tarmac	~	~	0.82
(ISO Weightings)	Excavator	Travelling 4 km/h	Tarmac	~	~	1.01
	Excavator	Travelling variable speed	Dirt track	~	~	3.03
Paddan et al.	Excavator	Filling trench	~	0.71	0.49	0.51
(1999)*	(foam seat)	Filling trench	~	0.59	0.38	0.24
(BS Weightings)		Filling trench	~	0.48	0.38	0.23
		Filling trench	~	0.92	0.81	0.61
		Idling	~	0.25	0.08	0.13
		Digging	~	0.28	0.18	0.25
		Digging	~	0.38	0.25	0.31
		Driving	~	0.56	0.46	0.81
	Excavator	Idling	~	0.03	0.04	0.04
	(foam seat)	Idling	~	0.03	0.06	0.04
		Idling	~	0.01	0.01	0.04
		Digging	~	0.14	0.06	0.08
		Digging	~	0.15	0.06	0.08
		Digging	~	0.24	0.11	0.09
	Excavator	Driving	~	0.43	0.32	1.00
	(suspension seat)	Idling	~	0.01	0.01	0.02

*Frequency weighted r.m.s. in m/s^2 , with multiplying factors according to ISO 2631 (x- and y-axis = 1.4, z-axis = 1.0)

It should be noted from Table 2.5 that Cann et al. (2003) and Paddan et al. (1999) applied the frequency weightings from BS6841 using W_b instead of W_k for vertical vibration and no multiplying factors. Although this is different to the other studies mentioned the differences between the weightings have been noted as being relatively small. The maximum difference varies from W_b giving 20% less weight than W_k at low frequencies to W_k giving about 25% greater weight than W_b at the highest frequencies, with the differences being much less at other frequencies. Therefore it could be possible that measurements made with instrumentation conforming to either standard could report the same value (Griffin, 1998a).

For the purpose of the meta-analysis presented in Table 2.5 the study by Paddan et al. (1999) has vibration magnitudes reported with the frequency weightings from BS6841

and the multiplying factors from ISO2631. Unfortunately Cann *et al.* (2003) only presented the values as a mean ± standard deviation for the worst axis so the same could not be applied.

In 1999 a whole-body vibration contract research report was published for the Health and Safety Executive (HSE), as part of a larger scale project aimed at identifying the number and distribution of workers exposed to hand-transmitted and whole-body vibration (Paddan *et al.*, 1999). The study measured three tracked vehicles within their 'excavator' category (as presented in Table 2.5); the type and size of excavators have not been specified in the report. Various operations were carried out depending on the vehicle, including digging soil with attached bucket (stationary), filling a trench using the bucket and attached spade (stationary) and digging tarmac (idling and driving). Out of the 16 sets of measurements only 2 of the measurements occurred whilst the vehicle was travelling. The most severe vibration magnitude for all the excavators was experienced during one of the measurements while the excavator was travelling. The median measured equivalent r.m.s. acceleration for all measurements was 0.91 m/s^2 for the ISO 2631-1 (1997) evaluation (most severe axis). Findings from a postal survey indicated that about 275,000 men were exposed to vibration from excavators within a one week period (Palmer *et al.* 1999).

Unfortunately Palmer *et al.*'s survey only provide estimates of vibration magnitudes for other types of earthmoving machines, including; Loaders (1.2 m/s^2), bulldozers (0.75 m/s^2), Graders (0.75 m/s^2) and Scrapers (1.5 m/s^2). These values are particularly high compared with the other vehicle types; greater numbers of exposure data are required to validate the values for these types of machines.

Paddan *et al.* (1999) suggested that '*a single estimate will not give a reliable indication of the vibration magnitude to which any individual is exposed, even if they reasonably reflect an average magnitude for all individuals using that category of vehicle*'. Furthermore, they added that the large differences between measurements are likely to be caused by several factors, including:

- Difference between vehicle designs
- Differences in the condition of vehicles and seats (wear and malfunction)
- Differences between modes of operation of vehicles (e.g. speed and road surface)
- Differences between operators in the manner of vehicle use.

27

Paddan and Griffin (2001; 2002) explored the WBV experienced in 100 vehicles, including excavators, dumpers, and tractors. The authors carried out the measurement according to both BS6841 and ISO 2631 in order to make comparisons between the standards. Findings indicated that ISO2631 tended to under-estimate the vibration exposure transmitted to the operator when compared with BS6841. This was evident for the vibration magnitudes of an excavator with suspension seat travelling on a dirt track; ISO 2631 produced a magnitude of 3.03 m/s^2 whereas BS 6841 produced a higher vibration magnitude of 3.27 m/s^2 for the seat. Excavators, loaders and dump truck drivers were observed to carry out most of their work in a fixed position, with forward or reverse driving required to move onto the next area to be excavated or load to be moved. Most of the time was spent sitting in the vehicle seat operating controls and levers while the engine was running (Paddan and Griffin, 2001).

The studies mentioned previously have surveyed a variety of different machines, with a large number choosing to measure excavators. It appears that excavators expose operators to a range of magnitudes depending on the type and the task performed. However, compared with other types of earthmoving machines they are not considered to be the most problematic for operators as the amounts of time driving on the tracks are usually short. In order to gain a clearer picture of the most problematic earthmoving machines a further meta-analysis was performed to focus more specifically on the problem machines that can be found in abundance throughout industry. Table 2.6 identifies specific studies that have measured the machines of interest. With the exception of Paddan et al. (1999) and studies by Mansfield (2003) and Mansfield and Atkinson (2003) the remaining studies in the meta-analysis were published after the formation of this thesis[1].

Out of all the machines highlighted in the table the bulldozers and articulated trucks have the worst overall profile for whole-body vibration exposure. Bulldozers run on tracks and are often tasked with smoothing over rough ground; the vibration is

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[1] It is important to acknowledge that when this PhD was formulated at the end of 2003 the current state of knowledge for measurement of whole-body vibration was still in its infancy. The amount of variability between machines, conditions, operators and work sites was unknown and limited data was available to make estimates of the vibration exposure experienced in a wide range of machinery. In response to the implementation of the Physical Agents (Vibration) Directive in 2002 there was an apparent need for improving this knowledge within the area.

dominant in the vertical direction for this type of machine. Articulated trucks tend to carry a variety of loads and can travel at higher speeds compared with most of the other machines. Subsequently the nature of the trucks tasks causes high dominant motion in the lateral axis, most likely due to the swaying of the machine during transit. The roller machines appear to have the lowest overall vibration profile, it would be unlikely for this type of machine to exceed the action value of the PA(V)D during an 8-hour working day. However, it is important to acknowledge the statistics are only based on data from four machines, and likewise for the articulated trucks and motor graders. The ability to characterise the whole-body vibration profile for a particular type of machine is still limited based on the sample sizes used in the current literature.

Table 2.6 Meta-analysis of WBV measurement studies presenting the r.m.s. ranges for specific categories of machines

Machine	Min	25th%ile	Median	75th%ile	Max	Axis	Studies
Bull-Dozer	0.33	0.51	0.66	0.91	1.00	X	Mansfield (2003); NIWL (2004); Scarlett & Stayner (2005a,b);Fairlamb & Haward (2005); VIBRISKS (2007)
(6 machines)	0.26	0.34	0.58	0.65	0.91	Y	
	0.44	**0.61**	**0.77**	**1.05**	**1.45**	**Z**	
Wheel Loader	0.28	**0.57**	**0.66**	**0.74**	**0.96**	X	Mansfield (2003); NIWL (2004); Scarlett & Stayner (2005a,b;2007); VIBRISKS (2007)
(16 machines)	**0.32**	0.53	**0.67**	**0.74**	0.92	Y	
	0.21	0.42	0.50	0.58	**0.96**	Z	
Articulated Truck	0.46	0.58	0.70	0.80	0.87	X	Mansfield (2003); Scarlett & Stayner (2005b)
(4 machines)	**0.70**	**0.76**	**0.85**	**0.94**	**0.98**	**Y**	
	0.54	0.56	0.58	0.61	0.71	Z	
Dump Truck	0.34	0.39	0.51	0.62	0.77	X	Paddan et al. (1999); Mansfield (2003); Mansfield & Atkinson (2003); NIWL (2004); Scarlett & Stayner (2005a,b); Fairlamb & Haward (2005)
(12 machines)	0.35	0.40	0.55	0.60	0.71	Y	
	0.37	**0.50**	**0.59**	**0.73**	**1.00**	**Z**	
Motor Grader	0.20	0.38	0.52	**0.63**	**0.70**	X	Fairlamb & Haward (2005); NIWL (2004)
(4 machines)	0.20	0.43	**0.53**	0.60	**0.70**	Y	
	0.50	**0.50**	**0.53**	0.58	0.60	**Z**	
Excavator	**0.14**	**0.40**	0.51	0.66	**1.93**	X	Paddan et al. (1999); Gould (2002); NIWL (2004); Scarlett & Stayner (2005a,b); Fairlamb & Haward (2005); Toward et al. (2005)
(41 machines)	0.06	0.31	0.40	0.72	1.65	Y	
	0.08	0.30	**0.57**	**0.80**	1.80	**Z**	
Roller	0.20	0.26	0.29	0.29	0.30	X	Umea (2004); Scarlett & Stayner (2005b)
(4 machines)	0.10	0.31	0.38	0.41	0.50	Y	
	0.30	**0.38**	**0.44**	**0.50**	**0.54**	**Z**	

(Data are presented with multiplication factors of 1.4 for horizontal and 1.0 for vertical axes. The worst axis is highlighted in bold)

2.4 Factors influencing the variability of whole-body vibration in vehicles

"When measurement is employed......the methods used may include sampling, which must be representative of the personal exposure of a worker to the mechanical vibration in question. The methods used must be adapted to the particular characteristics of the mechanical vibration to be measured, to ambient factors and to the characteristics of the measuring apparatus." (European Parliament and the Council of the European Union, 2002)

The statement above, from the Physical Agents (Vibration) Directive identifies some of the variability that needs to be taken into consideration when conducting vibration measurements. The vibration characteristics within any particular measurement can be affected by many variables, for example:

- The task the driver is conducting
- The speed of the vehicle
- The weight of the driver
- Suspension of the vehicle and of the seat
- The driving style adopted
- The changing road surfaces
- Adverse weather conditions
- Load being carried

The list above gives some indication of the complex set of variables that can influence the characterization, magnitude and direction of the vibration produced. The new vibration legislation has evidently increased the number of measurements conducted across Europe and within the UK. Consequently with the increase in vibration measurements there will be an increase in the number of inexperienced individuals who are required to take such measurements (Mansfield and Atkinson, 2003). Ideally the measurements will be taken by a skilled professional who has more expertise and understanding of the complications involved with assessing vibration emission and exposure levels.

Mansfield *et al.* (2003) suggests that "Vibration field measurements for risk assessments always assume that the vibration is nominally stationary, such that the sample measurement is representative of times when the vibration is not being measured". In a more recent account Mansfield (2005) highlights that "One of the problems with vibration measurement is that even if an incorrect method has been

31

used, most measuring equipment can still generate a number on a display. A non-expert has no way of knowing whether the measurement has been a success or not." (Mansfield 2005). The following sub-sections discuss the current knowledge on sources of variability for whole-body vibration exposure and how they should be considered during measurement and assessment of whole-body vibration.

2.4.1 Effect of measurement duration on reported vibration exposures

Previous field based studies on whole-body vibration have reported very short measurement times including as little as 30 second durations (e.g. Maeda and Morioka, 1998). This technique of producing a 'representative' vibration exposure can be valid if the vibration exposure is stationary for the full working day, i.e. when there is no change in the statistical properties of the vibration between time segments (Atkinson et al., 2002), and additionally, when the individual conducting the vibration measurement is experienced in such a technique (Mansfield, 2003).

There is no consensus between standards for an acceptable range of measurement times that should be employed. British Standard 6841 (1987) indicates a measurement time as short as 60 seconds for vibration exposures with low crest factors. International Standard 2631-1 (1997) states:

"The duration of measurement shall be sufficient to ensure reasonable statistical precision and to ensure that the vibration is typical of the exposures which are being assessed. The duration of measurement shall be reported........When complete exposure consists of various periods of different characteristics, separate analysis of the various periods may be required"

The standard continues to recommend a measurement period of 227 seconds for vibration signals at 0.5 Hz, when the analysis is done with a one-third octave bandwidth. That is based on requirements for signal processing to obtain a measurement error less than 3 dB (confidence level of 90%). This measurement time is comparable to the European Standard prEN14253 (2003) that states *"Where the daily work consists of long uninterrupted operations, a series of sample measurements, each of at least 3 min duration, should be taken at different times of the day....."* and also states that *"Where the daily work consists of operations of shorter duration, which are repeated several times during a working day......measurements can be made over complete work cycles."*

The recommendations on measurement duration in the standards mentioned previously have not been produced from scientific evidence. Considering that the number of assessments for whole-body vibration has been estimated by the Health and Safety Executive to amount to ~50,000 for the United Kingdom (Coles, 2002), it would be unwise to trust a figure that has not been assessed for its accurateness. With this increasing number of vibration assessments it could be beneficial to ascertain what the minimum measurement duration should be, in order to get an accurate representation of the full working exposure.

Despite there being a large number of studies investigating whole-body vibration in relation to back pain, seating dynamics, and exposure the number of research studies that have investigated long term vibration measurements is sparse. One study by Paddan (2000) looked at the influence of measurement period on the whole-body vibration experienced in army vehicles. Findings for the r.m.s. data suggested measurement periods greater than 5 minutes ensured the error was less than 1% for extrapolation to the full measurement duration of 10 minutes. The error increased to 6% for a 1 minute measurement duration compared with the full 10 minute period.

Since then research has taken the measurement duration further to assess changes in the vibration exposure throughout the entire working shift of a variety of commercial vehicle operators (Atkinson *et al.*, 2002), and analysed the data using pseudo measurement time epochs ranging from 10 seconds to 1 hour (Mansfield and Atkinson, 2003; Mansfield *et al.*, 2003).

Atkinson *et al.* (2002) discussed the preliminary findings of a larger scale study looking at long term vibration dose measurements for vehicle operators. The initial results presented in the paper were based on articulated HGV lorry drivers, with total measurements times ~2, 3, and 4 ½ hours, respectively. Practical problems associated with the semi-autonomous logging techniques were discussed accordingly, as it was discovered that driver movements caused 'artefacts' that masked the 'true' vibration exposure.

A number of solutions to this problem were considered, Atkinson *et al.* (2002) stated that "*one could filter the data using algorithms based on vehicle speed and/or SEAT values to remove all data where there is some element of doubt*". However, the author adds caution to this technique, as the filtering process could possibly remove true peaks in the data that are in fact caused by an end-stop impact. These end-stop impacts could result even at low speeds on roads where the driver is travelling over

speed bumps, for example. Alternatively or in combination with the previously mentioned idea, the possibility of eliminating the vibration magnitudes at the seat base, which indicate times where the engine is idle or off was also considered as a solution. However, the disadvantage for this resides in the fact that some vehicles engines will generate more low frequency vibration when idling compared with that at faster speeds (Atkinson *et al.*, 2002).

The second phase of the aforementioned study applied the filtering methods suggested, and continued to develop the analysis by partitioning the full working shift measurements into time epochs, using an unintelligent algorithm (Mansfield and Atkinson, 2003; Mansfield *et al.*, 2003). This enabled the authors to consider the effects of measuring for a variety of time frames, starting with 10 seconds and increasing up to a 60 minute measurement epochs. The time frames were then evaluated to decipher what the shortest acceptable time to measure for should be.

Mansfield and Atkinson (2003) only considered three commercial vehicles; Mansfield *et al.* (2003) extended their selection to 20 different vehicles. The average measurement time of the larger selection of vehicles was 391± 134 minutes (mean ± standard deviation) for the unfiltered and 185 ± 97 minutes for the filtered data, respectively. Each of the measurements lasted for the operator's full working shift. However, it became evident that many of these vehicles were not driven for the entire duration of the workers shift. In these instances the operator's daily exposure was calculated from the periods where vibration exposure occurred (i.e. during transit).

Findings of both studies demonstrated that the spread in the vehicles data substantially decreased as the measurement duration increased. This was evident in the vertical, fore-aft and lateral directions of vibration. The probability of a vibration magnitude occurring for any measurement of vibration within the full working day was calculated by Mansfield and Atkinson (2003); with the overall findings demonstrating that the shortest measurement time allowable should be 10 minutes, to give an accurate indication of the full daily exposure.

Mansfield *et al.* (2003) used set criteria according to ISO 8041 (1990) to evaluate whether the measurement data fell within an acceptable error margin. The coefficient of variation was calculated for each time epoch in order to accept or reject the measurement, based on the chosen error margins.

This method indicated that a measurement epoch of 10 minutes was sufficient when using a 25% variance level for the acceptance criteria. This finding is consistent with the previous study (Mansfield and Atkinson, 2003), however, a more defined acceptance criteria level of 12.5% indicated that the minimum measurement time should be 30 minutes, in order to be representative of the full daily working exposure.

The current research suggests that the longer the duration of r.m.s. measurement, the better the probability of the vibration value being close to the true daily exposure. The minimum measurement time of whole-body vibration in vehicles should be no less than 10 minutes in duration, with the ideal time of at least 30 minutes duration.

More recently Marjanen (2006) investigated long term continuous measurements of WBV in order to determine whether short term measurements can give an overall picture of the daily exposure of a machine or work phase. The results highlighted significant differences in daily exposure durations and vibration magnitudes; this was especially evident when the work required flexible hours. The daily exposure period showed large variability especially for the wheel loader, the main reason for this was the rapid change in winter conditions which determined the usage of the loader. The application of the findings from this particular study are limited considering the survey was carried out in Finland and the types of operations and conditions are not representative of those in the UK.

2.4.2 Effect of tyres and tyre pressure on whole-body vibration

Donati (1998) described a test method procedure for specific categories of industrial trucks devised for standard pr EN 13059 (2002). This standard has been established to encourage the collection of representative and comparable data for whole-body vibration measurements. The repeatability of measurements for the all-terrain trucks tested in this method was evaluated throughout a year to account for a range of temperature conditions. One of the vehicles vibration magnitudes fluctuated by ~40%, this was accounted for by the variation of tyre pressure. This sizable difference was not observed for the remaining two vehicles tested, where the vibration magnitudes only fluctuated by 10%. Nevertheless this effect of tyre pressure has been observed in a recent study by Sherwin et al. (2004), who quantified the amount of whole-body vibration transmitted to the operator for three tyre pressure settings (20, 50 & 60 psi respectively).

Sherwin *et al.* (2004) considered tyre pressure to be a factor influencing the transmission of whole-body vibration to operators. The authors conducted experiments on a Cut-to-length timber harvester using an experienced operator weighing 80 Kg to assess different tyre pressure settings of 138, 345 and 414 Kpa (20, 50 and 60 psi respectively). No statistical difference was found for the frequency weighted r.m.s. acceleration magnitudes between the three tyre pressures. Perhaps if the study was repeated with a larger sample size then the results would have been significant, especially as the vibration levels were observed to reduce considerably (55% reduction) on the operators seat in the vertical axes from the highest to the lowest tyre pressure settings. Hence, giving an indication that lower tyre pressure can reduce the severity of machine vibration in the vertical axes. The authors recommended that machines should be operated at lowest possible tyre pressure depending on the safe combination of tyre load, inflation pressure and speed. However it is important to highlight the major problem with the design of this study. The measurement durations for each test run only lasted 4 seconds, the validity of the findings must therefore be put into question.

Cann *et al.* (2003) compared the propulsion devices of the vehicles measured in their study. No statistically significant differences could be established between the vehicles with tyres and those that were on tracks (p=0.68). However, it should be noted that for the tracked category there were only two types of vehicles measured tracked loader and bulldozer, compared to the eight types of vehicles with tyres. Gould (2002) found a marginally higher mean vibration exposure level for the combined axes (1.52 m/s^2) of the excavators with tyres compared to the tracked excavators (1.24 m/s^2) that were investigated. However, only 4 of the 19 excavators had tyres so the comparison was unbalanced, this may have introduced bias.

There are many problems that can be identified with this type of analysis, the vehicles being compared are from different categories of machines, they are working on different tasks and terrain at different speeds, and operators controlling the machines will adopt a variety of driving styles. Therefore it is hard to make comparisons between the propulsion devices used when there are so many other factors affecting the results. Ideally a study of this nature would aim to control some of the factors by using the same operator, choosing similar machines for comparison, e.g. skid steer loader vs. a multi-terrain loader and a wheeled loader vs. tracked loader, and keeping the vehicles at the same speed. This control, however, is particularly hard to achieve while conducting the measurements in a field based setting.

2.4.3 Effects of road surface on whole-body vibration

It is widely known that changes in road surface and road roughness will have an impact on the amount of vibration exposed to drivers. One subjective assessment survey looked at the surface roughness characteristics and the perception of heavy vehicle operators in relation to rideability and comfort within their vehicle. The driver's worst rating was associated with the low frequency whole-body vibrations excited by the roughness wavelengths in the range of 4.55 to 19.5 m (Hassan and McManus, 2003). These ratings are particularly relevant to the drivers of off-road machines who will often experience low frequency vibrations while travelling over rough terrain. Despite this concern many studies have failed to analyse the influence of different surfaces and roughness on the magnitudes of vibration produced by such machines The type of surface is often recorded in exposure studies yet the study design fails to enable comparisons between terrains due to lack of other controlling factors, e.g. speed, driver, type of machine, task and so on.

One study has managed to distinguish between the road roughness, speed and the influence these factors have on WBV. Ahlin et al. (2002) investigated different road surfaces and categorised their roughness based on the international road roughness index. The differences in road roughness were found to affect the WBV levels of ambulance and truck drivers significantly greater than the differences in vehicle speed. However the measure used to calculated road roughness the 'international road roughness index' has been criticised for being a poor indicator of road roughness and poor predictor of whole-body vibration transmitted to the driver (Hassan and McManus, 2003).

Paddan (2003) also investigated the effects of road surface on the vibration magnitude of 21 work vehicles including, 10 cars, 4 vans, 6 lorries, and 1 mini bus. For the 5 axes of vibration investigated including z-floor, x-, y- and z-seat and x-backrest the vibration magnitudes for concrete were on average 23% higher than travelling over tarmac.

One type of road surface found in earthmoving machine environments is soil. The characteristics of soil can be influential on the vibration levels experienced by the operator. The movement of a machine over a particularly elastic deformable soil surface can significantly modify the natural profile of vibration spectra (Sherwin et al., 2004). More research is needed in this area to look at the effects of road surface, (especially surfaces relevant to earthmoving machines) on the vibration magnitudes experienced. There has been some interest in this area from the military perspective,

Von Gierke *et al.* (1991) produced a graphical representation of the typical vibration levels and frequency content encountered in a range of military and heavy vehicles over three types of terrain (presented in Figure 2.4). The main point to extract from this diagram is that as the terrain becomes rougher the range of the vibrations frequency content decreases and the acceleration value increases.
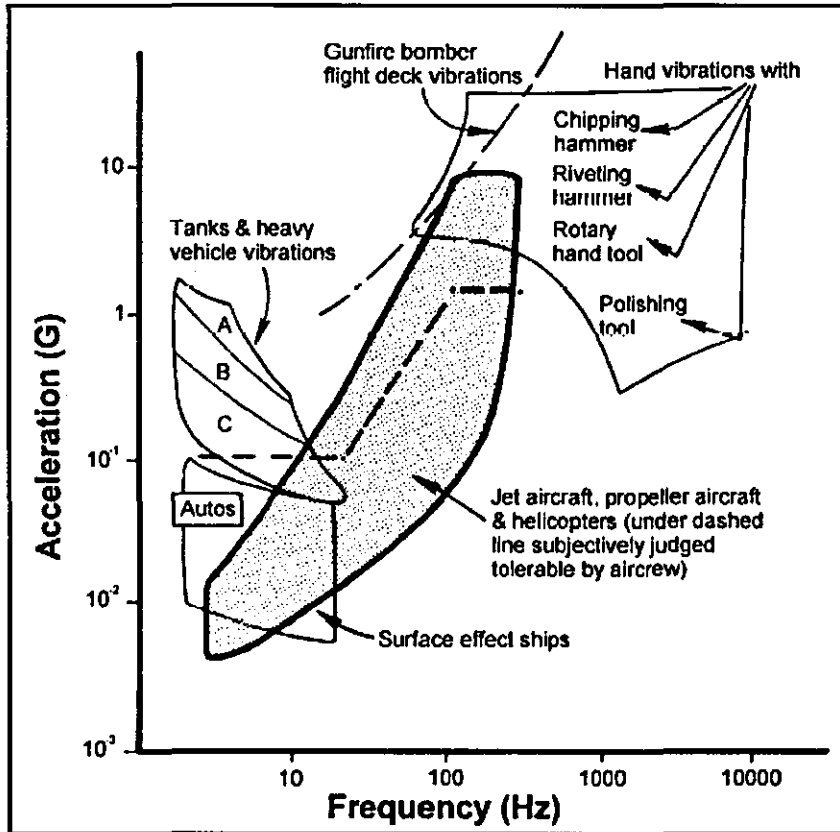
Figure 2.4 Characterization of vibration for land, sea and aircraft. Presented as approx acceleration ranges as a function of frequency. (A= rough terrain; B= Cross country; C= Concrete; 1G = 9.81 m/s2), Source: Von Gierke *et al.* (1991).

2.4.4 Effect of task and speed on whole-body vibration

Donati (1998) conducted tests on industrial trucks to identify the main parameters of the track and truck design that would be likely to affect the resulting vibration magnitude transmitted to the driver. The factors for the truck included the speed, the load and the tyres and for the operator their driving attitude and weight. A linear relationship was found between the vehicle speed and weighted vertical vibration for a 1.5 ton counterbalance truck.

Cann et al. (2003) made a statistical comparison of the mobility of a range of heavy construction equipment. The mobile equipment was found to have significantly higher levels of WBV (P<0.05) than the stationary vehicles. Thus, also giving an indication that vibration levels will increase with increasing speed. Although a relationship has been established between speed and whole-body vibration magnitudes the correlations between these two variables have not been widely established.

One study concerning professional drivers of all-terrain vehicles (Rehn, 2004) looked at the different stages of a harvester's loading cycle. Over 170 measurements were made in total throughout the four stages of the cycle; travelling without load (unladen), loading material, travelling with load (laden) and unloading the material. The mean vibration acceleration values for the root-mean-square (r.m.s.) and the vibration dose value (VDV) for each stage of the cycle are presented in Figure 2.5. Overall the mean vibration values were highest during the travelling activities, i.e. when the vehicle was travelling at its highest speeds. Travelling unladen resulted in higher vibration magnitudes than travelling laden, most likely as a result of the extra weight being carried. Loading also tended to produce higher vibration levels compared with unloading the vehicle; this is possibly due to the impact with the loading implement and the ground.

One way to determine the extent of the uncertainty in the measurement is to calculate the variation found between loading cycles. Pinto et al. (2005) measured the amount of uncertainty in vibration A(8) values in a range of different machines. One of the findings suggested a large proportion of the variability was attributable to differences between loading cycles. However, the amount of difference between loading cycles was not discussed in the study.

1.69 ± 0.60 m/s² r.m.s.
(range 0.46 - 3.08)

Travel unladen
(70 trials)

6.18 ± 2.51 ms-1.75   VDV
(range 2.49 - 17.77)

0.41 ± 0.12 m/s² r.m.s.
(range 0.26 - 0.63)

Unloading
(24 trials)

2.66 ± 1.11 ms-1.75 VDV
(range 1.39 - 6.50)

Harvester

0.55 ± 0.18 m/s² r.m.s.
(range 0.29 - 0.89)

Loading
(27 trials)

4.68 ± 2.50 ms-1.75 VDV
(range 2.35 - 12.84)

1.10 ± 0.53 m/s² r.m.s.
(range 0.52 - 2.62)

Travel laden
(50 trials)

3.57 ± 1.69 ms-1.75 VDV
(range 1.20 - 8.85)
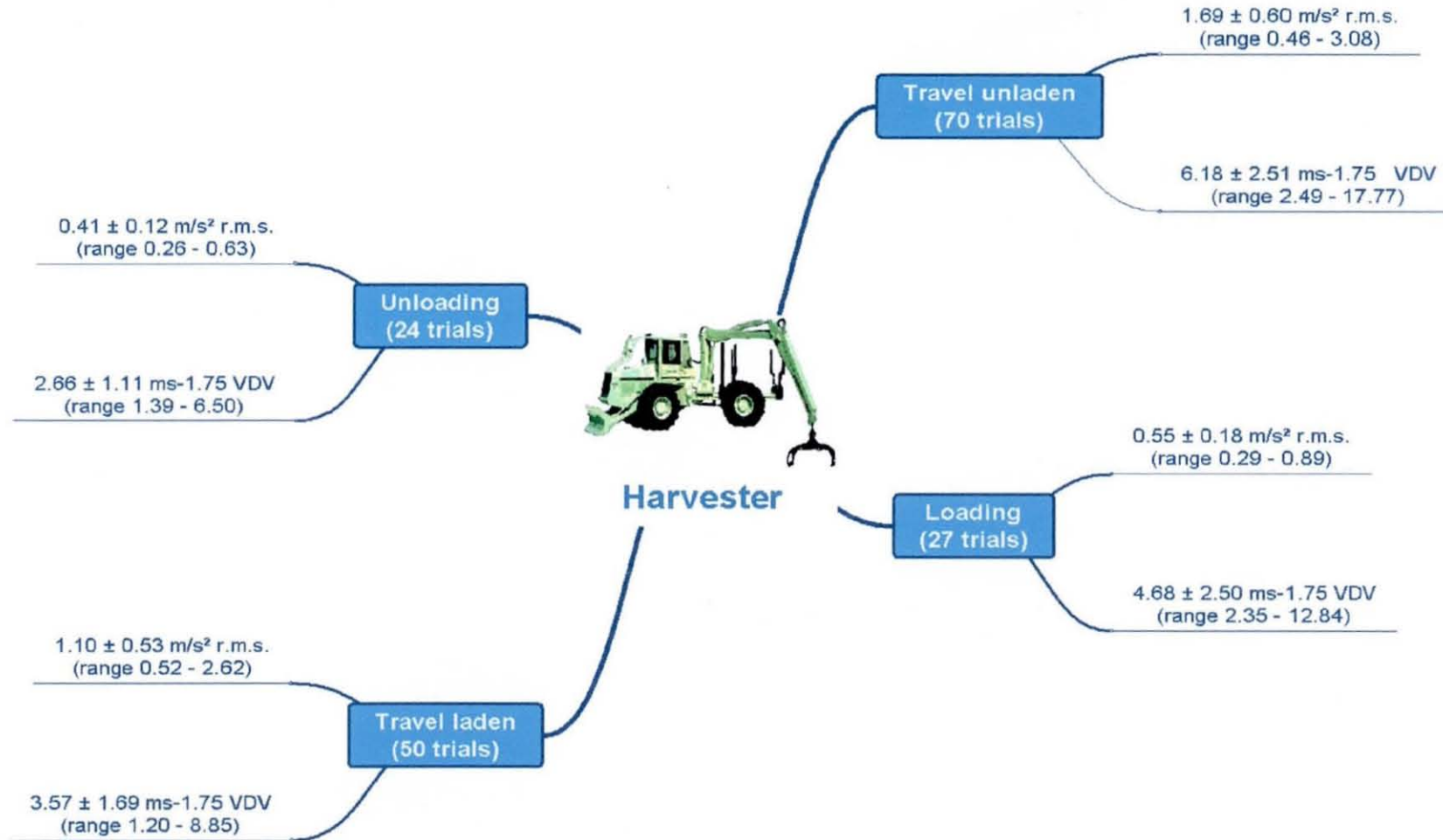
Figure 2.5 Vibration magnitudes for a harvester during a loading cycle, from Rehn (2005). Values are mean ± standard deviation for the root-mean-square (r.m.s.) and the vibration dose value (VDV), with the range in parantheses.

There have been attempts to measure the variation in loading cycles; Rehn *et al.* (2005) quantified the variability in loading cycles for forwarder machine operators. The results highlighted large amounts of variability for the whole-body vibration exposures, therefore suggesting that different conclusions could be made regarding a health risk assessment depending on which cycle was sampled. A breakdown of the loading cycle found that operators were exposed to the highest vibration magnitudes during travelling tasks and while the vehicles were travelling empty. There was up to a 36% variation between measurements while the vehicle was travelling empty, and this was largely dependent upon forwarder model and terrain type. This was contrary to travelling with a load (48% coefficient of variation), the type of forwarder and operator was found to be the most important predictors for variation, during this particular task. However, it is important to also consider that a percentage of the variation could be due to the difference in measurement durations. Some measurements for travelling were only 16 seconds in duration, with the longest measurement of 892 seconds.

Kittusamay (2000) suggests that the relative variance is more dependent on differences in the specific tasks performed rather than the equipment being used or the operator using the equipment. This was based on the findings from a sample-to-sample study of 13 specific tasks. Of these tasks 54% had a coefficient of variation below 10% and the remaining 46% had coefficients of variation ranging from 12.7% to 48.8%. These studies had different methodological approaches which could account for the different conclusions drawn from the results. Rehn *et al.* (2005), discussed previously, focused on variation in 3-axes of vibration for 11 forwarder machines (forestry log transportation) with 11 operators and broke down the tasks into travel empty, travel loaded, loading and unloading. Kittusamay (2000) focused on variation in the vertical direction for 3 backhoe loaders, 4 excavators and 1 loader with 8 operators and broke down the tasks into low/high idling, chip concrete, digging, riding, smoothing rocks and loader tasks. Considering that most machines will be assigned to individual tasks based on the ability of that machine it is probable that they will also produce different amounts of variation within their work cycles. A larger scale study is needed to understand and characterise the differences between machine categories and their related tasks.

2.4.5 Summary for whole-body vibration exposure

Many studies have investigated whole-body vibration exposure in a variety of machines. Some have chosen the controlled conditions of an ISO ride vibration test track (e.g. Scarlett *et al.*, 2002), while others have opted for the less controlled but

more realistic conditions in different working environments (e.g. Figure 2.3). Unfortunately the lack of comprehension and coherence between the relevant standards has resulted in an abundance of variety when it comes to the measurement techniques and assessments used. With vibration exposures being assessed using the older version of ISO2631-1 (1985), the British Standard 6841 (1987) and others with the current version of ISO2631-1 (1997). If the older ISO standard was used then the data cannot be used to judge relative severity of the vibration in different axes without consideration of the differences in the frequency weighting methods, as previously discussed in Section 2.2 (Griffin, 1998a). With the implementation of the Physical Agents (Vibration) Directive there is an increased need to characterise whole-body vibration exposures across industry using the methods specified in the Directive and ISO. However, standardisation of the methods used will not eliminate the amount of variability inherent to measurement and assessment of whole-body vibration exposure. Therefore a greater understanding and quantification of this variability is essential for progress and to ensure the correct assessments and mitigation strategies are applied in order to reduce the likelihood of occupational disorders in the driver population.

2.5 Factors influencing the variability of individual responses to whole-body vibration

Characterising the profile of machine vibration and work environments is one way to develop the understanding of the potential health and safety risks facing operators during their daily work. However, only focusing on machine measurements will not provide insight into the whole picture of emission and exposure. In order to fully characterise whole-body vibration environments and the operators using the machines it is important to quantify the differences observed between individuals and between tasks on the effects of whole-body vibration exposure.

The type of task performed by the machines can influence the working posture of the operators. Depending on the machine and task operators have been found to adopt a number of different postures, including; twisted necks during underground mining tasks (Eger et al., 2006), flexed or twisted trunks during excavating tasks (Kittusamy and Buchholz, 2001) repetitive arm motions and awkward static postures, also during excavation (Buchholz et al., 1997), and static postures during fork lift operations (Bovenzi et al., 2002). Exposure to awkward postures and whole-body vibration can result in localized fatigue or pain and contribute to the development of musculoskeletal disorders. In addition the seated posture itself can lead to inactivity that may cause injury (Magnusson and Pope, 1998). Therefore it is important to measure the postural

requirements of the work, when characterising whole-body vibration in a work place, to ensure a holistic view of the operators exposure is adopted (Kittusamy and Buchholz, 2004)

A review by Kittusamy and Buchholz (2004) found awkward postures to be the consequence of improper cab design and work procedures. Some of the characteristics of a poorly designed cab were highlighted by the authors; poor visibility of the task, limited room in the cab, excessive forces required to operate levers/pedals, and improper seat designs. The characteristics of the seat design can alter the posture depending on the; height and inclination, position and shape of backrest, and the presence of armrests (Magnusson and Pope, 1998).

Magnusson and Pope (1998) recommend the following considerations should be taken into account in all kinds of work to help prevent musculoskeletal disorders or to reduce the risk of impairment post injury;

- Provide the possibility for variation of sitting posture or variation between standing and sitting
- Avoid flexed, twisted, and hyper-extended standing postures
- Avoid extreme postures of the head, especially neck flexion under WBV
- Avoid work with unsupported arms
- Provide a seat with sufficient inclination and a good back support. In a vehicle, good vibration damping characteristics
- Avoid driving or lifting in flexed or twisted postures. Avoid lifting directly after driving
- Avoid prolonged sitting in constrained or fixed postures without stretching

Zimmerman *et al.* (1997) carried out a questionnaire survey to determine the prevalence of musculoskeletal symptoms among operators of heavy earthmoving machines, including number of lost work days and doctors visits. The two greatest body parts with musculoskeletal symptoms included both the lower back (60%) and the neck (44%). Interestingly the three variables assessed (missed work, doctors visits, and body part symptoms) were largely dependent on the type of equipment being used, including; backhoe loaders, dozers, scrapers and loaders. Thus suggesting machine specific issues can arise depending on the task demands and exposure within each machine. Although there has been some attempt to characterise different postural requirements under exposure to vibration, there has been little attempt to

determine which types of earthmoving machines expose operators to the worst types of conditions. It is important to characterise the hazards experienced in different types and models of machines and to determine if these hazards are representative for those experienced across a range of different work sites. Furthermore, it is important to ensure the real working postures highlighted above can be accurately reflected in the modelling of human response to vibration. Currently there are only a few studies that have attempted to accurately reflect the working postures of earthmoving machinery operators. The Physical Agents (Vibration) Directive also requires employers to consider improving the layout of cabs as a method of minimising risk, but gives no guidance on how cab layout might interact with vibration.

The following sub-sections aim to: highlight the current state of knowledge regarding the human responses to whole-body vibration, identify where further developments are needed, and to outline the different ways of assessing the responses.

2.5.1 Physiological responses to whole-body vibration

The human body relies on a number of different structures and mechanisms to help regulate the transmission of shocks and vibration through the body, including; bone, cartilage, synovial fluids, soft tissues, joint kinematics, and muscular activity (Cardinale and Wakeling, 2005). Differences in vibration frequencies have been found to alter the activities of the autonomic nervous system. Jiao *et al.* (2004) found that vibrations at 6 Hz influenced both sympathetic and parasympathetic nerve activities, while at 1.8 Hz the vibrations primarily influenced parasympathetic nerve activities. The findings were correlated to ratings of driver fatigue and according to the authors accumulation of both mental stress and physical fatigue can differ depending on the vibration frequencies.

Changes in joint kinematics and muscle activity can be controlled on a short time basis and are used by the body to change its vibration response to external forces. Muscles can alter their damping to a vibration input by changing the tissue stiffness. Activated muscles will absorb more vibration energy compared with muscles in rigor (Cardinale and Wakeling, 2005). Muscular activation remains a function of personal skills and habits, but Conti (2000) believes it can be optimized with training and experience. This in turn could help to minimize the transmission of large forces in the low back structure.

2.5.2 Biomechanical responses to whole-body vibration

Biomechanical responses involve two types of loading; external and internal to the body. External load is commonly caused by forces acting on body parts, and internal load is caused by muscles or other soft tissues within the body. When vibration enters the body it is then transmitted through muscles, bones and tissue, until eventually the energy is lost. Several measures are available that can give estimations of the load placed on the body, both subjective and objective (Thuresson, 2005).

Different objective methods can be applied to evaluate biomechanical responses to whole-body vibration. Some of the most common methods include mechanical impedance, apparent mass and seat-to-head transmissibility. The measurement of the mechanical impedance or apparent mass can help in the understanding of the dynamic response of the human body to vibration. It can be used to show internal resonances of body parts and therefore provide an indication of the frequencies of vibration to which the body is most sensitive. Researchers are interested in the resonance frequency of the human body as the '*vibration at that frequency will be amplified by a build-up of stored energy in the repeated stretching and compression of tissue*' (Mansfield, 2005). Calculations of apparent mass and transmissibility are presented in the methods section of this thesis (Chapter 3).

In addition to providing understanding of the fundamental human responses to vibration the information can also assist in the design of protective suspension seats that can provide some isolation from vibration above 3 Hz. Most conventional seats resonate around 4 Hz and provide isolation above ~6 Hz with an adults sitting weight (Mansfield, 2005).

During sitting, the lumbar spine supports the upper body mass so that the load in the lumbar spine is about 450N. The lumbar spine is situated close to the human/seat interface and therefore the input forces might provide an estimate of the forces in the lumbar spine. Apparent mass data indicate that at 3 Hz the force will be about 20% higher (540 N) and between 10-15 Hz the force will be about 50% lower (225N) (Sandover, 1998). Many studies have been performed to investigate the apparent mass of subjects exposed to translational whole-body vibration (e.g. Fairley and Griffin, 1989; Mansfield and Griffin, 2000; Mansfield and Griffin, 2002; Rakheja *et al.*, 2002; Wang *et al.*, 2004). One consistent finding across studies is that seated subjects' fundamental resonance frequency exists in the region around 4 - 5 Hz for vertical vibration exposure.

Fairley and Griffin's (1989) model was developed from a large study where the apparent masses of 60 subjects (males, females, adults and children) were measured. Subjects were exposed to vertical vibration with a magnitude of 1.0 m/s² r.m.s. and with no backrest support. The apparent masses of most subjects had a peak at just below 5 Hz. The authors found the peak in the apparent mass to be non-linear with vibration magnitude. At low magnitudes of vibration the peak occurs at higher frequency than at high magnitudes. This phenomenon is known as a 'softening effect', whereby the body loses stiffness as acceleration magnitude increases (Mansfield, 2005), it has been explored by a number of researchers (Hinz and Seidel, 1987; Mansfield, 1998; Mansfield and Lundström, 1999; Mansfield and Griffin, 1999).

The apparent mass measurement may not be affected much by motions of body parts far from the driving point at the seat. Therefore the measurement of transmissibility through the body could be used to understand both the dynamic response of the body parts and the relative movement between the head and the body or between the head and the driving point. Transmissibility data may also be useful to identify the mechanisms contributing to the characteristics of the apparent mass. Transmissibility represents the ratio between the motion at one measurement point in the body and the motion at another point, for example the transmission from the seat to the head or the seat to the spine, It can also support predictions of movement from a drivers seat in a field setting, but carrying out the measurements in a laboratory environment (Mansfield, 2005).

Measurements of seat-to-head transmissibilities have been conducted for many years (e.g. Messenger and Griffin, 1989; Paddan and Griffin, 1988a, 1988b, 1993, 1994 and 1996; Matsumoto and Griffin, 1998). The studies will be described in more detail in Chapter's 7 and 8 of this thesis. The fundamental resonance for the seat-to-head data supports the findings of the apparent mass measurements, where a peak in resonance is observed between 4 -5 Hz (highlighted in Figure 2.6).
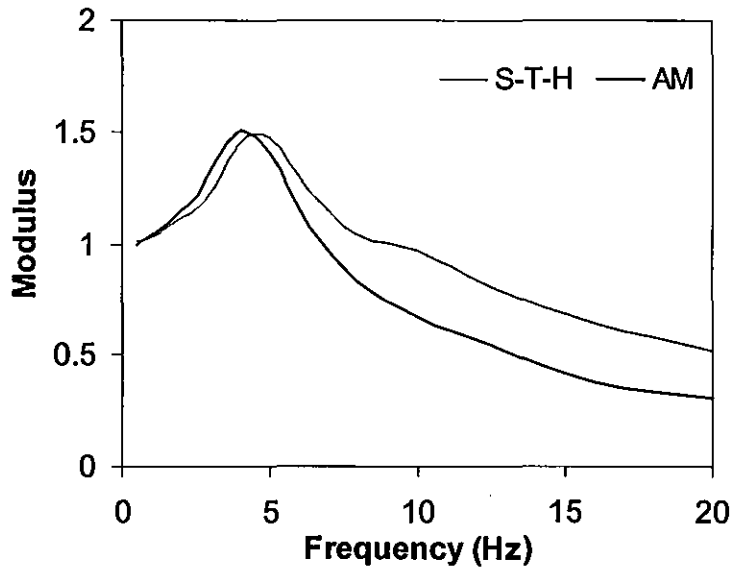
Figure 2.6 Idealized values for seat-to-head (S-T-H) and normalised apparent mass (AM) from ISO5982 (2001).

Figure 2.6 is based on International standard 5982 (2001) idealized curves for the biomechanical responses of the seated human body. The standard included studies if they conformed to a well-defined and restricted range of similar conditions, as follows:

- Seated individuals
- Exposed to sinusoidal or broad-band random vertical vibration
- Unweighted r.m.s acceleration lower or equal to 5 m/s^2
- Feet resting flat on the vibrating platform (including feet hanging freely for applications of seat-to-head transmissibility)
- Back unsupported
- Individual body masses are within 49 kg to 93 kg

It is suggested in the standard that 'in view of the restrictions imposed on posture and vibration excitation levels, the values defined for each of these functions might be more applicable to drivers of off-road, heavy road and industrial vehicles.' This could be debatable considering the types of applications mentioned are likely to involve more complex conditions than those specified for inclusion in the standard. Drivers of such vehicles may have contact with a backrest, as well as armrests and they may adopt a variety of driving postures (like the ones discussed at the start of Section 2.5). The

standard also fails to take account of the human responses to vibration in additional axes, including horizontal and rotational movement.

Paddan and Griffin (1994) suggested that *'caution should be exercised in the interpretation of any single curve showing an 'average' transmissibility of a group of subjects'*: Sitting posture and individual differences in body dimensions including height and weight have explained most of the variation in seat-to-head transmissibility (Messenger and Griffin, 1989) as opposed to differences within an individual's transmissibility. Paddan and Griffin (1994) found the median data for 12 subjects to differ greatly from the transmissibility of some of the subjects. For a back-off (no backrest contact) condition inter-subject variation was found to be up to 18 times greater than intra-subject variability.

Providing a backrest has been shown to increase the vibration transmissibility at frequencies above 5 Hz, with no backrest contact there is typically a resonance around 4 – 5 Hz and with a backrest the resonance frequency increases to around 6 – 7 Hz (Paddan and Griffin, 1988a, 1988b, 1993, 1994 and 1996). Wang *et al.* (2004) found the apparent mass response to be strongly influenced by combined effects of hand position and back support condition, while the peak magnitude was further affected by the seat height. Above the primary resonance up to 18 Hz the apparent mass magnitudes generally increased when the back was supported. Backrests have also been found to increase vibration discomfort, with subjects found to be particularly sensitive to vibration in the fore-and-aft direction (Parsons and Griffin, 1982).

The amount of variation found in the transmission of vibration due to postural changes has been explored by a number of researchers (e.g. Paddan and Griffin, 1988a; Messenger and Griffin, 1989; Kitazaki and Griffin, 1998; Hinz *et al.*, 2002; Howarth, 2003). It appears the studies have not addressed the types of postures adopted by many operators of heavy machines. One more recent study did include an assessment of a twisted posture that could typically be observed in operators of earthmoving machines (Mansfield and Maeda, 2005). The authors evaluated the apparent masses in the range of posture conditions for subjects exposed to vibration. In a dynamic twisting posture, including a continuous arm motion task, the peak in the apparent mass was attenuated, indicating a different biomechanical response was experienced in the moving posture. It was suggested that the change in biomechanical response was due to either the extended arms acting as a passive vibration absorber or that the twisting action interfered with the usual acceleration-muscle feedback system. The authors found a small but significant increase for the resonant frequencies in the

twisted static posture compared with the back-off upright posture. The relationship reversed at frequencies above 10 Hz however no statistical analysis was presented for such frequencies.

Wang *et al.* (2004) suggests that although the strong influence of sitting postures on the biomechanical response has been recognized, the effects of variables influencing posture have not been systematically assessed.

Zimmerman and Cook (1997) investigated the effects of vibration frequency and postural changes on subjects' response to seated WBV exposure. They found significant interactive effects between pelvic orientation, vibration frequency and seated human's response to WBV. The authors concluded from the results that proposed standards should consider occupant posture during vibration exposure if their intent is to decrease the incidence of WBV associated low back pain. Kitazaki and Griffin (1998) reinforces this notion by suggesting that any forces causing injury from WBV will not be well predicted by biomechanical models incapable of representing the appropriate body motions and the effects of body posture.

Part 1 of ISO 2631 (1997) does acknowledge factors that may affect human response to vibration; *'population type (age, gender, size, fitness, etc); experience, expectation, arousal and motivation (e.g. difficulty of task to be performed); body posture; activities (e.g. driver or passenger); financial involvement.'* Annex B provides more informative information on these effects suggesting that *'it is sometimes assumed that environmental factors such as body posture, low temperature, and draught can contribute to muscle pain. However, it is unknown if these factors can contribute to the degeneration of discs and vertebrae.'*

British standard 6841 (1987) also discuses influential factors *'body positions and seating conditions may be expected to be particularly important in determining the hazardous effects of vertical (z-axis) WBV. However, these factors differ in each application and are not enumerated in this standard'.....'The perception of body orientation and postural stability can also be affected by vibration.'*

CEN Report 12349 (1997) provides greater detail compared with the International and British Standard; *'WBV containing frequencies within the fundamental resonance frequency of the body may cause severe motion of the shoulders. This leads to increased response from the muscles in the body region. Many drivers complain about disorders in the neck-shoulder. Several ergonomic factors may be suspected to give*

raise to these complaints, e.g. twisted head postures, hand-lever manoeuvring, stress and WBV.'

International Standard 2631-part 5 (2004) defines a method of quantifying whole-body vibration containing multiple shocks in relation to adverse health effects on the lumbar spine. It is stated that the assessment method is *'based on the predicted response of the bony vertebral endplate (hard tissue) in an individual who is in good physical condition with no evidence of spinal pathology and who is maintaining an upright unsupported posture.'* In Annex A further reference to health effects is presented *'The peak compression in the spine is affected by anthropometric data (body mass, size of endplates) and posture......A bending forward or twisting posture is likely to increase the adverse health effect'.* Despite this acknowledgement of postural differences in adverse health effects, twisted or bent postures are not mentioned in the equation used for assessment of risk. The R (risk) calculation includes a constant representing the static stress due to gravitational force, this constant is given as 0.25 MPa and it is stated that this *'can be normally used for driving posture'.* There are no measures or guidance given for occasions when the "driving posture" includes bending or twisting. Annex B does highlight that *'different postures can change the way the body responds to multiple loads, inconsistent with the model constraints'.*

Even though these standards and guidance have acknowledged additional factors influencing the human body during exposure to vibration they fail to provide any detail explanation or justification for how to manage them. Understanding of how typical working postures interact with the vibration and how this influences the risk to individuals is still unknown.

2.5.3 Psychological responses to whole-body vibration

'Vibration can interfere with the acquisition of information (e.g. by the eyes), the output of information (e.g. by hand or foot movements) or the complex central processes that relate input to output (e.g. learning, memory, decision-making)' (Griffin, 1998b)

In laboratory studies vibration has been observed both to improve and to reduce task performance. This may be because it fatigues or arouses or, because of increased task difficulty, motivates (BS6841, 1987). In 'normal upright' postures whole-body vibration has been found to impair performance, in terms of tasks requiring visual acuity and manual control (e.g. Lewis and Griffin, 1978; McLeod and Griffin, 1989; Griffin, 1990). Tracking performance has also been compromised during whole-body

vibration exposure (Smith et al., 2004). Reaction time performance and mental workload have also been impaired by the combined exposure to noise and vibration (Ljungberg et al., 2004).

The only standard to attempt an assessment procedure for activity interference and vibration exposure is British Standard 6841 (1987). The standard suggests that four processes may result from vibration exposure;

- The acquisition of information via the senses

- Information processing

- Levels of arousal, motivation or fatigue

- Intentional actions.

According to the standard there is limited evidence to suggest that whole-body vibration directly affects cognitive processes. This is partly due to the difficulty in trying to separate the direct effects from those caused by changes in arousal or motivation. The standard acknowledges that '*arousal, motivation and fatigue are aspects of the behavioural state of an individual and, although they are not readily quantifiable, their effects can be very great.*' Currently the effects of vibration cannot be easily or reliably predicted and therefore are not specified in the standard. The influence of vibration effects on task performance can be highly dependent on the type of task being performed.

Weighting W_g is specified in BS6841 for the purpose of quantifying the severity of motions which may interfere with activities using hand control and vision, when the dominant motion is in the range from 1.0 Hz to 80 Hz. W_d is used for the horizontal axes at the seat but it only relates to hand control.

The guidance provided in the standard is primarily intended for environments with low crest factor motions. Therefore if the crest factors exceed 6 or when only long term effects of vibration are of interest the standard advises to seek additional guidance from the scientific literature. The standard also fails to '*cover the potential effects of intense vibration on human performance and task capability since such guidance depends critically on ergonomic details related to the operator, the situation and the task design.*' In a separate section it is suggested that '*although the potential effects on human performance are not covered, most of the guidance on whole-body vibration measurement also applies to this area.*'

2.5.4 Summary for human responses to whole-body vibration

Human responses to vibration are complex; psychological, physiological and biomechanical components can vary greatly depending on the characteristics of the vibration and on the characteristics of the human. Responses have not been fully understood despite large numbers of studies in this area attempting to address the issue. Developments are needed in this area to improve the understanding of the different responses and the interactions between them in order to characterise the human response to vibration. Currently the standards acknowledge the influencing factors that can alter the response to vibration, yet they still cannot provide clear advice on how postures and vibration interact.

2.6 Conclusions

This chapter reviewed the available literature on methodologies adopted for the measurement and assessment of whole-body vibration in vehicles. Exposure studies of vibration experienced in off-road machines and the human response to whole-body vibration were also reviewed. The literature has demonstrated that:

- Current standards that are concerned with the measurement and assessment of whole-body vibration are not consistent for both the methodologies employed and the magnitudes outlined for health risks.

- Guidance within the standards lacks clarity on what methods to use in particular situations, which might result in collection of data that may not be valid and representative of the vibration exposure.

- Greater knowledge is required to generate a dose-response relationship of whole-body vibration and health effects to ensure that current standards guidance and the new European limits for vibration exposure are appropriate.

- Whole-body vibration magnitudes are higher in off-road compared to on-road machines, yet the amount of studies trying to full characterise vibration profiles particularly in earthmoving machines is still small.

- Many factors influence the amount of vibration transmitted to the driver, including: machine type, speed, terrain, suspension characteristics, task, driving style, driver characteristics, tyre pressure.

- The amount to which environmental and vehicle factors influence the vibration magnitude has not been widely documented. There is a need to quantify how much variability exists in order to understand how this will affect a health risk assessment.

- Little attempt has been made to characterise working postures with vibration exposures. There is a need to understand what postures are realistically adopted by operators in order to fully characterise the risk imposed on them during their working lives.

- Although Standards acknowledge that posture plays an important part in the risks arising from whole-body vibration exposure, there are no methods for using posture within a vibration risk assessment.

- The shortest measurement time for collecting whole-body vibration data should be no less than 10 minute duration, with a preference of collecting for 30 minutes where possible. This will help ensure the data being collected is representative of the vibration exposure for the entire working day.

- Human responses to whole-body vibration are complex and interact in a complex manner. Although many studies have tried to establish these responses there is still many unknowns in how the vibration damages the body, and how postures can change the human response during vibration exposure. Currently the lack of understanding has resulted in standards that may fail to provide the correct advice for reducing health risks as a result of long-term exposure to vibration.

Chapter 3 - Methods and Data Analysis

3.1 Overview of Experimental Designs

One major field study and two major laboratory studies were conducted for this thesis. The field study and lab study were each analysed in two stages, 5 chapters of the thesis are dedicated to reporting these studies. The field based study was formulated at the Environmental Ergonomics Research Centre at Loughborough University, in collaboration with Caterpillar Inc. Only industries within the United Kingdom were investigated to establish the ergonomic exposures and characterization of whole-body vibration exposures among the off-road machinery operators. The first of the two major laboratory studies was conducted at the National Institute of Industrial Health, Japan (now National Institute of Occupational Safety and Health). The second study was conducted in the laboratory at the Environmental Ergonomics Research Centre, Loughborough University. Both of these studies investigated the biomechanical response of human subjects to ergonomic risk exposures determined from the field study. This chapter describes the equipment used, the test configurations, calibration and validation methods, in addition to the experimental designs. Analysis methods are also described in the following chapter; they include both the frequency domain analysis and statistical analysis. Table 3.1 provides an outline of all the studies that form this thesis. The following sections have been broken down into the equipment configurations for the field (Section 3.2) and for the laboratory (Section 3.4), validation of the hardware (Section 3.3.4) and software (Section 3.3.5), and experimental methodologies for the field (Section 3.5) and for the laboratory (Section 3.6).

Table 3.1 Outline of field and laboratory studies main objectives and measurement conditions

Study	Objectives	Equipment	Measurements	Conditions
1 Part a (Ch4)	To target specific types of earthmoving machines and take a large sample of each type of machine to enable comparisons to be made for different operations, sites and variation to determine how much difference should be accounted for in a health risk assessment. To determine which machines expose operators to the most harmful magnitudes of vibration and to collect representative data from the working environment to use in a controlled lab setting.	Triaxial accelerometers: NexGen Ergonomics x 2, Eurosense SEN 021F x 2, Larson Davis meters, Biometrics DataLogger, Garmin GPS loggers, Video camera.	Seat acceleration, in the three translational axes Speed, Location data, Task analysis, Postural observations.	Open cast coal mine, Granite quarries, Airport terminal construction, Building construction, Road construction, Scrap metal yard, Builders yard, Landfill site.
1 Part b (Ch5)	To determine the variation inherent to whole-body vibration exposure to help understand how this variation will affect health risk assessments. To determine how much variability exists between WBV measurements of daily exposures and between work cycles in earthmoving machines. To establish if there are large variations in WBV measurements for similar machines across different sites			
2 (Ch6)	To understand the interactions between typical vibration exposures and twisted postures observed in study 1; to improve understanding of the biomechanical responses of the human body. To validate the methods used with previous single-axis findings from the research literature, in order to apply the methods for use in a multi-axis test environment.	JNIOSH Multi-Axis Shaker, Bruel and Kjaer 4326A triaxial accelerometer amplified using a Nexus charge amplifier, Kistler force plate, Bite bar comprising 6 x accelerometers amplified using nexus charge amplifier.	Apparent mass, Seat-to-head transmissibility.	Twisted back and neck posture, Upright forward facing posture, Vertical vibration (1 – 20 Hz, 1.0 m/s^2 r.m.s. unweighted), Rigid wooden seat, No backrest contact.

3 Part a (Ch7)	To measure the dynamic response of exposure to dual-axis fore-and-aft and vertical vibration in a range of driving postures observed in study 1. To evaluate the interactions between WBV and non-neutral twisted postures on seat-to-head transmissibilities. To evaluate the interactions between WBV and armrest support on seat-to-head transmissibilities	LBORO Multi-Axis Shaker, Bite Bar comprising 6 x accelerometers amplified using a charge amplifier, Dual-axis goniometer (SG110 Biometrics).	Seat-to-head-transmissibility, Neck angle.	Twisted back and neck posture, Upright forward facing posture, Armrest support, No armrest support, Vertical and fore-and-aft vibration (1 – 20 Hz; z- 1.1 m/s^2 r.m.s, x-1.4 m/s^2 r.m.s. unweighted random signal), Earthmoving machine suspension seat with backrest contact.
3 Part b (Ch8)	To compare different driving postures on reaction time performance and perceived workload during exposure to fore-and-aft and vertical vibration. To evaluate the interactions between WBV and non-neutral twisted postures. To evaluate the interactions between WBV and armrest support	LBORO Multi-Axis Shaker, Dual-axis goniometer (SG110 Biometrics), Reaction time software (LabView), NASA Task Load Index.	Visual motor reaction time, Subjective workload, Neck angle, Seat acceleration.	

3.2 Ethics Approval

Prior to commencing the experiments Ethics approval was obtained from the Department of Human Sciences Ethics Committee at Loughborough University for the field study (G02-P1 Quantification of vibration exposure of vehicle occupants) and for the laboratory study (G04-P1 Use of multi-axis vibration simulator and G04-P3 Subjective and Objective measures of human response to whole-body vibration). Ethics approval was also obtained from the Research Ethics Committee of the National Institute of Industrial Health (National Institute of Occupational Safety and Health), Japan. The experimental procedures adhered to the guidelines in ISO13090-1 (1998), and this included written consent from all participants.

3.3 Field Study

3.3.1 Accelerometers and Measurement Systems

Two units of two types of measurement system were used for data collection in the field study. The first two systems comprised a standard human vibration meter (Larson Davis). The second two were data acquisition systems in the form of stand-alone data loggers (Biometrics); they enabled discrete waveforms to be stored for later analysis on a computer.

The acceleration at the seat was measured using piezoresistive accelerometers (strain gauge) and Integrated Circuit Piezoelectric (ICP) accelerometers. The piezoresistive accelerometers (S2-10G-MF, NEXGEN Ergonomics) were used with the Biometrics DataLoggers (P3X8 V2.11). They had a cross-axis sensitivity of less than 5%, with an accuracy of better than ± 2% full scale and a maximum operating range of ±10g (98 m/s^2). Gravity was used to calibrate the piezoresistive accelerometers, the output for a vertically inclined accelerometer provides a measure of +1g (9.81 m/s^2) acceleration and for an inverted accelerometer provides a measure of −1g (-9.81 m/s^2) acceleration. These accelerometers are only suitable for the measurement of low frequency vibration (Mansfield, 2005). The systems were also fitted with low-pass 'anti-aliasing' filters set to 100 Hz.

The ICP accelerometers (Eurosense SEN 021F; PCB356M86) were used with the Larson Davis meters (HVM100). The accelerometers were calibrated before each measurement using a calibrator that produced vibration at 159.2 Hz at 10 m/s^2 r.m.s. The sensitivity of the accelerometer was stored once it reached the correct value of 10 m/s^2 r.m.s. All systems complied with ISO8041 (2003).

3.3.2 Data Acquisition

For the Biometrics a sample rate of 500 Hz was selected to ensure the characteristics of the signal were retained. The highest frequency of interest was 100 Hz so a sample rate of 500 Hz ensured an accurate sample was obtained. The sample rate should be at least three times the highest frequency of interest in the signal (Mansfield, 2005). Ideally the sample rate would be 512 Hz as this would provide a convenient resolution to be selected when analysing the frequency domain. However, the DataLog systems did not allow for selection of such a sampling rate.

For the Larson Davis HVM100's the sampling recorded root mean square (r.m.s.) data every 10 seconds, and vibration dose values (VDV) were integrated over 1-minute periods.

3.3.3 Signal Processing

Signal processing was performed with two pieces of in-house software created in LabView. Frequency weightings were applied in accordance with ISO2631-1 (1997)/ ISO 8041 (2003) they are designed to not affect those frequencies where the body is most sensitive and to attenuate at those frequencies where the response of the body is less sensitive (Mansfield, 2005). The weightings include a multiplication of 1.4 to both the horizontal axes (x-axis, y-axis) and a multiplication of 1.0 to the vertical (z-axis).

Statistical measurement parameters identified in ISO2631-1 (1997) were used for the evaluation of health effects and whole-body vibration exposure. The r.m.s was used on the frequency weighted acceleration data to give the square root of the average of the squared values. It is the basic vibration evaluation method measured in m/s^2. Vibration Dose Values were also calculated from the frequency weighted acceleration. The mathematical equations for the r.m.s. and VDV are presented in Equation 3.1 and Equation 3.2.

a_w is the frequency-weighted r.m.s. acceleration, in m/s^2

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{1/2}$$

T is the measurement duration, in seconds;

$a_w(t)$ is the frequency weighted acceleration at time t.

Equation 3.1

VDV is the vibration dose value in m/s$^{1.75}$

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

T is the duration of measurement, in seconds;

$a_w(t)$ is the instantaneous frequency-weighted acceleration;

Equation 3.2

Vibration dose value (VDV) is the time integral of the acceleration and can be applied to a number of vibration forms. The equation for VDV outlines the use of the fourth root to calculate the vibration value. The equations for r.m.s. and VDV are similar apart from the power values and the measurement time division for the r.m.s.

Vibration Dose Value is more suitable than r.m.s. for high crest factors as it accumulates the presence of occasional or repeated shocks in the signal. The VDV responds more readily to the shock than r.m.s. and maintains this influence as time passes. It has been suggested to present a more reliable measure of the risk exposed to operators (Griffin, 1998; Sandover, 1997; Stayner, 2001). VDV is now used in a small number of institutes, yet seldom used in industry and it has no legal framework. There has been much debate about the validity of using VDV as the presence of operator 'artefacts' resulting from getting in and out of the seat and losing contact during transit can have a large influence on the outcome of the metric. The measurement 'artefacts' from the operator getting in and out of the seat was determined at the start of this thesis (highlighted in Appendix A1). During the course of this research the r.m.s. has become the preferred metric for the assessment of risk. The PA(V)D has been implemented into UK legislation using the r.m.s. and also widely across Europe. For this reason the thesis has only focused on the assessment of r.m.s, although the VDV has been reported in an appendix and it will be referred to again in the general discussion (Chapter 9).

Spectral analysis was used to extrapolate the power spectra from the vibration data. The Power Spectral Density (PSD) indicates how the energy of the vibration is distributed with response to frequency. The parameter of the PSD calculation included window size (4096 samples), overlap (50%) and window function (Hanning). The window size chosen resulted in the calculation of PSDs with a frequency resolution of 0.12 Hz.

3.3.4 Validation of Hardware

Darlington and Tyler (2004) revealed that whilst individual instruments are capable of producing repeatable measures of vibration, the mean weighted accelerations reported by different instruments in the same environment could vary considerably. They found that results could differ by 30% between commercially available instrumentation system. For this reason it was important to ensure that all of the measurement systems' used in this thesis were validated prior to use. For the measurement assemblies used during the field study this involved validating all systems against one another and validating to a known calibration frequency and magnitude.

A validation study was carried out to test the agreement between all systems used to record whole-body vibration data. The validation was carried out to authenticate all data acquisition systems. This included the Biometrics Data Logger and Larson Davis meters (HVM100) with the attached accelerometers. The accelerometers were mounted onto a shaker in the Environmental Ergonomics Laboratory at Loughborough University. The ambient temperature of the test environment was 23.6°C with a relative humidity of 45%. This is within the acceptable environment conditions as specified in ISO 8041 (2005). All the measurement systems were set to acquire vibration at all frequencies. The Larson Davis meters (HVM100) recorded unweighted r.m.s. values every second and the Biometrics Data Logger recorded the raw unweighted accelerations at 500 Hz. Each axis of the accelerometer was tested separately at a range of frequencies. Test frequencies ranged from 2 Hz up to 80 Hz, this encompassed the range within the frequency weighting filters that could be tested using the shaker. Spot frequencies were tested at 1/3 octave intervals. The r.m.s. magnitude of the shaker was set to approximately 1 m/s². Table 3.2 outlines the Larson Davis and Biometric set-ups that were used during the validation process.

The absolute r.m.s. values obtained from the measurement systems are presented in Figure 3.2. They illustrate the coherency between the Biometric Datalogger / accelerometer and the Larson Davis meters / accelerometers. There is good

agreement at all frequencies. An example of one of the test frequencies is presented in Figure 3.1. The percentage differences between the measurement units at each frequency are highlighted in Table 3.3, the smallest differences were found between the two Larson Davis meters. The differences between the Biometrics and LD1 were very similar to the differences between the Biometrics and LD2.

Table 3.2 Larson Davis meters and Biometric Datalogger settings used during validation

Meter	Larson Davis Meters		Biometrics Loggers
Accelerometer	Eurosense SEN 021F	PCB356M86	S2-10G-MF, NEXGEN
Operating Mode	Vibration	Vibration	None
Sampling rate	14400 samples/s (1 sec mode)	14400 samples/s (1 sec mode)	500Hz
Weighting	Off	Off	None
Gain	X: 40 Y: 40 Z: 40	X: 40 Y: 40 Z: 40	None
Sensitivity	X: 9.452e + 00 mV/g Y: 8.864e + 00 mV/g Z: 9.597e + 00 mV/g	X: 9.515e + 00 mV/g Y: 9.305e + 00 mV/g Z: 9.619e + 00 mV/g	0.1 Volts/m/s² (after amplification)
ADC Resolution	16 Bits	16 Bits	13 Bits

The International Standard for 'Human response to vibration – measuring instrumentation' ISO8041 (2005) outlines acceptable tolerance levels for error resulting from the vibration measuring equipment. The tolerance of indication at the reference frequency under reference environmental conditions must be within ± 4% for the vibration value. The percentage error difference between the measurement systems came below this limit for the x-axis: 1.7% ± 1.23σ (0.0 – 3.8 range), y-axis: 2.1% ± 1.36σ (0.0 – 3.7 range), and z-axis: 1.8% ± 1.27σ (0.0 – 3.5). The findings authenticate the systems by indicating that data collected in any situation will yield the same acceleration values using any of the measurement assemblies.
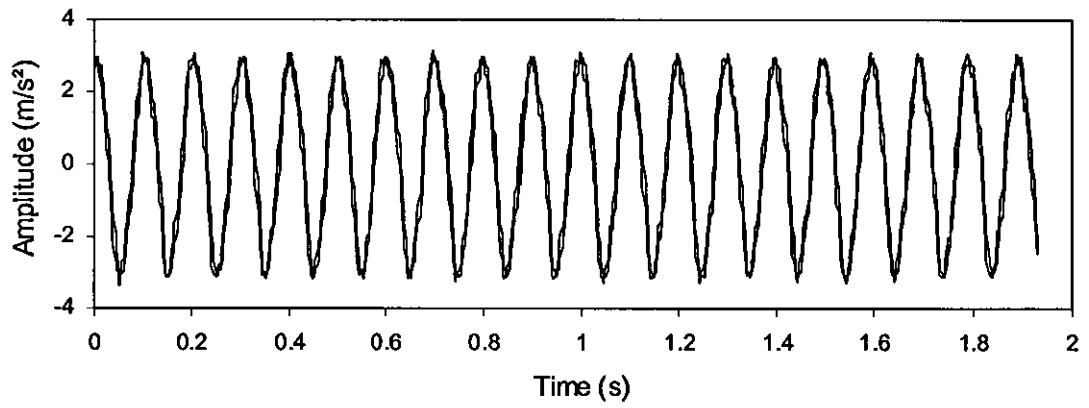
Figure 3.1 Output from two accelerometers (Biometric loggers) mounted on a shaker with an excitation of 10 Hz.

Table 3.3 Percentage difference between the three measurement units

Frequency (Hz)	x-axis			y-axis			z-axis		
	LD1-LD2	LD1 - Biom	LD2 - Biom	LD1-LD2	LD1 - Biom	LD2 - Biom	LD1-LD2	LD1 - Biom	LD2 - Biom
2	1.0	2.6	3.6	0.2	3.5	3.3	0.3	3.4	3.1
2.5	0.4	2.8	3.2	0.9	3.6	2.7	0.0	2.9	2.9
3.15	0.5	2.6	3.1	0.4	3.5	3.1	0.1	2.9	2.8
4	0.4	2.8	3.2	0.5	3.4	2.9	0.1	3.4	3.5
5	0.1	3.2	3.1	0.0	3.0	3.0	0.2	2.7	2.9
6.3	0.0	2.9	2.9	0.0	3.7	3.7	0.3	3.2	3.5
8	0.0	2.8	2.8	0.0	3.6	3.6	0.0	2.9	2.9
10	0.0	2.0	2.0	0.0	3.3	3.3	0.0	2.9	2.9
12.5	1.0	2.0	2.9	1.0	1.9	2.9	0.0	2.8	2.8
16	0.0	2.0	2.0	0.0	2.9	2.9	0.0	2.0	2.0
20	1.1	1.9	3.0	0.0	3.0	3.0	1.0	1.9	1.0
25	0.0	2.0	2.0	0.0	1.9	1.9	1.0	2.0	2.9
31.5	0.0	1.6	1.6	0.0	3.0	3.0	0.2	2.1	2.3
40	0.3	0.4	0.7	1.3	2.3	3.6	0.0	2.0	2.0
50	0.1	0.0	0.1	1.9	0.0	1.9	1.0	0.0	1.0
63	2.9	3.8	1.0	2.0	2.0	0.0	1.0	2.5	3.4
80	0.5	3.0	2.5	1.9	3.7	1.9	2.6	0.4	3.0
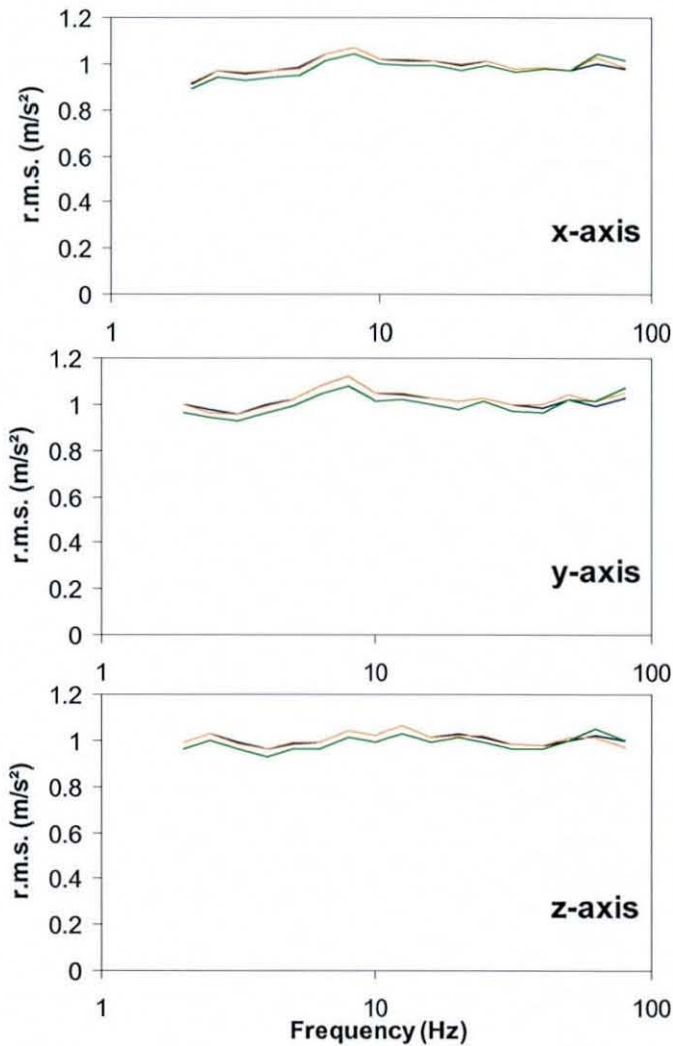
Figure 3.2 Absolute r.m.s. magnitudes (m/s²) obtained at spot frequencies for all the measurement systems, including Larson Davis HVM100 (LD1 orange top line, and LD2 yellow middle line) and Biometrics DataLog (Biom green lower line).

Another phase of this validation included the evaluation of the anti-aliasing filters set to 100 Hz. The anti-aliasing filter for 100 Hz was checked during the calibration process of all the equipment, using a Brüel & Kjaer calibration exciter Type 4294. It produces a frequency of 159.2 Hz with an acceleration level of 10 m/s^2. With the 100 Hz filter activated the accelerometer did not register the excitation. Once the filter had been de-activated the accelerometer gave a reading similar to the excitation level of the calibration exciter.

3.3.5 Validation of Software

The custom written analysis software created in LabView was validated with software packages available commercially for the assessment of vibration, including; VATS and HVLab. The software conformed to ISO8041 (2003). The frequency and phase response of the digital implementation of W_d and W_k frequency weighting curves fall within the tolerance intervals defined by ISO8041.

3.4 Laboratory Configurations

3.4.1 Accelerometers and Force Platform

Bruel and Kjaer 4326A triaxial accelerometer was used to measure the vibration at the seat, during study 2. The accelerometer was amplified using a Nexus charge amplifier. It has a maximum operational peak of 2000g and maximum shock level of ± 5000g, with a sensitivity of 0.30 pC/m/s² or 3 pC/g.

The force at the seat was measured using a Kistler 9281C force plate. The influence of the mass of the plate was removed using a mass cancellation technique in the frequency domain by subtracting the apparent mass of the unloaded force plate.

3.4.2 Accelerometers and Bite Bar

The bite bar used in Study 2 and 3a (presented in Figure 3.3) weighed 245g. It had tri-axial accelerometers mounted on the left and right side and a single vertical axis accelerometer mounted on the rear with a counterbalance mounted to the front of the bar.
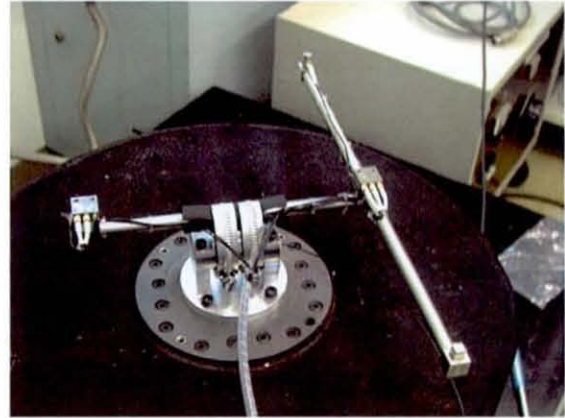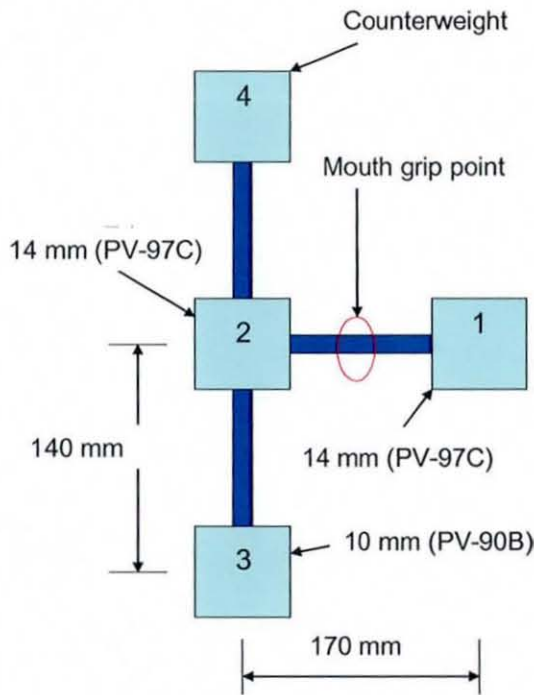
Figure 3.3 Bite Bar used in Study 2 and 3a

3.4.3 Multi-Axis Shaker Systems

The first system used to generate vibration for study 2 was an IMV multi-axis shaker (IMV Corp. Ltd.). The machine is part of the vibration test laboratory at the National Institute of Occupational Safety and Health, Japan (Figure 3.4). The maximum payload for the system is 200kg and it is driven in a frequency range of 0.13 – 150 Hz by seven electrodynamic shakers, one in the horizontal x axis, two in the horizontal y axis and four in the vertical axis. The maximum acceleration is 3.5 m/s² peak. The table working surface is 1.5 m x 1.0 m with a table weight of 500kg. The shaker had low cross-talk between axes (typically <5%). Subjects sat on a horizontal flat seat with dimensions of 600 (w) x 400 (d) mm which was 540 mm above the footrest that moved with the seat. The seat had a vertical braced wooden backrest which was 460 mm wide.

The second system used was a six-axis shaker situated at the Environmental Ergonomics Research Centre, Loughborough University, UK (Figure 3.4). The maximum payload for the system is 600kg and it is driven in a frequency range of 0 – 25 Hz by 6 hydraulic rams in a 'stewart platform' configuration. The displacement is; ± 15 cm for the x-axis and y-axis, ± 9 cm peak to peak vertical, ± 17° roll/pitch, and ± 27° yaw. The maximum acceleration is; 6 m/s² for x-axis and y-axis, 8 m/s² for the vertical, and 200°/s² rotation.

| Multi-axis shaker system and seating used for Study 2 | Multi-axis shaker system and seating used for Study 3 |
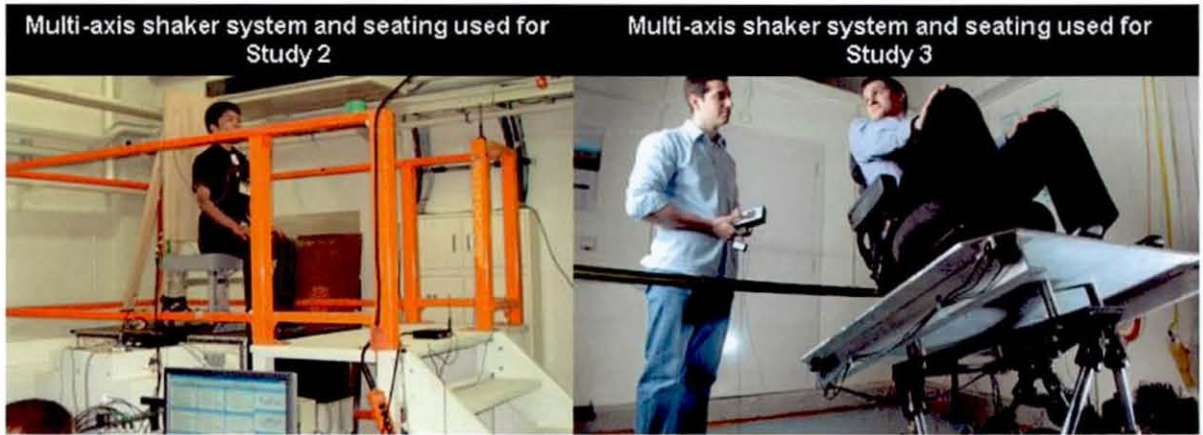
Figure 3.4 Multi-axis shaker systems and seating used for the laboratory studies.

3.4.4 Measurement Systems and Data Acquisition

In Japan the vibration data was acquired with a multi-channel data acquisition system (Pulse Version 8), it has a total of 12 measuring channels. The system can perform to ISO2631-1 (1997) using the 6 axis accelerometers to measure and evaluate the human response to vibration on the seat. Force and acceleration signals were acquired using Pulse. Data was acquired at 512 samples per second via anti-aliasing filters set at 170 Hz. Coherence, phase, apparent mass and seat-to-head transmissibility were recorded through the data acquisition system.

In the UK the vibration data was acquired with a multi-channel data acquisition system. Acceleration signals were acquired using the LabView software from Computer A and the reaction time signals were acquired with LabView software running on Computer B.

3.4.5 Validation of Suspension Seat

The Seat Effective Amplitude Transmissibility value (SEAT) was calculated to determine the isolation efficiency of the suspension seat. The methodology for measuring the transmissibility of a seat is defined in ISO10326-1 (1992). One triaxial accelerometer is mounted at the base of the seat on the floor and the second triaxial accelerometer is placed between the seat pan and the operator (mounted in a semi-rigid disc). Calculations from the ratio of the frequency-weighted acceleration occurring on the surface supporting the operator to the frequency-weighted acceleration entering the base support of the seat are presented in Equation 3.3.

$$SEAT = \frac{rms_{seat}}{rms_{floor}} \times 100\%$$

Equation 3.3

If the SEAT value is greater than a 100% then it suggests that the operator on the seat is subjected to vibrations of a greater severity than would be if they were sat on the floor. If the value is lower than a 100% then it suggests that the seat is isolating some of the vibration found on the floor and therefore presents a reduced risk to injury and discomfort. Figure 3.5 presents the vertical transmissibilities and Figure 3.6 presents the SEAT values for 12 subjects sat on the suspension seat. There is clear evidence the suspension seat is functioning correctly, there is attenuation in the vertical axis and 100% or more transmissibility in the horizontal axes. This is to be expected with this type of vertical isolation system.
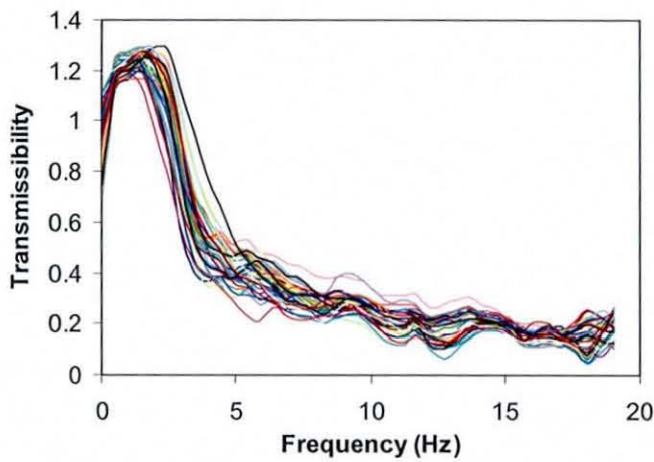
Figure 3.5 Vertical transmissibilities for 12 subjects, with 3 repeat trials on an air suspension seat.
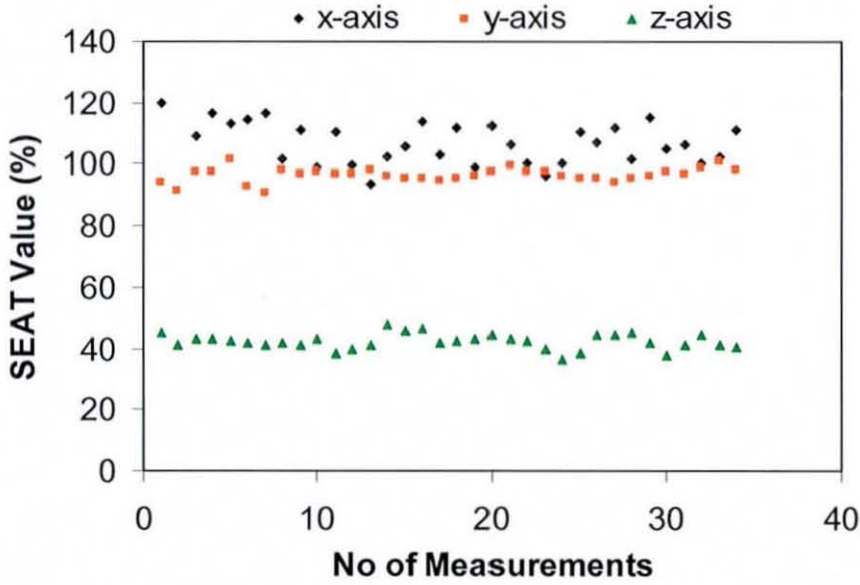
Figure 3.6 Seat Effective Amplitude Transmissibility values for 12 subjects, with 3 repeat trials on an air suspension seat.

3.4.6 Validation of Software

The reaction time software was validated by comparing signals from an accelerometer mounted on the keyboard and comparing the results with those obtained from the software, the correlation between the reaction time software and the actual response time was $R^2 = 0.997$, as can be observed in Figure 3.7.
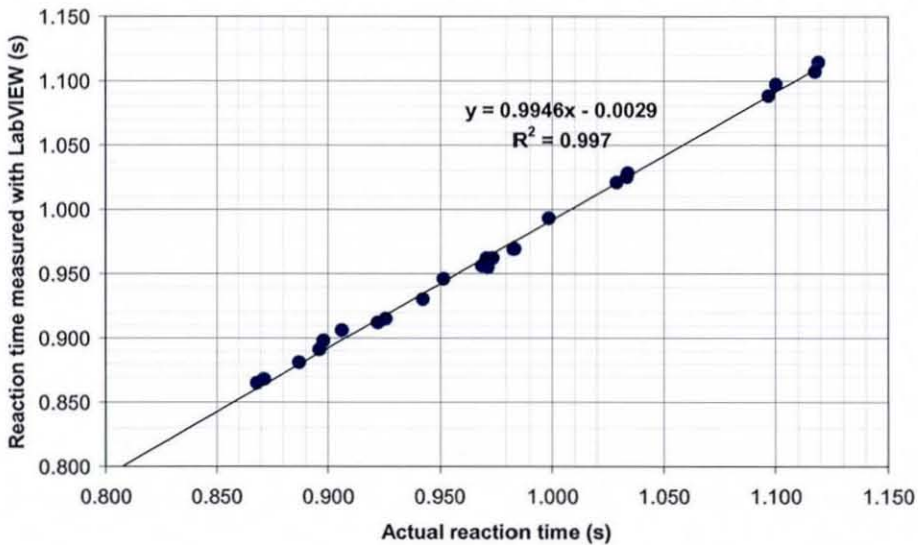
Figure 3.7 Correlation between the reaction time software (LabView) and reaction time measured at the key press.

3.5 Field Methodology

This section discusses the methodology applied throughout the vibration data collection period. Outlined in Section 3.5.1 is the general test procedure for all the vibration measurements. A pilot study was carried out at the start of the project, the details and summary of the findings are discussed in Section 3.5.3. The details of the machines investigated and the sites visited are presented in Section 3.5.4.

3.5.1 General Procedure

The vibration measurements were conducted according to ISO 2631-1 and the Physical Agents (Vibration) Directive. All four vibration measuring systems identified in Table 3.2 were used throughout the test period. The procedure was the same for each of these measuring systems. One accelerometer was fitted in a Society of Automotive Engineers (SAE) flexible disc (as defined in ISO10326-1, 1992), and positioned on the seat pan beneath the ischial tuberosities (Figure 3.8). The accelerometers at the seat pan measured in 3 translational axes; in the fore-and-aft (x-axis), lateral (y-axis), and vertical (z-axis), respectively. The SAE disc was orientated to ensure the accelerometer was aligned with the correct axes.

The Biometric DataLoggers recorded the raw signal of the vibration at a sampling rate of 500 Hz. The Larson Davis meters conditioned the vibration signal and logged the r.m.s. data every 10 seconds, with the vibration dose values integrated over 1-minute periods. In the vertical direction, weighting W_k was used (frequency range 0.5 – 80 Hz); in the horizontal directions, weighting W_d (0.5 – 80 Hz) was used.

Systems with integrated global positioning (GPS) were used to log the speed of each machine during each measurement period. The system did not always produce a signal in certain machines. This may be due to the location of these machines especially at a quarry face where the reception of satellites becomes limited.

All the pieces of measuring equipment were synchronised with the GPS, video and observers personal watch. This ensured accurate time event data could be recorded and matched with the resulting acceleration time histories.

Minimum interference was caused during the setting up process. In most cases the equipment was prepared before arriving at the machine, and setup was complete during the operators standard break periods. Details of the operator, machine and work tasks were also collected during this process. Quick setup times were essential to

reduce disturbance to the operators and to ensure they carry out the same tasks as any other working day.

After the measurement run had been completed the equipment was removed from the machine and data downloaded to a pc computer ready for the analysis phase.

Figure 3.8 Typical location of mounting for the seat surface accelerometer, highlighting the vibration axes measured.

3.5.2 Analysis of Whole-Body Vibration Data

This section discusses the stages of analysis that were performed on the vibration data collected throughout the field study. The analysis was carried out using a two-stage process. The first stage of the process involved correlating the GPS data with the acquired running r.m.s. data, in order to calculate the vibration emission values for every machine. This involved synchronisation of the data in order to remove the planned break periods when the operator stopped operation (highlighted in Figure 3.9). The vibration emission data findings are discussed in Chapter 4.
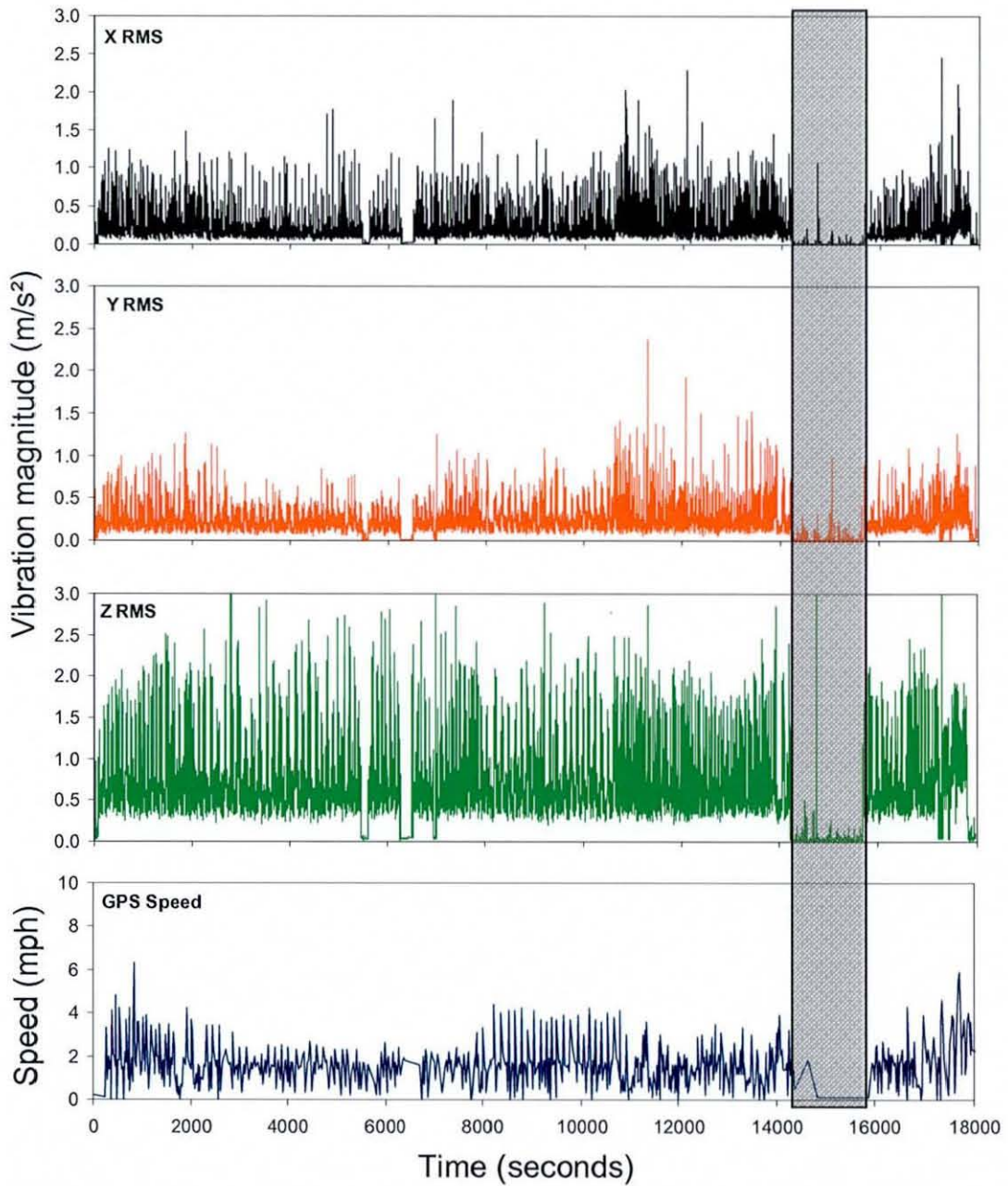
Figure 3.9 Illustration of analysis process for removal of stationary periods during breaktimes. Data was synchronised with GPS speed, grey area highlights the measurement section that was removed for the calculation of emission.

The synchronisation process enabled the stationary break periods in the measurement to be identified and taken into account when calculating the machine emission value. Firstly the r.m.s. for the full measurement duration was calculated using Equation 3.1 presented in Section 3.3.3. Secondly the calculation for the r.m.s. emission value was calculated using Equation 3.4.

$$a_{exp} = \sqrt{\frac{T_{md}}{T_{exp}}(a_{md})^2}$$

Where:

a_{exp} is the r.m.s. value minus stationary break periods

T_{md} is the full measurement duration

T_{exp} is the measurement duration minus stationary break periods

a_{md} is the r.m.s. of the full measurement duration

The second stage of the analysis involved breaking the data down into work cycles for the study presented in Chapter 5. The r.m.s. value for each work cycle was calculated using Equation 3.1 presented in Section 3.3.3. Once all of the work cycles had been calculated for a machine the coefficient of variation in Equation 3.5 was calculated to determine the variability found between work cycles and between days, in the three axes of vibration.

$$C_v = \frac{\sigma}{\mu}$$

Where:

μ is the mean

σ is the standard deviation

The Total$_{r.m.s.}$ value in Equation 3.6 was calculated by combining the data obtained within each work cycle to produce an overall vibration work cycle emission value.

$$Total_{r.m.s.} = \sqrt{\frac{1}{T}\sum_{n=1}^{n=N} a_{wn}{}^2 t_n}$$

Where:

T is the sum of all of the vibration exposure times over all cycles

a_{wn} is the frequency-weighted r.m.s.

t_n is the exposure time for cycle n

N is the number of cycles.

3.5.3 Pilot Study

A pilot study was carried out in two locations to help familiarity with the vibration measuring equipment and to help determine the measurement methodology that was going to be applied throughout the field investigations. The first location was a machine test ground and the second was a proving ground; both sites were used to test Caterpillar's machines. A variety of test machines were used to perform a number of different tasks. The data from the pilot study are presented in Appendix A2.

Location 1 was used to measure a mini-excavator, skid steer loader and a small wheel loader during loading and driving operations. The mini-excavator was also used with a hammer attachment to carry out a hammering operation on a metal plate. The dominant axis of vibration for the mini-excavator was the vertical (z-axis) for the hammering operation and while the machine was travelling; when the machine was performing an excavation the fore-and-aft (x-axis) dominated the vibration. Both the wheel loader and skid steer loader produced the worst magnitudes of vibration in the fore-and-aft direction in almost every operation. The only discrepancy was for the skid steer loader where the vertical axis dominated during the travelling operation. During the loading operation the driver performed two styles of driving, normal and aggressive; as expected, the vibration magnitudes increased during the aggressive driving style by more than 50%.

Location 2 was used to measure the vibration in two compact wheel loaders and a telehandler during loading operations and driving. The driving at this site was split into two categories of terrain. The first was driving on concrete and the second was driving on a man-made rough axle track. The worst vibration exposure was experienced while the operator was driving over the axle track and rough terrain, followed by the vibration during the loading cycle operation. Travelling on concrete produced the lowest

magnitudes of vibration. The dominant axis for the wheel loaders was the fore-and-aft in all operations apart from model 908 when it travelled on concrete. The vertical axis dominated the vibration for the telehandler during travelling operations and the fore-and-aft dominated when this machine was performing static / hydrostatic functions.

3.5.4 Machine and Site Characteristics: Main Study

Ten sites were visited for the field study; they are identified in Table 3.4. In total twelve different categories of off-road machines were investigated and one crusher machine, this machine exposed the operator to standing vibration.

Table 3.4. Classification of sites visited for whole-body vibration testing.

Site	Type	ID Number
Croft	Granite quarry	1
Mountsorrel	Granite quarry	2
Wedge	Building merchants	3
Hicks	Open cast coal mine	4
Tilbury	Scrap metal yard	5
Heathrow	Airport terminal construction	6
M25	Road widening construction	7
Harlestone	Landfill site	8
Wood Lane	Landfill site	9
Fort Dunlop	Building development area	10

Twelve different types of machine groups were measured during the field study. The typical work tasks and the type of terrain experienced in the machine groups are highlighted in Appendix A3. Specific information about the individual machines and the operators of the machines are presented in Chapter 4 Section 4.3.1 and Appendix A4 (including images of the individual machines).

Bulldozer machines (otherwise known as track-type tractors) are tracked earthmoving machines that are fitted with a blade attachment at the front of the machine and sometimes with a ripper at the back. They are capable of travelling on steep and rough terrain, which is essential for their main work function of smoothing irregular ground surfaces, ripping up the ground and for pushing earth into piles. The machines measured in this study weighed from 6270 kg up to 48520 kg, the range of machines included small, medium and large dozers.

Tracked loaders (sometimes known as crawler loaders) are tracked earthmoving machines that are usually fitted with a bucket and are capable of working on steeper and softer ground than equivalent wheel loaders. They are typically used for either transporting material between locations on a work site, for smoothing irregular ground surfaces and for loading tasks (e.g. loading lorries, depositing material in a crusher). The machines measured in this study weighed 15145 kg or 19589 kg.

Wheel loaders are mainly used to move material, their primary activity involves loading cycles to transport material between different material piles or for loading material into aggregate trucks, machines are fitted with a bucket attachment for this purpose. The machines measured in this study weighed from 22590 kg up to 73780 kg.

Dump trucks and articulated trucks are primarily used to transport large volumes of material between different areas of a site. They are typically loaded with either an excavator or a wheel loader depending on the size and volume of the material being transported. The machines measured in this study weighed from 15778 kg up to 85000 kg for the dump trucks and from 27000 kg up to 31270 kg for the articulated trucks.

Motor graders are typically used to smooth the access roads for all the other machines operating at the work sites. They have four wheels at the back underneath the cab with a ripper attachment and 2 wheels at the front with a scraper in-between. The machines measured in this study weighed from 18440 kg up to 35000 kg.

Excavator's primary task is to excavate earth and move the earth to different areas or into the back of a truck to be taken elsewhere. They are normally tracked earthmoving

machines fitted with a large bucket at the front of the cab. The machines measured in this study weighed from 7000 kg up to 78000 kg.

Rollers only task was to smooth out areas of the work site in order to create a flattened surface. The machines were fitted with two wheels behind the cab and a roller in front of the cab. The machines measured in this study weighed between 12130 – 20700 kg.

The skid steer loader measured for this study weighed 2223 kg. Its sole purpose was to fill bags with sand from the pits located at the builder's yard. The machine only travelled a short distance to the pit and back to the sand bag. The machine is fitted with a small bucket at the front and it is operated using a joystick.

The material handler measured for this study weighed 30000 kg. Its sole purpose was to move pieces of scrap metal into the crusher pile. Sometimes this involved moving around the small scrap yard to pick up metal in different areas. The cab body could be raised in order for the operator to work the attached gripper arm.

The compactor measured for this study weighed 32734 kg. It was fitted with studded wheels at the front and back that had the capability to compact the ground beneath them. The machine was required to travel around different sections of the site in order to compact the surface where other machines would be operating.

The challenger tractor has tracks similar to the bulldozers yet it is more typically designed to be an agricultural machine. The one measured for this study had an added attachment called a "hex" (kind of compactor). It was required to flatten out a large area of ground before building work could commence. The total weight of the challenger tractor without the attachment was 15286 kg.

3.6 Laboratory Methodology

3.6.1 General Procedure

Before each experiment the accelerometers were calibrated according to ISO5347-5 (1993). Subjects completed a health screening questionnaire to ensure there was no previous history of back pain, and gave informed consent to participate. For both experiments the order of presentation of the postures was randomised using a Latin-Square design. More details about the experiments are provided in the three chapters on the laboratory studies (6, 7 and 8). The following section highlights the different methods used for each study.

3.6.2 Measurement and Analysis of Biomechanical Response

3.6.2.1 Apparent mass measurements

For a rigid structure the apparent mass is equal to the weight. However, if the structure has some compliance such as the human body the apparent mass provides a measure of the frequencies where the structure resonates (Mansfield and Maeda, 2005). The apparent mass M(f) was calculated using the cross spectral density (CSD) method, presented in Equation 3.7. Cross-spectral density (CSD) functions were used to measure the relationship between the signal generated at the seat and the resultant signal generated by the body. The transfer functions were calculated using the CSD method to ensure the two signals correlated to one another, this reduced the influence of noise and also generated the phase difference between the signals.

$$M(f) = \frac{CSD_{force\text{-}acceleration}(f)}{PSD_{acceleration}(f)}$$

Equation 3.7

Where:

CSD (f)   is the cross spectral density between the acceleration and the force

PSD (f)   is the power spectral density of the acceleration at frequency f

The measured force of the subjects' body mass and the mass of the force plate needed to be removed from the calculated response. In order to do this a mass cancellation technique was employed ($M_s(f)$), presented in Equation 3.8.

$$M_S(f) = \frac{F(f) - F_e(f)}{A(f)}$$

Equation 3.8

$$= M_m(f) - m_e$$

Where:

$F(f)$ is the measured force

$F_e(f)$ is the force acting on the equipment

$A(f)$ is the measured acceleration

And:

$M_m(f)$ is the measured apparent mass

$M_e(f)$ is the apparent mass of the equipment

Variability in the apparent masses of subjects was partly attributed to their different static masses, as reported previously (Fairley and Griffin, 1989). Therefore in order to counteract this influence and allow comparisons between individuals the apparent mass was normalised by dividing the measured value of the apparent mass at the lowest frequency to obtain the static mass of the subject, as presented in Equation 3.9.

$$M_n(f) = \frac{M(f)}{M_s(f)}$$

Equation 3.9

Where:

$M(f)$ is the apparent mass

$M_s(f)$ is the apparent mass of the static mass at the lowest frequency

3.6.2.2 Seat-to-head transmissibility

The transmissibility $T(f)$ was calculated to determine the ratio between motions at the seat to motions at the head. Similar to the apparent mass method the calculation was done using the cross spectral density method, as presented in Equation 3.10.

$$T(f) = \frac{CSD_{Seat\text{-}head}(f)}{PSD_{Seat}(f)}$$

Equation 3.10

Where:

CSD (f)   is the cross spectral density between the seat and head acceleration

PSD (f)   is the power spectral density of the seat acceleration at frequency f

Calculations of roll, pitch and yaw were also carried out to determine the extent of rotation at the head. The data from the accelerometers mounted on the bite bar were used in the calculations (z-right, z-left, z-back, x-right and x-left) and measures of the separation distance between the accelerometers (0.17 m or 0.14 m). The calculations are presented in Equation 3.11.

$$Roll = \frac{(z - right) - (z - left)}{0.17\,m}$$

$$Pitch = \frac{(z - back) - (z - left)}{0.14\,m} \qquad \text{Equation 3.11}$$

$$Yaw = \frac{(x - right) - (x - left)}{0.17\,m}$$

3.6.3 Protocol adopted for Study 3

The schematic presented in Figure 3.10 highlights the protocol and timeline used to take measurements of biomechanical, performance and subjective variables. The independent variables that were randomised are positioned on the left side of the schematic and the measured dependent variables are shown along the time line to the right of the schematic. The transmissibility measurements were taken during the first minute of exposure and the reaction time task was performed during the third (last minute) of exposure, followed by the NASA TLX subjective scales (Hart and Staveland, 1988).
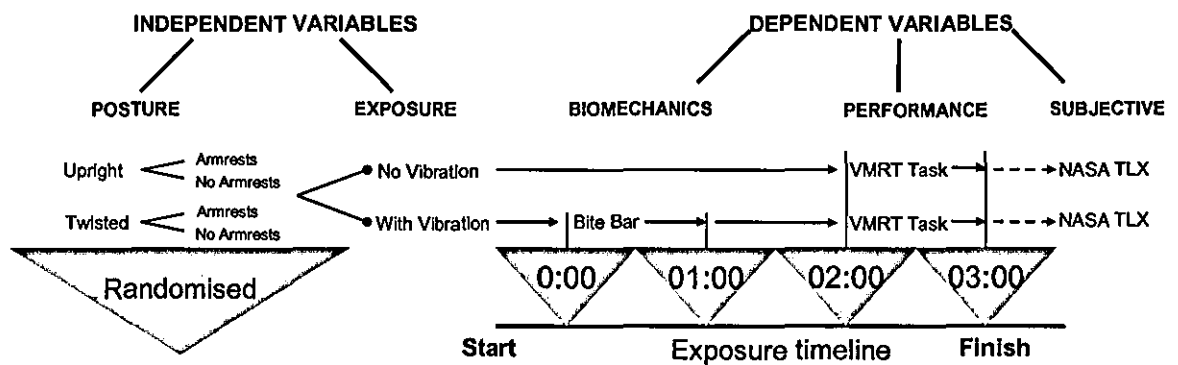
Figure 3.10 Schematic of laboratory protocol for Study 3

3.6.3.1 Measurement and Analysis of Performance and Subjective Response

The measurements of performance and workload were carried out during the same experiment as the seat-to-head transmissibility for Study 3. As described at the start of this chapter the study has been divided into two parts for presentation of the results in Chapter 7 for the seat-to-head transmissibility (Study 3 Part A) and Chapter 8 for the performance and workload measures (Study 3 Part B).

The reaction time software was validated before the study commenced (as described previously in Section 3.3.5. The detailed account of the performance test is provided in Chapter 8. Following the performance test the NASA Task load index (Hard and Staveland, 1988) was administered by presenting the rating scales to the participants and asking for their response. The NASA TLX is a multi-dimensional subjective rating tool that is used to derive a mental workload score based upon six workload sub-scale ratings. A description of each subscale is provided below:

- Mental demand. How much mental demand and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching etc)? Was the task easy or demanding, simple or complex, exacting or forgiving?

- Physical demand. How much physical activity was required e.g. pushing, pulling, turning, controlling, activating etc. Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

- Temporal demand. How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

- Effort. How hard did you have to work (mentally and physically) to accomplish your level of performance?

- Performance. How successful do you think you were in accomplishing the goals of the task set by the analyst? How satisfied were you with your performance in accomplishing these goals?

- Frustration level. How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

3.6.4 Participant Characteristics

Participants who volunteered for Study 2 were from an engineering course at a university in Tokyo and all of them were Japanese. Unfortunately there was only one female available to participate. For the next study there was a greater number of females to ensure a representative number of males and females could be measured. The participants in Study 3 were from an international mix including; English, Greek, Canadian, Jamaican, Danish, German, and Swedish. A breakdown of their details is in Table 3.5.

Table 3.5 Participant characteristics for Study 2 and Study 3

Study 2 – Participant details for Japanese volunteers based in Tokyo

Gender (ID no.)	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m²)
Male (1)	22	165	56	21
Male (2)	24	173	90	30
Male (3)	23	172	62	21
Male (4)	22	183	71	21
Male (5)	22	170	77	27
Male (6)	24	181	81	25
Female (7)	25	160	54	21
Male (8)	25	179	75	23
Male (9)	23	175	60	20
Male (10)	24	171	56	19
Male (11)	22	163	53	20
Male (12)	25	177	60	19
Male (13)	23	173	63	21
Male (14)	25	172	60	20
Male (15)	22	184	78	23

Study 3 – Participant details for International volunteers based in Loughborough

Gender (ID no.)	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m²)
Female (1)	21	177	66	21
Female (2)	21	176	65	21
Female (3)	23	156	55	23
Female (4)	23	164	51	19
Female (5)	34	173	64	21
Female (6)	35	169	58	20
Female (7)	25	159	50	20
Female (8)	34	182	73	22
Female (9)	35	162	51	20
Female (10)	21	164	69	26
Male (1)	24	176	70	23
Male (2)	27	181	86	26
Male (3)	19	174	77	26
Male (4)	21	178	86	27
Male (5)	24	185	84	25
Male (6)	19	185	84	24
Male (7)	23	171	75	26
Male (8)	25	184	91	27
Male (9)	25	183	72	22
Male (10)	29	169	81	28
Male (11)	24	190	107	30

3.6.5 Statistical Analysis

A variety of statistical methods were used to determine if there were significant differences between conditions. An overview of the statistical methods used in the experiments is provided in Table 3.6. Non-parametric methods were used for statistical analysis of apparent mass and seat-to-head transmissibility and parametric methods were used for analysis of reaction time performance and subjective workload.

Table 3.6 Parametric and non-parametric methods used for statistical analysis

Experiment (Chapter)	Independent variables (factors)	Levels of Factors	Dependent variables	Statistical Method
Study 2 (Ch6)	Posture	1. Upright 2. Twisted	1. Apparent mass 2. Seat-to-head transmissibility	Wilcoxon
Study 3 Part a (Ch7)	Posture	1. Upright 2. Twisted 3. With armrests 4. Without armrests	1. Seat-to-head transmissibility	Wilcoxon
	Gender	1. Males 2. Females		Mann-Whitney U
Study 3 Part b (Ch8)	Exposure	1. No-vibration control 2. Vibration treatment	1. Reaction time 2. Subjective workload	Repeated measures 2-way analysis of variance for significant main effects and interactions
	Posture	1. Upright 2. Twisted 3. With armrests 4. Without armrests		

The Wilcoxon and Mann-Whitney U tests are both non-parametric therefore fewer assumptions of the data needed to be met. The Wilcoxon test compared two conditions (e.g. upright vs. twisted) using the same participants exposed to each condition. It was used because the data was assumed to not be normally distributed and would most likely have violated an assumption of the independent t-test. The

Mann-Whitney U test did something similar but the comparison between conditions was based on different participants taking part. In the case of Study 3 the different participants were the males and females. Statistical significance was accepted at the 5% level ($p<0.05$).

Before the repeated measures analysis of variance (ANOVA) was used the assumptions of parametric data were met. The statistical analysis was used to test for any significant main effects and interactions of exposure (no-vibration control vs. vibration treatment) and posture (upright vs. twisted; with armrests vs. without armrests, for the measures identified in Table 3.6. The Tukey *post-hoc* test was used following the ANOVA to determine the exact nature of the significance between the individual conditions. Statistical significance was accepted at the 5% level ($p<0.05$).

Chapter 4 – Study 1 Part a

Evaluation of risks from whole-body vibration exposure

This chapter discusses a large scale field study designed to establish the types of earthmoving machines that pose the greatest risk to health, and therefore the machines that need to be targeted for whole-body vibration health risk assessments. Research was carried out under real operating conditions to investigate the magnitudes of occupational exposure to whole-body vibration. The study aimed to quantify whole-body vibration emission found in earthmoving machines from different types of construction, mining, scrap metal, and landfill sites. This enabled estimates of operators' daily exposure to whole-body vibration to be determined, and to consider the consequences of different work patterns on the operators' exposure profile (in line with the current regulations).

4.1 Introduction

The introduction throughout Europe of the Physical Agents (Vibration) Directive (2002) has resulted in heightened awareness of the possible risks associated with high magnitude chronic exposure to whole-body vibration (WBV), and the requirement to perform risk assessments. The PA(V)D (2002) specifies that where there is likely to be a risk from vibration exposure employers are required to assess the exposure levels.

Attempts have already been made to estimate the exposure profiles for on- and off-road vehicles. It is clear that overall profiles demonstrate that operators driving off-road machines will be exposed to greater magnitudes of vibration, particularly in the horizontal directions, when compared with drivers of on-road vehicles. This is mainly due to the nature of the working environment; the road surface has a big influence on the vibration characteristics (Von Gierke *et al.*, 1991; Ahlin *et al.*, 2002; Paddan, 2003). On-road machines will generally be operating on smoother roads and will therefore only experience similar conditions if the operator is driving the machine over a poorly maintained road with potholes and irregular surfaces (Paddan *et al.*, 1999; Paddan and Griffin, 2001). Earthmoving machines, in particular, are adapted to working on mixed terrain conditions and in some cases they are responsible for shaping the rough terrain. Another concern is heavy machines tend to expose operators to lower frequencies which coincides with the most sensitive frequencies of the body (Griffin, 1990).

Measurements and assessment of risks from vibration have been in occurrence for over 30 years. It is the methods used and the evaluation of risk that has evolved throughout the centuries. In the Seventies Boulanger *et al.* (1978) measured a small selection of machines in a working quarry. Despite the advancement of machines the r.m.s. values of the bulldozers and mechanical scrapers are at the lower end of the scale compared to more recent data (Cann *et al.*, 2003; Mansfield, 2003). This is contrary to presumptions that today's machines should be engineered to a higher standard with lower vibration emission. The methods used back then could have underestimated the risks, considering different frequency weightings and equipment were used. However, it could also be due to the operating conditions of the machines and the driving style of the operators. Although variability between measurement conditions will always exist it is important to ensure the methods used to evaluate WBV are consistent so that this factor can be excluded as one of the possible sources of variation.

Comparison of the WBV measurements throughout the 21st Century still highlight discrepancies between the methods used and the vibration magnitudes of different categories of machines. This makes it more difficult to compare across the different studies, Kittusamy (2000) for example, used the older version of ISO2631 (1985) to evaluate WBV in heavy construction vehicles. Cann *et al.* (2003) measured similar machines in accordance with ISO 2631-1 but used the frequency weightings from BS6841 (1987) without the multiplication factors. Mansfield (2003) used frequency weightings from ISO2631-1 (1997) and presented the data with and without the multiplication factors (1.4 for x-and y- and 1.0 for z-axis). The latter study adopted the methods most commonly used since the introduction of the PA(V)D, however the sample size was still too small and measurement durations too short to make any inferences about the typical vibration profiles of the machines. In order to provide greater knowledge of the risks facing operators today, the study reported in this chapter targeted a large sample of earthmoving machines and evaluated health risks using the same methodology as outlined in the PA(V)D (2002) and ISO2631-1 (1997).

Previous studies have collected some data on the earthmoving machine types targeted for this study. Some of the machine types produced higher vibration emissions in one particular direction. The study by Cann *et al.* (2003) is excluded from this selection due to the absence of multiplication factors and the inability to apply them because only the worst axes are shown. If this data was included it would underestimate the horizontal vibration and skew the overall data:

- Bulldozers, Dump Trucks and Rollers had dominant vibration in the vertical direction (Paddan *et al.,* 1999; Mansfield, 2003; Mansfield & Atkinson, 2003; NIWL, 2003);

- Articulated Trucks had dominant vibration in the lateral direction (Mansfield, 2003);

- Wheel Loaders alternated between both of the horizontal axes, lateral and/or fore-and-aft (Mansfield, 2003; NIWL, 2003);

- Excavators varied in the dominant axis of vibration depending on whether they were excavating (fore-and-aft direction was highest) or tracking (vertical direction was highest) (Paddan *et al.,* 1999; Gould, 2002; NIWL, 2003);

- Motor Graders had no dominating vibration in any direction (NIWL, 2003).

The machines which produced the highest vibration magnitudes, on average, included the bulldozers and articulated trucks, followed by the wheel loaders. Three of the excavators were found to expose operators to vibration greater than the exposure limit value of the PA(V)D. This is most likely because these machines were performing erroneous tasks for the size of the machines, for example, flattening earth and moving steel plates (Gould, 2002). Machines with crawlers (tracks) appear to expose operators to higher vibration magnitudes due to the nature of their work and the design of the machines. It is hypothesised that machines with crawlers will expose operators to the highest vibration magnitudes in the current study, during tracking movements (i.e. moving on tracks). Over 60% of all the machines from the meta-analysis exceeded the exposure action value of the PA(V)D. It is therefore not unrealistic to expect a similar percentage of the machines in the current study to also exceed 0.5 m/s^2 r.m.s. Although a few of the measurements exceeded the PA(V)D limit value it is unlikely that any of the machines targeted for this study will exceed the limit within an 8-hour period. Mansfield (2003) found machines in the quarrying industry would only exceed the action value set out by the PA(V)D. They would not exceed the limit value unless the workers are exposed to the vibration levels for longer than 40 hours a week.

Tracked loaders are another type of machine targeted in this study. To the best of the authors knowledge (when the study commenced) only one paper had published data for these machines (Cann *et al.,* 2003). They are similar to wheel loaders in their overall design but the chassis sits on crawlers instead of tyres. One could assume because of their design and ability to travel over rough terrain they are going to exceed the action value like the machines measured by Cann *et al.* (2003). The tracked

loaders worst axis of vibration was in the fore-and-aft direction (mean 1.01 m/s^2 ± 0.18 σ). With the inclusion of these machines in the overall machine sample, it is hypothesised that 'over seventy percent machines will expose their operators to vibration above the action value.'

Surveys have been produced for the Health and Safety Executive (HSE) looking at a larger selection of machinery (Paddan et al., 1999; Paddan and Griffin, 2001). The studies attempt to characterise the vibration profiles for a large range of machines, however, many have not assessed multiple numbers of the machine types targeted for this study. Some studies have focused on multiple samples, but on one type of machine, for example Rehn (2004) measured all-terrain vehicles, and Gould (2002) only measured excavators.

The research at the time also failed to measure for acceptable lengths of time. One group of researchers determined that the minimum measurement duration should be at least 30 minutes and preferably 1 hour to ensure an accurate estimate of the daily exposure is obtained (Mansfield et al., 2003; Mansfield and Atkinson, 2003). This study aims to target specific types of earthmoving machines and take a larger sample of each type of machine to enable comparisons to be made for different operations, sites and variation to determine how much difference should be accounted for in a health risk assessment.

4.2 Hypotheses

It is important to establish if there are typical magnitudes of whole-body vibration encountered in different machine types while operating in real working environments. The aim of this research was to evaluate WBV magnitudes from the seat of operators over a large selection of earthmoving machines. The findings will highlight the machines that pose the greatest health risk to their operators so that risk reduction measures can be put in place. The study was designed to test the following hypotheses:

Hyp^1: Machines with crawlers performing tracking tasks will produce the greatest whole-body vibration emission.

Hyp^2: Lateral vibration will dominate the exposure profile for articulated trucks*.

Hyp^3: Vertical vibration will dominate the exposure profile for bulldozers; dump trucks; and rollers*.

Hyp^4: Fore-and-aft vibration will dominate the exposure profile for excavators during digging tasks; wheel loaders during loading tasks; and tracked loaders during earthmoving tasks*.

Hyp^5: Over 70% of the machines will exceed the exposure action value of the Physical Agents (Vibration) Directive within 8-hours of operation.

Hyp^6: No machines will exceed the exposure limit value of the Physical Agents (Vibration) Directive within 8-hours of operation.

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* Acceptance criteria is based on 75% of the measurements meeting the assumptions of the hypothesis

4.3 Experimental Method

The experimental method was designed to answer the hypotheses; this involved taking long measurements of whole-body vibration on 43 earthmoving machines during January to November 2004. Repeat measurements were taken twice, three times or four times on 7 different types of machines, this made 61 whole-body vibration measurements in total. Machine groups included wheel loaders, tracked loaders, skid steer loader, bulldozers, motor graders, articulated dump trucks, rigid dump trucks, excavators, material handler, compacter, rollers and challenger (tracked tractor). A range of industry sectors in the UK were targeted from granite quarries to construction sites. Machines of the same type and model were evaluated at the different sites to allow for comparison across the variety of working environments. Repeat measurements were made at four of the sites on a variety of machines; this included four wheel loaders, two track loaders, two articulated trucks, one motor grader and one excavator. In total 10 different sites were visited to collect data. The breakdown of sites and machines are presented in Appendix A3. Details of the machines' operations and terrain characteristics are presented in Chapter 3.

4.3.1 Machines and Operator Characteristics

The machines and operators that took part in the study are presented in Table 4.1. Pictures of the machines are provided in Appendix A4. The study was designed so that minimal interference was caused to the operators who were required to perform their daily work tasks. In order to achieve this equipment set-up was completed as fully as possible before approaching the machine and operator. The equipment was set-up in the machine during break times or periods of inactivity. Information about the machine and operator was also collected during these times.

Table 4.1. Characteristics of machines measured in this study and details of machine operators

Machine Characteristics			Operator Characteristics		
Type (ID)	Model	Weight (kg)	Age (years)	Height (metres)	Weight (kg)
Bulldozer (BD1)	D31E	~6270	60	1.80	105
Bulldozer (BD2)	D3G	~7810	40	1.78	102
Bulldozer (BD3)	D5N	~13250	20	1.85	73
Bulldozer (BD4)	D6M	~16500	58	1.73	89
Bulldozer (BD5)	D85EX	~28000	57	1.65	89
Bulldozer (BD6)	D7RII	~34900	46	1.78	92
Bulldozer (BD7)	D8R	~37875	54	1.84	116
Bulldozer (BD8)	D9R	~48520	51	1.73	89
Tracked loader (TL1)**	953C	~15145	58	1.96	114
Tracked loader (TL2)**	953	~15145	48	1.80	73
Tracked loader (TL3)	953C	~15145	62	1.88	102
Tracked loader (TL4)	963B	~19589	62	1.88	102
Tracked loader (TL5)	963B	~19589	60	1.68	102
Tracked loader (TL6)	963B	~19589	55	1.78	86
Wheeled loader (WL1)	966F	~22590	54	1.88	102
Wheeled loader(WL2^{Op1})**	972G	~22590	42	1.68	92
Wheeled loader(WL2^{Op2})**	972G	~22590	48	1.73	92
Wheeled loader (WL3)***	972G	~25490	53	1.73	127
Wheeled loader (WL4)**	970F	~73780	59	1.83	86
Wheeled loader (WL5)	L180D	~27000	44	1.73	76
Wheeled loader (WL6)	980G	~30500	39	1.68	64
Wheeled loader (WL7)	980G	~30500	58	1.73	67
Wheeled loader (WL8)	980G	~30207	50	1.75	79
Wheeled loader(WL9)****	988F	~46454	36	1.78	83

**Repeat measurements made on two occasions; ***Repeat measurements made on three occasions; ****Repeat measurements made on four occasions

92

Machine Characteristics			Operator Characteristics		
Type (ID)	Model	Weight (kg)	Age (years)	Height (meters)	Weight (kg)
Articulated Trucks (AT1)	TA30	~27000	57	1.68	79
Articulated Trucks (AT2)**	735	~29760	51	1.68	57
Articulated Trucks (AT3)***	A40D	~31270	24	1.80	76
Dump Trucks (DT1)	777B	~85000	48	1.73	67
Dump Trucks (DT2)	777D	~15778	45	1.76	79
Dump Trucks (DT3)	777B	~85000	65	1.73	83
Motor Grader (MG1)**	16H	~24748	47	1.83	115
Motor Grader (MG2)	16H	~35000	60	1.85	95
Motor Grader (MG3)	14G	~18440	58	1.73	111
Excavator (EX1)***	345BL	~50540	55	1.85	111
Excavator (EX2)	70CL	~7000	29	1.97	105
Excavator (EX3)	320CL	~23950	54	1.68	70
Excavator (EX4)	RH30	~78000	48	1.73	92
Roller (R1)	BW216	~15630	21	1.73	64
Roller (R2)	BW213	~12130	36	1.78	83
Roller (R3)	BW219	~20700	29	1.80	80
Skid Steer (SSL)	753	~2223	33	1.75	89
Material Handler (MH)	M325C	~30000	40	1.88	108
Compactor (CP)	825G	~32734	36	1.78	83
Challenger (CL)	85D	~15286	22	1.70	70

**Repeat measurements made on two occasions; ***Repeat measurements made on three occasions; ****Repeat measurements made on four occasions

4.4   Experimental Procedure

Measurement durations varied depending on the operation of the machine. The average measurement duration was 131 ± 67(σ) minutes (range 22 - 326 minutes).

However, in common with many types of earth moving machines, the work usually required some waiting time where the machine was stationary (e.g. waiting for another operator to suitably position a lorry; queuing at a site bottleneck).

The vibration measurements were conducted according to ISO 2631-1 (1997) and the Physical Agents (Vibration) Directive (2002). Two sets of instrumentation were used, one for real time acceleration and one for averaged metrics. Both instruments had a tri-axial accelerometer fitted to the seat pan in a flexible disc beneath the ischial tuberosities (presented in Chapter 3). The accelerometer measured vibration in 3 translational axes; the fore-and-aft (x-axis), lateral (y-axis), and vertical (z-axis) direction. The first set of instrumentation was a Biometrics DataLogger with anti-aliasing filters; it recorded the raw data sampled at 500Hz. The data was downloaded to a PC for post-analysis using software developed in LabVIEW, and compliant with ISO 8041 (2005). The second set of instrumentation, the Larson Davis meters, conditioned the vibration signal and logged the r.m.s. data every 10 seconds, with the vibration dose values integrated over 1-minute periods.

For both sets of instrumentation the acceleration signals were frequency weighted according to ISO 2631-1 (1997). Weighting W_k (frequency range 0.5 − 80 Hz) was used in the vertical direction and weighting W_d (0.5 − 80 Hz) was used in the horizontal directions.

4.4.1 Analysis Procedure

The analysis was carried out using a two-stage process. The first stage involved post-analysis of the vibration metrics for the entire measurement acceleration history, of every machine. The second stage of the process involved correlating GPS data with the acquired running r.m.s. data in order to synchronise both data sets; an example of this process is illustrated in Chapter 3. This process enabled the stationary periods in the measurement to be identified and taken into account when calculating the machine emission value. The calculation for this is presented in Equation 4.1. The weightings and multiplying factors from ISO2631-1 (1997) have been applied to the r.m.s. metrics. Additionally, the horizontal axes (x-axis and y-axis) were multiplied by a factor of 1.4 to account for the sensitivity of the human body to this direction of vibration.

$$a_{exp} = \sqrt{\frac{T_{md}}{T_{exp}}(a_{md})^2}$$

<div align="right">Equation 4.1</div>

Where:

a_{exp} is the r.m.s. value minus stationary break periods

T_{md} is the full measurement duration

T_{exp} is the measurement duration minus stationary break periods

a_{md} is the r.m.s. of the full measurement duration

4.4.2 Power Spectral Density Values

Power Spectral Density (PSD) calculations were also performed. The spectral density indicates how the energy of the vibration is distributed with response to frequency. The parameter of the PSD calculation included window size (4096 samples), overlap (50%) and window function (Hanning). The window size chosen resulted in the calculation of PSDs with a frequency resolution of 0.12 Hz.

4.4.3 Observations and Task Analysis

Observations of video data and high level task analysis allowed for identification of any distinct tasks encountered during the operating cycle, e.g. loading versus hauling. This enabled comparison of such tasks to help identify tasks that subjected operators to the greatest amounts of vibration exposure. It also enabled information to be recorded about the typical postures adopted by the machine operators.

4.5 Results

This section discusses the findings from the field measurements of whole-body vibration in earth moving machines. It has been split into three main sections; the first Section 4.5.1 discusses the whole-body vibration emission values produced by each machine, grouped by machine type. Within this section is a sub-section (4.5.2) discussing the power spectra of the machines; and a sub-section (4.5.3) discussing the relationships between the machine types' worst axis of vibration. The second section

compares the findings to the European Physical Agents (Vibration) Directive and highlights the machines which pose the greatest risk to operators. The third section (4.5.5) discusses the observations and confounding evidence that can influence the evaluation of risk from WBV. Within this section there are a number of sub-sections discussing the effect of task change on WBV (4.5.5.1); the human factors design issues (4.5.6); seating and cab design (4.5.6.1) and the impact of organisational and social issues on the assessment of risk (4.5.6.2).

4.5.1 Whole-Body Vibration Emission Values

Emission values are presented in this section for all the machines measured during the study. The emission values include natural pauses in the work where the machine is stationary for a short period of time e.g. waiting for a bottleneck at a crusher. It does not, however, contain periods when the machine is stationary and the operator is out of the machine for a break or when they are sorting out a problem. Measurement durations were typically 102 ± 58 minutes (range 12.2 – 273). The minimum duration was the skid steer loader operating at a builder's yard. Unfortunately due to the limited operation of the machine this was the maximum duration that could be measured. The machine types have been categorised into the following groups for analysis and presentation of the results:

- Bulldozers
- Tracked Loaders
- Wheel Loaders
- Articulated Trucks
- Rigid Dump Trucks
- Motor Graders
- Excavators
- Rollers
- Other – miscellaneous machines

Figure 4.1 presents the individual emission data. Nearly all the machines produced vibration emission below 1.0 m/s^2, with the exception of one bulldozer, one tracked loader and a challenger tractor. All of the bulldozers, tracked loaders and articulated trucks produced emission values greater than 0.5 m/s^2 in either one, two or three directions of vibration. The severity of these emission values are compared with the PA(V)D limits in Section 4.5.4.

96
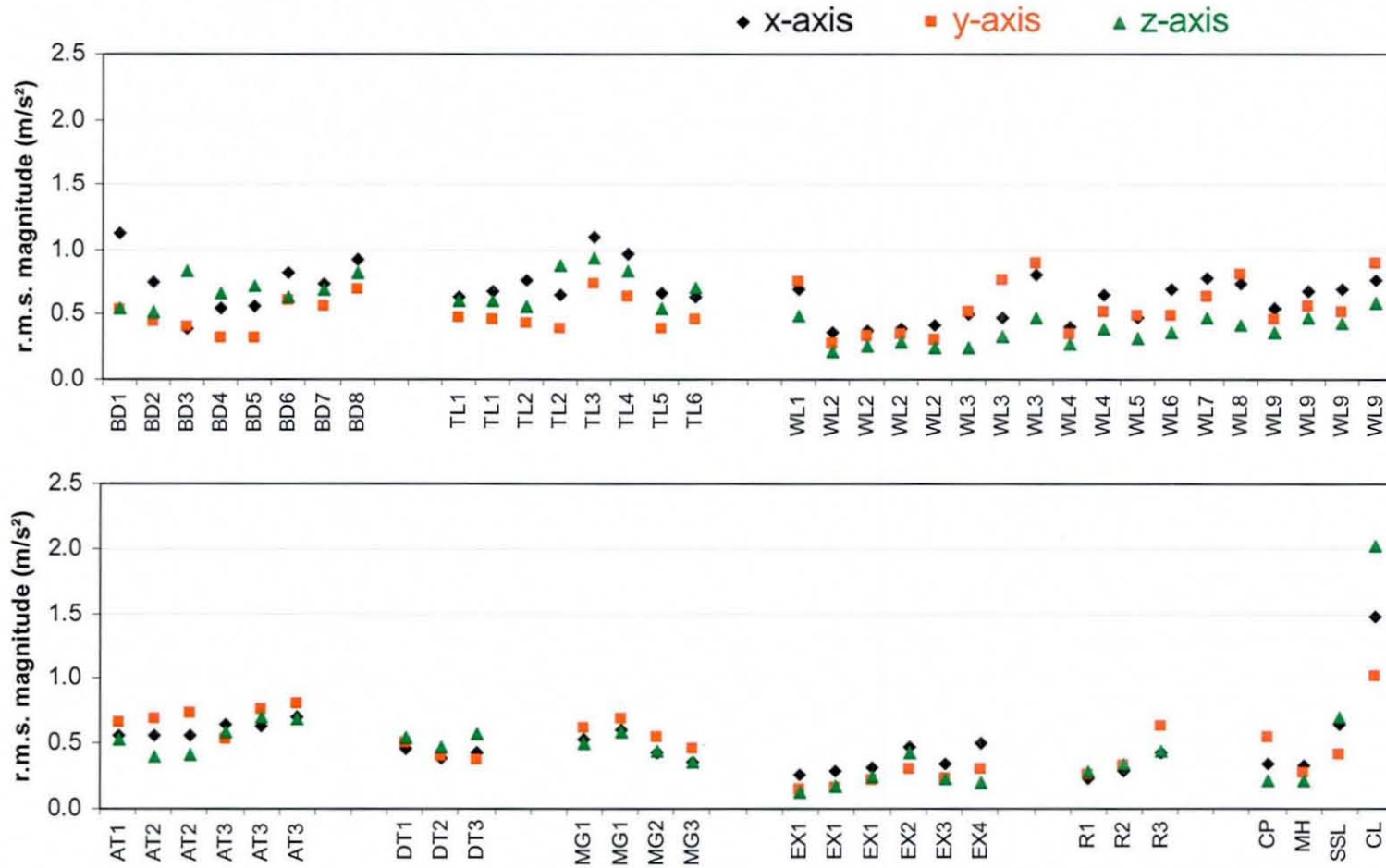
Figure 4.1 Emission values for all the measurements of earthmoving machines at 10 different work sites. Presented with the ISO2631-1(1997) frequency weightings and multiplication factors for the horizontal axes.

4.5.2 Power Spectral Density

Power spectra measured at the seat of the machines are presented in Appendix A5. The bulldozers primarily have the greatest energy in the fore-and-aft vibration, which is dominated by very low frequency component below 1 Hz. The likely cause of this could be due to manoeuvring and the machine rocking back-and-forth due to changes in the ground profile. There is also some energy in the lateral component above 5 Hz for many of the machines, possibly as a result of the grousers pass frequency. The three machines with the worst axis of vibration in the vertical direction (BD3, 4 and 5) have the highest energy for the vertical component at frequencies above 5 Hz.

The tracked loaders also had high energy in the fore-and-aft vibration dominated by very low frequency components below 1 Hz, most likely due to the same reasons stated above for the bulldozers considering they are both tracked machines. There is also significant lateral vibration at frequencies above 5 Hz but below 15 Hz, particularly for TL4 and TL6, which happen to be the same model of machine. TL2 on one of the measurements and TL6 both have dominant vibration in the vertical axis with most of this energy centred around 5 Hz.

Wheel loaders in the horizontal axes are dominated by low frequency vibration below 1 Hz, as might be expected for such a machine performing a task with rapid and repeated changes of direction. The vertical vibration component had energy at peak frequencies between 2 – 2.5 Hz. The peak is likely to be the result of a bounce mode of the tyres on these wheel loaders. WL9 had significant vertical vibration at 2 Hz while the machine was tasked to clear debris from a quarry blasting site. Despite the high vertical energy at this frequency the lateral vibration still dominated the r.m.s. magnitude.

The remaining earthmoving machines and stationary crusher machine present very different frequency spectra profiles, as could be expected for such a range of machines and tasks. The articulated truck had a vertical vibration component centred around 2.2 Hz, and the dump truck had vertical vibration lower than this centred around 1.6 Hz. Both of the motor graders had vertical vibration component centred around 2.2 Hz, however MG2 had significantly more vertical energy at this frequency compared to MG1. The material handler and compactor both had very low vibration energy across all three axes. The skid steer loader had some energy in the vertical and fore-and-aft components centred between 2 – 4 Hz. The final machine presented

is the Pegson Crusher, this machine had high vertical vibration energy between 12 – 14 Hz.

4.5.3 Comparison of Worst Axis across Machine Types

The worst axis has been determined for every measurement. Although the worst axis varied between different machine types and between different measurements, there were some underlying trends found between machines in each category.

4.5.3.1 Tracked Machines

Three different categories of tracked machines are presented in Table 4.2 including bulldozers, tracked loaders and excavators. The worst vibration axis for 77% of the machines investigated was the fore-and-aft, with the remaining 23% of machines exhibiting the highest vibration magnitudes in the vertical direction.

The dominant axis of vibration occurred in the fore-and-aft direction for five of the dozer measurements and in the vertical direction for three of the measurements. There was no relationship found between the size / weight of the dozers and the dominant axis of vibration. Nevertheless, it should be noted the small and large machines exhibit the worst axis in the fore-and-aft direction and the medium sized machines exhibited the worst axis in the vertical direction.

The smallest machine, BD1, exhibited the greatest vibration magnitudes in the fore-and-aft direction of all machines in the sample. The second smallest machine, BD2, did not exhibit similar vibration magnitudes even though this machine was operating in the same work area. This suggests that terrain did not influence the difference found between these two machines, the work cycle durations were also similar between machines. One possible cause of this difference could be the age of the machines: BD2 was a new machine and BD1 was over 5 years old. Another possibility is due to the design of the machine, the machines were from different machine manufacturers and so the shape of the body and component parts differed between the dozers. The driving style of the operator is also likely to influence the outcome of the vibration assessment.

Table 4.2 Frequency weighted r.m.s. emission values for machines with tracks

Machine Type	ID	Site (measure)	r.m.s. (m/s²) a_{wx}	a_{wy}	a_{wz}	Duration	Operation
Bull-Dozer	BD1	6 (m1)	1.12	0.53	0.55	97	Level Superficial
Bull-Dozer	BD2	6 (m1)	0.74	0.45	0.52	114	Level Superficial
Bull-Dozer	BD3	1 (m1)	0.40	0.41	0.84	273	Level Granite
Bull-Dozer	BD4	7 (m1)	0.55	0.32	0.66	64	Level SF/Six F
Bull-Dozer	BD5	6 (m1)	0.57	0.32	0.73	153	Level Superficial
Bull-Dozer	BD6	6 (m1)	0.82	0.61	0.64	176	Level Clay/SF
Bull-Dozer	BD7	4 (m1)	0.74	0.57	0.69	115	Level Coal
Bull-Dozer	BD8	4 (m1)	0.92	0.70	0.83	123	Level Coal
Tracked Loader	TL1	7 (m1)	0.63	0.48	0.61	132	Level/Load SF
Tracked Loader	TL1	7 (m2)	0.68	0.46	0.60	26	Level SF
Tracked Loader	TL2	7 (m1)	0.77	0.43	0.57	66	Level SF
Tracked Loader	TL2	7 (m2)	0.65	0.39	0.88	90	Level SF
Tracked Loader	TL3	8 (m1)	1.10	0.74	0.93	21	Move SF/Rocks
Tracked Loader	TL4	8 (m1)	0.97	0.64	0.83	57	Move SF/Rocks
Tracked Loader	TL5	9 (m1)	0.66	0.40	0.55	36	Level/Load TS
Tracked Loader	TL6	10 (m1)	0.64	0.46	0.71	75	Level/Load SF
Excavator	EX1	6 (m1)	0.26	0.15	0.14	155	Load Clay/SF
Excavator	EX1	6 (m2)	0.28	0.16	0.17	144	Load Clay/SF
Excavator	EX1	6 (m3)	0.31	0.21	0.24	45	Load Clay/SF
Excavator	EX2	6 (m1)	0.35	0.23	0.23	37	Load Rocks
Excavator	EX3	6 (m1)	0.47	0.30	0.43	42	Load/Move SF
Excavator	EX4	4 (m1)	0.50	0.30	0.21	83	Load Coal

Note: Worst axis is highlighted. Values are presented with 1.4 multiplication factor for the horizontal axes (SF = Superficials; TS = Top Soil).

The dominant axis of vibration for 6 of the tracked loaders was the fore-and-aft direction and for the remaining 2 the vertical axis was dominant. TL2 produced higher

vertical vibration during the second measurement compared with the first. This changed the dominant axis from the fore-and-aft to the vertical. The operations were different on the two separate occasions; on the first measurement the task involved levelling out earth on a steep incline and on the second the machine was levelling earth on a flatter gradient. TL6 exhibited higher vibration magnitudes in the vertical direction during the levelling operation. TL4 and TL5 were the same model as TL6 yet they did not demonstrate comparable trends for their vibration profiles. This discrepancy could be caused by the increased amount of travel involved in the levelling operation at this site and the type and condition of the seat could have increased the amount of vertical vibration.

The highest vibration magnitudes were measured on TL3 and TL4. These machines were different models and TL4 was heavier than TL3, however, these machines were both measured at the same site and they were both operated by the same operator. It was noted that the operator used the machines more aggressively than the other operators observed in this study. However, the increase in vibration magnitude might also be due to the conditions of the site and the task operation. The tracked loaders were travelling in a small area, requiring the machine to frequently change direction over a range of gradients. Tasks requiring frequent acceleration and deceleration (as occurred on this site) would be expected to have a greater magnitude of fore-and-aft vibration; similarly, machines working on rough terrain would be expected to have elevated vibration magnitudes. As aggressive driving, poor terrain and frequent acceleration and deceleration are all factors likely to increase the vibration magnitude, it is unsurprising the machines operated at this site were those with the greatest vibration magnitudes.

4.5.3.2 Wheel Loaders

Table 4.3 highlights the trends observed in the wheel loaders. One consistent finding for all the wheel loaders is the highest magnitudes of vibration were found in the horizontal axes. The worst axis of vibration was predominantly the x-axis (71% of the machines), with the remaining machines producing the worst vibration in the y-axis (29% of the machines). This difference may be due to the variation in loading cycles. The wheel loaders that have greater amounts of travel in their work cycles may be expected to exhibit higher magnitudes of lateral vibration as the machine travels over more varied ground away from areas designed to be appropriate for road delivery vehicles and at higher speeds. For example, WL9 was measured on four separate occasions and during the fourth measurement the machine was performing a different

task in the quarry pit. This task involved travel over greater areas and subsequently the resulting vibration magnitudes were increased in all axes, especially in the horizontal. The task may also have been performed at higher speeds due to the urgency of clearing the blasting site however the GPS was not able to pick up a signal in that particular area.

Table 4.3 Frequency weighted r.m.s. emission values for wheel loaders

Machine Type	ID	Site (measure)	r.m.s. (m/s²)			Duration	Operation
			a_{wx}	a_{wy}	a_{wz}		
Wheel Loader	WL1	2 (m1)	0.69	0.75	0.49	195	Loading Granite
Wheel Loader	WL2 Op1	4 (m1)	0.38	0.34	0.26	85	Loading Coal
Wheel Loader	WL2 Op2	4 (m1)	0.36	0.28	0.21	35	Loading Coal
Wheel Loader	WL2 Op1	4 (m2)	0.39	0.35	0.29	38	Loading Coal
Wheel Loader	WL2 Op2	4 (m2)	0.42	0.31	0.24	31	Loading Coal
Wheel Loader	WL3	2 (m1)	0.50	0.52	0.25	61	Loading Granite
Wheel Loader	WL3	2 (m2)	0.48	0.77	0.33	152	Loading Granite
Wheel Loader	WL4	4 (m1)	0.41	0.34	0.28	134	Loading Coal
Wheel Loader	WL4	4 (m2)	0.64	0.53	0.39	126	Loading Coal
Wheel Loader	WL5	1 (m1)	0.48	0.50	0.32	181	Loading Granite
Wheel Loader	WL6	5 (m1)	0.70	0.50	0.36	120	Loading Scrap
Wheel Loader	WL7	5 (m1)	0.77	0.64	0.48	45	Loading Scrap
Wheel Loader	WL8	2 (m1)	0.74	0.80	0.42	59	Loading Granite
Wheel Loader	WL9	2 (m1)	0.56	0.46	0.36	184	Loading Granite
Wheel Loader	WL9	2 (m2)	0.68	0.57	0.47	141	Loading Granite
Wheel Loader	WL9	2 (m3)	0.69	0.53	0.44	99	Loading Granite
Wheel Loader	WL9	2 (m4)	0.77	0.89	0.59	23	Pushing Debris

Note: Worst axis is highlighted. Values are presented with 1.4 multiplication factor for the horizontal axes.

4.5.3.3 Trucks, Motor Graders and Rollers

Table 4.4 presents the data for the machines considered to be spending the majority of their task cycle travelling; this includes the articulated trucks, dump trucks and the motor graders. The lateral axis dominates the vibration magnitudes for both the motor graders and articulated trucks. The only deviation from this pattern can be found in one of the three measurements taken on an articulated truck AT3, where the fore-and-aft axis is found to dominate the vibration magnitude. This discrepancy could be attributable to the change in load being carried. The overall weight of the load was different on that particular measurement day, and this could alter the centre of mass of the machine and thus affect the dynamics of the vehicle. The dump trucks produced the highest vibration magnitudes in the vertical direction.

Table 4.4 Frequency weighted r.m.s. emission values for trucks, motor graders and rollers

Machine Type	ID	Site (measure)	r.m.s. (m/s²)			Duration	Operation
			a_{wx}	a_{wy}	a_{wz}		
Articulated Truck	AT1	2 (m1)	0.56	0.65	0.53	147	Transport granite
Articulated Truck	AT2	4 (m1)	0.57	0.70	0.40	120	Transport coal
Articulated Truck	AT2	4 (m2)	0.56	0.73	0.41	109	Transport coal
Articulated Truck	AT3	6 (m1)	0.65	0.53	0.58	161	Transport SF
Articulated Truck	AT3	6 (m2)	0.63	0.76	0.70	60	Transport clay/SF
Articulated Truck	AT3	6 (m3)	0.70	0.81	0.69	150	Transport clay
Dump Truck	DT1	2 (m1)	0.46	0.50	0.54	245	Transport granite
Dump Truck	DT2	2 (m1)	0.39	0.40	0.48	199	Transport granite
Dump Truck	DT3	4 (m1)	0.43	0.37	0.57	134	Transport coal
Motor Grader	MG1	4 (m1)	0.60	0.69	0.59	114	Smooth track
Motor Grader	MG1	4 (m2)	0.54	0.62	0.51	98	Smooth track
Motor Grader	MG2	6 (m1)	0.44	0.54	0.45	143	Smooth clay/lime
Motor Grader	MG3	6 (m1)	0.36	0.46	0.35	146	Smooth clay/lime
Roller	R1	6 (m1)	0.44	0.64	0.45	103	Smooth superficial
Roller	R2	6 (m1)	0.29	0.33	0.35	74	Smooth superficial
Roller	R3	7 (m1)	0.22	0.26	0.28	48	Smooth superficial

4.5.4 Whole-body Vibration Exposure Compared with PA(V)D

The r.m.s. emission values for all of these machines are presented in Figure 4.2. The values fall within one of three categories of magnitudes. Category 1 (0.25 - 0.50 m/s²) presents the machines of least concern as these vibration magnitudes fall below any of the criteria imposed by the Physical Agents (Vibration) Directive for 8-hours of exposure per day. Category 2 (0.50 – 1.00 m/s²) identifies machines of some concern where action needs to be taken to ensure the vibration magnitudes are monitored and reduced where possible. All of the machines in this category would expose operators above the 0.5 m/s² A(8) Exposure Action Value (EAV) during a working day. The high priority category 3 (1.00 m/s² – above) pinpoints the machines of greatest concern, there are only 3 machines in this category. One of the machines in particular would certainly exceed the 1.15 m/s² A(8) Exposure Limit Value (ELV). This will be discussed in the following section.
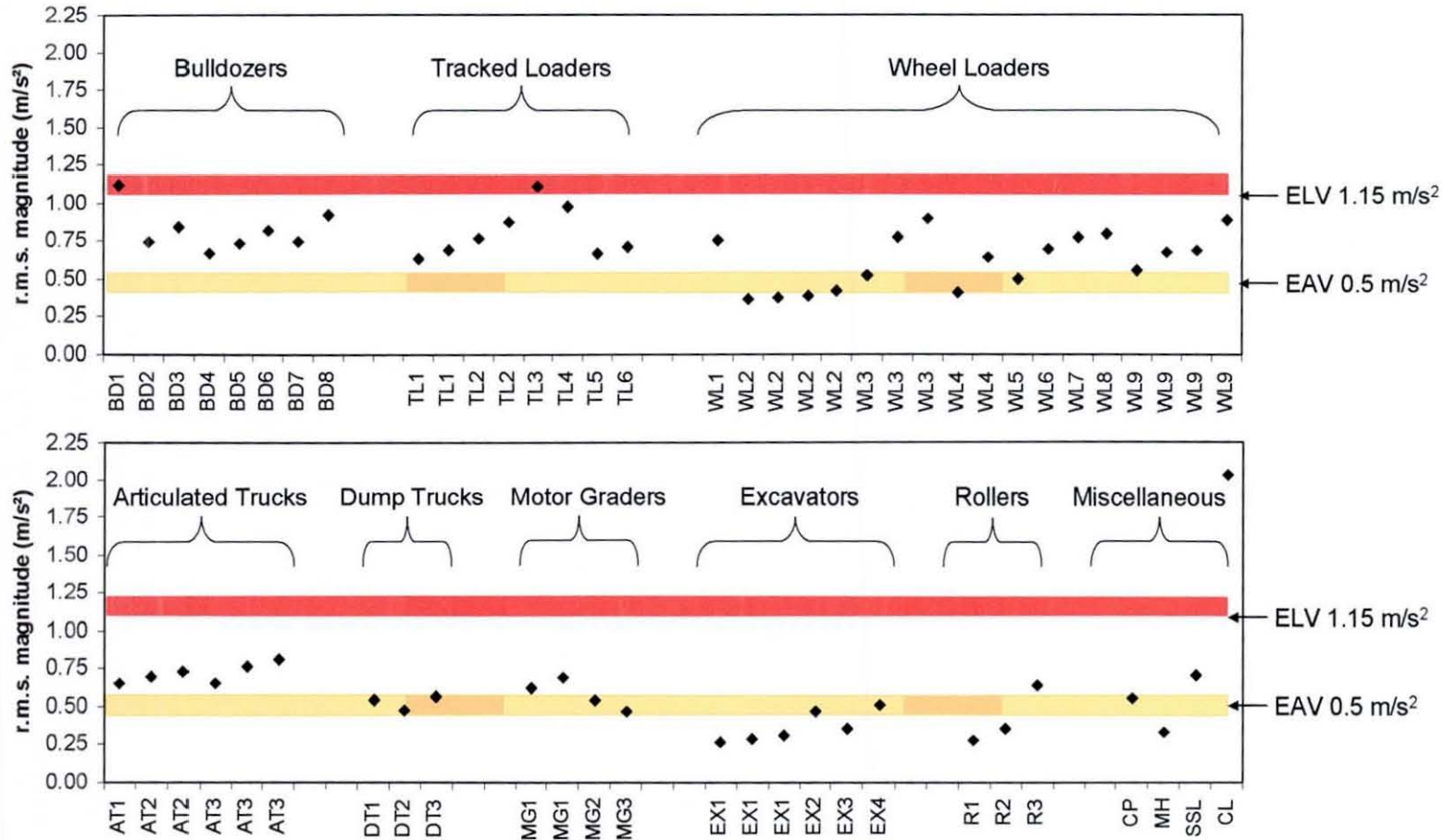
Figure 4.2 Comparison of PA(V)D limits (based on exposure for 8-hour period) with emission values of all the earthmoving machines measured at 10 different work sites. Only the worst axis is presented for each machine.

This section highlights the time it would take for the operators to exceed the EAV and ELV during a typical working day. Table 4.5 highlights the machines propelled by tracks, Table 4.6 highlights the wheel loaders and Table 4.7 presents the trucks, motor graders, rollers and miscellaneous machines. The typical number of hours worked (excluding breaks) has been included in the tables. Although this cannot be interpreted as the "accurate" exposure duration due to periods of inactivity, it can give an indication of the likelihood of the operators exceeding the EAV and ELV. The number of points accumulated per hour is based on the exposure points system developed by the Health and Safety Executive. Once an operator exceeds 100 points they will reach the EAV and once they exceed 529 points they will exceed the ELV.

Table 4.5 Time to PA(V)D Exposure Action and Limit Values for machines with tracks

Machine Type	Worst axis	Action Value		Limit Value		Points per hour	Hours worked
		Hours	Mins	Hours	Mins		
Bull-Dozer 1	1.12	1	35	8	26	63	11
Bull-Dozer 2	0.74	3	39	19	19	27	11
Bull-Dozer 3	0.84	2	50	14	59	35	10
Bull-Dozer 4	0.66	4	35	>24		22	9
Bull-Dozer 5	0.73	3	45	19	51	27	11
Bull-Dozer 6	0.82	2	58	15	44	34	11
Bull-Dozer 7	0.74	3	39	19	19	27	11
Bull-Dozer 8	0.92	2	21	12	30	42	11
Tracked Loader 1	0.63	5	02	>24		20	9
Tracked Loader 1	0.68	4	19	22	52	23	9
Tracked Loader 2	0.77	3	22	17	50	30	9
Tracked Loader 2	0.88	2	34	13	39	39	9
Tracked Loader 3	1.10	1	39	8	44	61	9.5
Tracked Loader 4	0.97	2	07	11	14	47	9.5
Tracked Loader 5	0.66	4	35	>24		22	9.5
Tracked Loader 6	0.71	3	58	20	59	25	8
Excavator 1	0.26	>24		>24		3	11
Excavator 1	0.28	>24		>24		4	11
Excavator 1	0.31	20	48	>24		5	11
Excavator 2	0.35	16	19	>24		6	11
Excavator 3	0.47	9	03	>24		11	11
Excavator 4	0.50	8	00	>24		13	11

Table 4.6 Time to PA(V)D Exposure Action and Limit Values for Wheel Loaders

Machine Type	Wors t axis	Action Value		Limit Value		Points per hour	Hours worked
		Hours	Mins	Hours	Mins		
Wheel Loader 1	0.75	3	33	18	48	28	10.15
Wheel Loader 2 O1	0.38	13	51	>24		7	11
Wheel Loader 2 O2	0.36	15	25	>24		6	11
Wheel Loader 2 O1	0.39	13	08	>24		8	11
Wheel Loader 2 O2	0.42	11	20	>24		9	11
Wheel Loader 3	0.52	7	23	>24		14	10.15
Wheel Loader 3	0.77	3	22	17	50	30	10.15
Wheel Loader 4	0.41	11	53	>24		8	10.15
Wheel Loader 4	0.64	4	52	>24		20	10.15
Wheel Loader 5	0.50	8	00	>24		13	10
Wheel Loader 6	0.70	4	04	21	35	25	9
Wheel Loader 7	0.77	3	22	17	50	30	9
Wheel Loader 8	0.80	3	07	16	31	32	10.15
Wheel Loader 9	0.56	6	22	>24		16	10.15
Wheel Loader 9	0.68	4	19	22	52	23	10.15
Wheel Loader 9	0.69	4	12	22	13	24	10.15
Wheel Loader 9	0.89	2	31	13	21	40	10.15

All of the bulldozers, tracked loaders and articulated trucks would exceed the EAV in half a days work, only one of the bulldozers (BD1) and one of the tracked loaders (TL3) exceeded the limit value on the day tested. However, BD8, TL3 and TL4 all had the potential to exceed the limit value as they all had vibration magnitudes approaching that limit within their normal working hours, so any overtime could have pushed them over. Eight out of the nine wheel loaders would exceed the EAV after half a day. Out of these machines it is important to highlight that two of the wheel loaders measured on more than one occasion produced different emission values during the repeat trials. WL4 for example, on the first measurement would not exceed the EAV during a full day, compared with the second measurement where the machine would exceed the EAV after 5 hours of operation. These differences are discussed further in the variability study presented in Chapter 5.

Table 4.7 Time to PA(V)D Exposure Action and Limit Values for Trucks, Motor Graders, Rollers & Miscellaneous

Machine Type	Worst axis	Action Value		Limit Value		Points per hour	Hours worked
		Hours	Mins	Hours	Mins		
Articulated Truck1	0.65	4	44	>24		21	10.15
Articulated Truck2	0.70	4	04	21	35	25	11
Articulated Truck2	0.73	3	45	19	51	27	11
Articulated Truck3	0.65	4	44	>24		21	11
Articulated Truck3	0.76	3	27	18	19	29	11
Articulated Truck3	0.81	3	02	16	07	33	11
Dump Truck1	0.54	6	51	>24		15	10.15
Dump Truck2	0.48	8	40	>24		12	10.15
Dump Truck3	0.57	6	09	>24		16	11
Motor Grader1	0.69	4	12	22	13	24	11
Motor Grader1	0.62	5	12	>24		19	11
Motor Grader2	0.54	6	51	>24		15	11
Motor Grader3	0.46	9	27	>24		11	11
Roller1	0.64	4	52	>24		20	11
Roller2	0.35	16	19	>24		6	11
Roller3	0.28	>24		>24		4	9
Compactor	0.55	6	36	>24		15	11
Material Handler	0.33	18	21	>24		5	9
Skid Steer Loader	0.71	3	58	20	59	25	1.15
Challenger	2.03	0	29	2	34	206	8

Two out of the four excavators has the potential to reach the EAV in a full days work and all of the dump trucks would exceed the EAV in a full days work. Out of the motor graders one would exceed the EAV after half a day and the remaining two would exceed the EAV after a full day. Only one of the three rollers would exceed the EAV during a full day.

The material handler would not exceed any exposure limits during a typical working day, whereas the compactor is very likely to exceed the EAV. The skid steer loader produces a vibration emission higher than 0.5 m/s^2, yet the machine is only operated for short periods of time totalling around 1¼ hours a day. Therefore this machine is unlikely to exceed the EAV during a typical day's operation. If this machine was operated in a construction site by an employee who also operated additional vibrating machines then it could become problematic.

The worst machine out of all the ones measured for this study was the challenger tractor. It would exceed the EAV in half an hour and the ELV in 2½ hours. Despite this the machine is continuously operated for 8 hours a day. The machine's primary task was to flatten the ground ready for building construction to commence. The attachment with this machine was called a "Hex" (Figure 4.3), considering the vibration magnitudes produced during this operation it is not surprising to find the attachment is not authorised for use with this type of machine by the manufacturer.

Figure 4.3 Challenger tractor flattening ground with an unauthorised hex attachment

4.5.5 Observations and Confounding Factors for the Evaluation of Risk

There are many factors that can influence the assessment of risk from exposure to whole-body vibration. In order to test some of the assumptions about these confounding factors a number of mini-studies were carried out along side the field study. Observations of the working environment were also recorded during the trials. They are discussed in the following section.

4.5.5.1 Effect of Task Change on Whole-Body Vibration Emission/Exposure

During the study there were limited opportunities to measure the vibration magnitudes of certain machines carrying out different task operations. The machines performing different tasks included a selection of the tracked loaders (loading cycles versus levelling the ground and travelling), one wheel loader (performing loading cycles and pushing operations), and a separate wheel loader (loading a crusher machine on one occasion, and a train on the second). The trucks investigated during this project were also carrying out a variety of tasks including travelling loaded and unloaded and being loaded. The findings from these machines are presented in the following section.

Some of the machines were measured using the Larson Davis meters; this meant their task cycle could not be broken down in certain cases because of the short task duration.

4.5.5.2 Articulated and Dump Trucks Task Breakdown

The breakdown of the articulated and rigid dump trucks operations are presented in Figure 4.4. The three tasks included travelling loaded, travelling unloaded and being loaded. The main trend in both the articulated and the dump trucks is the lowest magnitudes of vibration are always found while the trucks are being loaded. This is not surprising as the machines are nominally stationary during this operation. When the machines are travelling unloaded the fore-and-aft vibration is consistently higher compared with the machines travelling with a full load, where the lateral vibration is greater. This could be due to the change in pitch mode of the machines when the back is lighter. Similar trends can be observed in the vertical axis; however, the difference is not as great. With a smaller load the machine is likely to rock more due to the decrease in stabilisation weight from front to back.
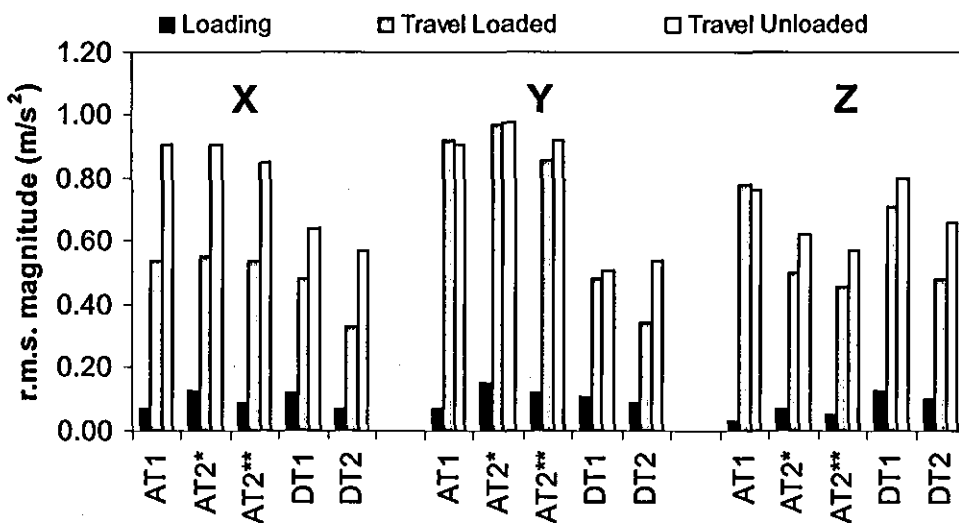
Figure 4.4 Frequency weighted acceleration for individual tasks of articulated dump trucks and rigid dump trucks. Horizontal axes are presented with 1.4 multiplication factor (note: *day 1 measurement and **day 2 measurement).

4.5.5.3 Tracked Loaders Task Breakdown

Three of the track-type loaders measured during the project carried out a variety of tasks during data collection. This included loading aggregate lorries, levelling the ground and travelling on concrete or top soil / demolition material (presented in Figure 4.5). For TL1, the loading tasks exposed the operator to the highest magnitudes of

vibration in each axis whilst travelling exposed the operators to the lowest magnitudes of vibration. In the x-axis, trends were similar for TL5 and TL6. Travelling exposed the operator to the greatest magnitudes of vibration; levelling exposed the operator to the lowest magnitudes of vibration. However, the highest magnitudes of vibration measured on machine 6 occurred in the z-direction for the levelling task. For travelling, the magnitudes measured in the x- and z-directions both equalled 0.85 m/s^2 r.m.s. The difference between the vibration magnitudes in the x-direction for TL1 when compared to TL5 and TL6 could be caused by the differences in terrain conditions: TL1 was travelling on concrete whilst the other machines were travelling off-road over top soil or demolition material.
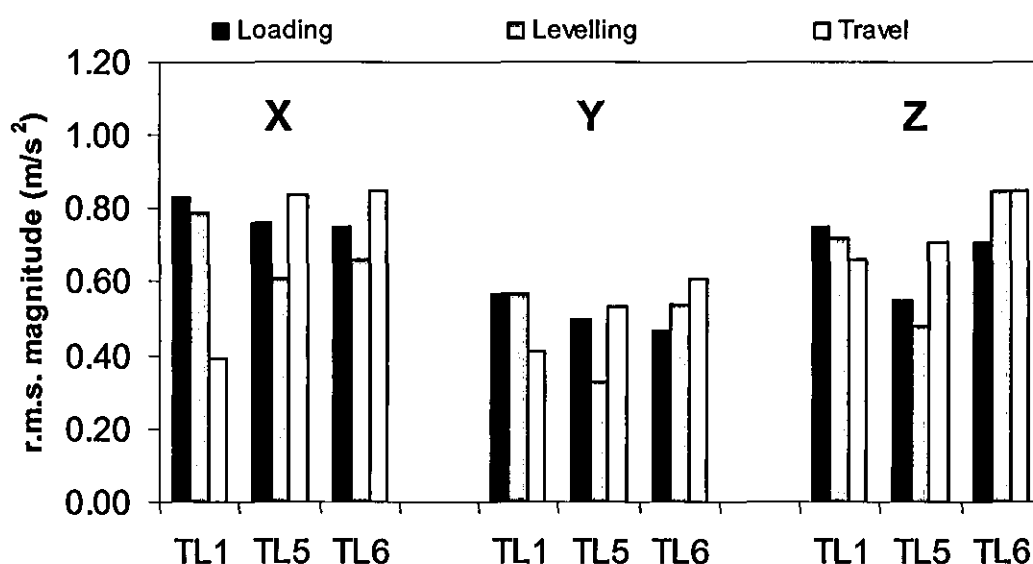
Figure 4.5 Frequency weighted acceleration for individual tasks of tracked loaders. Tasks include; loading (black fill), levelling (grey fill) and travel (white fill). Horizontal axes are presented with 1.4 multiplication factor. (Note: 'TL1' was travelling on concrete; both 'TL5' and 'TL6' were travelling on top soil).

4.5.5.4 Wheel Loaders Task Breakdown

Only two of the wheel loaders investigated during the testing period carried out distinctly different tasks. Wheel Loader 9 was measured on 4 different occasions. Three of the measurements captured the machine loading crushed granite material into an aggregate lorry. The remaining measure captured the vibration profile after a quarry blasting operation. The machine was required to manoeuvre large pieces of rock debris into piles at the quarry face. Data are presented in Figure 4.6. The different tasks carried out by the operator of this wheel loader demonstrate how the task demands can influence the resulting vibration emission value. The increased vibration experienced during this operation may be due to a combination of factors.

The operator may adopt a more aggressive driving style during this operation compared with the loading operation as they experience greater time constraints; they would be subjected to harder driving conditions on the uneven rocky quarry floor; and greater speeds whilst the machine is travelling to the quarry pit. Unfortunately this could not be verified with the GPS system as it could not acquire a signal at the quarry face.
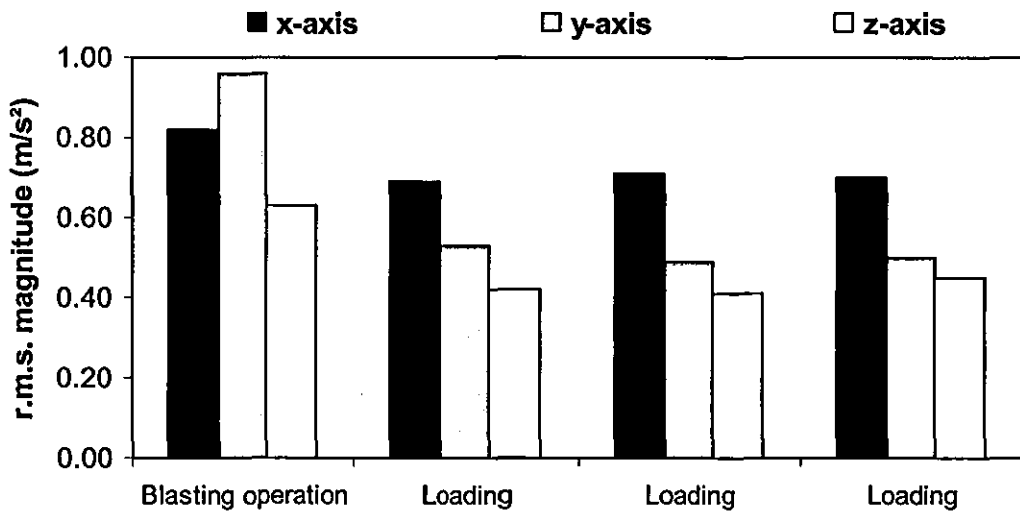
Figure 4.6. Frequency weighted accelerations for wheel loader 9 carrying out different tasks at site 2. Horizontal axes are presented with the 1.4 multiplication factor.

Wheel loader 4 was carrying out two distinct tasks. The first one involved loading a train with coal and the second task involved loading the crusher machine with coal. Predominantly the tasks are very similar, as in both instances the wheel loader is collecting coal from a stock pile and delivering it to either the crusher or the rail wagon. However a fundamental difference is during the crusher operation the wheel loader travelled forward and backwards along a straight path from the stock pile to the crusher, during the train operation the WL was continuously changing direction within a smaller area. This could be one of the contributing factors for the increased vibration magnitudes experienced during the train operation. Another factor could be due to the time constraints of the train trying to keep to a tight schedule. Figure 4.7 highlights the differences found between these two operations; the vibration magnitudes are 36, 36 and 28% higher for the fore-and-aft, lateral and vertical directions while the machine is loading the cargo train.
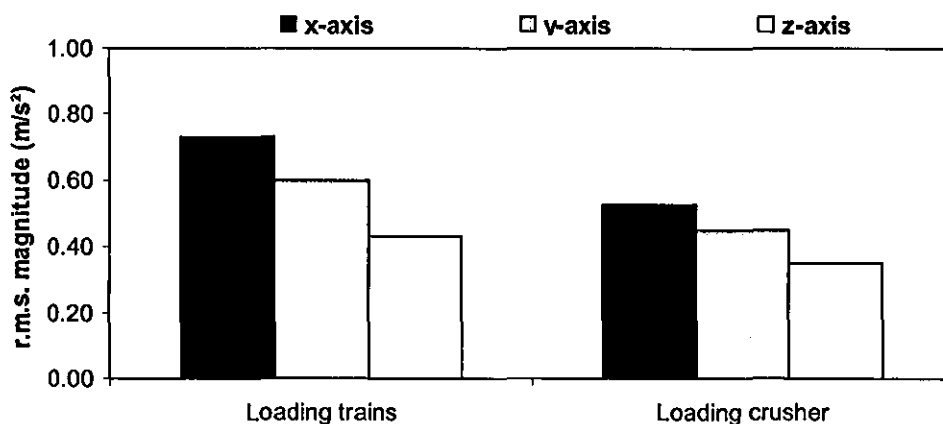
Figure 4.7 Wheel Loader 4 carrying out different loading tasks at site 4. Values are presented with 1.4 multiplication factor for the horizontal axes.

4.5.6 Human Factors Engineering Issues for WBV Exposure

4.5.6.1 Seating Postures and Cab Design

Observations and discussions with the drivers highlighted a number of concerns with the seating and overall cab design. Smaller cabs restricted visibility in addition to the obstructions from the external equipment, for example, the bucket and boom. Depending on the machine type and task there were a number of specific observations recorded for the types of postures adopted. these are highlighted in Table 4.8. Tracked mobile machines were characterised by regular twisting during reversing manoeuvres. Bulldozer operators, in particular, were found to adopt twisted postures, greater than 20° from neutral in the trunk and neck. Due to the size of the machine and nature of the tasks performed the operators were usually required to manoeuvre over large areas of ground. The result of this meant that operators were adopting twisted postures for extended periods of time in order to maintain good visibility in the direction of travel. Tracked loader operators were also found to adopt twisted postures of a similar degree of rotation. However, the nature of the tasks performed by this machine prevented the operators from being exposed to long periods of static twisted postures and they occurred less frequently than in the bulldozers.

Wheel loaders were characterised by forward facing postures combined with occasional twisting and bending of the back and neck, during 'v' shape motion operations. In certain cases operators complained about the vibration transmitted through the hand operated controls.

Drivers of articulated and dump trucks were found to spend the majority of their time in a forward facing posture. During the task cycle they were also found to bend their neck

113

to the side just below the horizontal in order to view the rear of the vehicle with the side-view mirror. The drivers of the dump trucks also had very restricted visibility in all directions due to the size of the machine and the height of the cab.

Motor graders were characterised with mainly forward facing postures with occasional flexion of the neck and even less frequent twisting of the trunk, during backing up manoeuvres. Operators of the roller machines were also found to adopt mainly forward facing postures with occasional twisting. Excavators, on the other hand, were found to adopt a flexed neck and bent trunk position during excavation of deep earth. They did have regular break periods in between while they were waiting for the next lorry to arrive.

The typical arm postures varied greatly between the different machines and different operations. A variety of different designs were found in the operator cabs (presented in Figure 4.8). Not all of the operators chose to use the armrests even if they were provided. This may be due to a number of reasons, they could have interfered with the driver's task, they may have been uncomfortable and not ergonomically correct for the driver's posture (un-adjustable, wrong size) or perhaps they have become accustomed to driving without them.

Figure 4.8 Example of armrest arrangements and different seats mounted in the machines

Table 4.8 Typical Work Tasks and Postures Adopted during Operation of Machines

Machine Type	Work Tasks	Postural Observations
Bulldozers (8)	Levelling Tracking Ripping	Upright posture and regular twisting of the trunk (>20°) and neck during reversing manoeuvres. Mainly static prolonged twists on longer ground. Arms supported with or without armrests during operation of controls (armrests depends on cab design)
Tracked Loaders (6)	Levelling Loading Tracking	Upright posture and regular twisting of the trunk (>20°) and neck during reversing manoeuvres. Mainly static prolonged twists on longer ground. Operations over shorter distances with direction changes involved operators twisting regularly. Arms resting on armrests operating controls (control location depends on cab design)
Wheel Loaders (8)	Loading/unloading Travelling Scraping	Mainly upright posture with occasional twisting and bending of the back and neck Arms supported (depending on cab design) during operation of bucket controls. Some cases drivers complained of hand-arm vibration from the controls. Arms are unsupported and shoulders raised, when grasping the steering wheel during manoeuvres and travelling.
Articulated Trucks (3)	Transportation of materials	Upright posture with occasional side bend of the neck to look in side-view mirror Arms unsupported and raised in order to grasp the steering wheel.
Dump Trucks (3)	Transportation of materials	Upright posture with occasional side bend of the neck to look in side-view mirror Very poor visibility from the cab
Motor Graders (3)	Smoothing terrain	Upright posture with occasional flexion of the neck and very infrequent twisting of the trunk during reversing manoeuvre.
Excavators (4)	Excavating earth Moving earth from mounds Loading trucks Tracking	Flexion of the neck and bending of the back during excavation of deep earth. Upright posture (~0°) adopted during loading tasks and tracking Arms are mainly supported with armrests during operation of controls. Some of the armrests were not adjustable.
Rollers (3)	Smoothing terrain	Mainly upright posture with infrequent twisting Arms are unsupported and raised slightly to grasp steering wheel. Positioned across the midline of the body.

115

4.5.6.2 Organisational and Social Issues

Organisational constraints and social pressures also need to be taken into account for a health risk assessment. For example, at a number of the sites operators are required to unblock crusher machines when rocks or other material become jammed. One of these machines (Pegson Crusher) was measured at Site 6. Findings indicated that vibrations dominated in the vertical axis (z-axis) with an r.m.s. value of 1.68 m/s², that amounts to 141 points per hour or only 42 minutes to reach the EAV. If this machine was not maintained properly and required regular attention it could push an operators overall exposure above the limit value threshold. Factors like this need to be taken into consideration for a WBV health risk assessment.

Additional social and organisational factors identified included:

♦ Increased pressure to get the job done in many of the organisations, especially the road construction due to large financial penalties if the job ran over the deadline.

♦ Many operators stayed in their machines during breaks due to lack of facilities or because they had no desire to visit a canteen area

♦ Many of the operators take regular overtime to increase their earning potential.

♦ Safety culture varied between sites. It is possible that those most likely to agree to participate in this study could be those with the most well established safety cultures, thus biasing the sample towards best practice.

4.6 Discussion

Previous research has highlighted concerns over the link between work environments involving exposure to whole-body vibration and the development of low back pain (Stayner, 2001). In order to understand how the risk to workers health can be controlled the quantification of exposure to whole-body vibration in earthmoving machines, and data concerning typical work environments needed to be systematically recorded. There have been a number of studies addressing this issue but so far they have failed to take multiple measurements of similar machines. The current study was

design to gain deeper understanding of the typical vibration magnitudes produced in different environments under a variety of operations.

This study aimed to fill a gap in the knowledge of vibration profiles in earthmoving machines across some of the biggest industries; coal mining, quarries, and construction. It is important to determine whether a small sample of measurements, for a particular machine sub-set, can be applied across a variety of environments for WBV health risk assessments. The study was designed in order to test the hypotheses outlined in Section 4.2. They will be accepted or rejected in the following sections.

4.6.1 Whole-Body Vibration Emission Values

The findings from the WBV emission data support the first hypothesis '*Machines with crawlers performing tracking tasks will produce the greatest whole-body vibration emission*'. Out of the different categories of machines the bulldozers and tracked loaders exposed their operators to high magnitudes of vibration. The worst individual machine was the challenger tractor; in addition to being propelled by crawlers the machine was also carrying a "hex" attachment. Discussion with the manufacturers highlighted the issue of non-compliance with the use of the attachment. It was not an authorised attachment for this type of machine performing a ground shaping task. It was clear from the initial video observations of the driver, that during the operation they were being subjected to large amounts of vibration and shocks due to their body movements in the cab.

The group of excavators did not produce high magnitudes of vibration, this is most likely because of the tasks they were doing. All the excavators were digging earth, loading trucks or moving earth from one pile to another, therefore they were not involved in tracking tasks.

4.6.2 Power Spectral Density

It is important to understand what typical frequency components are produced by the machines to ensure the nature of the vibration can be characterised. The frequency components are important for determining what combination of magnitude and occurrence in whole-body vibration is the most detrimental for the musculoskeletal system, since the number of load cycles increased with the frequency of vibration (Rehn, 2004). In the current study the power spectra were characterised in as many machines as possible, depending on the availability of appropriate measurement equipment (Appendix A5). It must be acknowledged that the measurements were

117

taken at the seat and not at the floor therefore the findings can only be based on assumptions of how the seat is working to attenuate the vibration at certain frequencies.

The bulldozers and tracked loaders were found to have the greatest energy in the fore-and-aft vibration, which was dominated by very low frequency components below 1 Hz. There are limited control measures for this problem, as fore-and-aft suspension mechanisms for a seat could not prevent this. The remaining vibration experienced in this machine was found to have the most energy above 5 Hz, primarily as a result of the characteristics of the vibration frequency spectrum generated by the dozers and loaders track undercarriage, as was the case in Scarlett and Stayner's study (2005a, b). The machines with the worst axis of vibration in the vertical direction (BD3, 4 and 5; TL2 and 6) had the highest energy for the vertical component at frequencies above 5 Hz. It is impossible to suggest whether better selection of suspension seats would attenuate these components considering there was no measurement of the floor vibration.

Wheel loaders also had horizontal axes dominated by low frequency components below 1 Hz. In many cases this is a behavioural issue due to the task and not the machine itself (e.g. for a 'V-shaped' motion loading task with short duration). ISO2631-1 (1997) allows for vibration at frequencies below 1 Hz to be neglected if the frequency range below 1 Hz is not relevant or important. Notini *et al.* (2006) argues that the origin of the vibration will not directly affect the biomechanical responses to it yet the effect of omitting the low frequency vibration below 1 Hz was generally found to be greater than 20% in the case of ISO2631-1 metrics for the x- and y-axes. Regardless of the debate on ISO2631-1 filter frequency there is scope to reduce this component through training to ensure the operators do not drive the machines in such way that promotes these components. The vertical vibration component had energy at peak frequencies between 2 – 2.5 Hz. WL9 had significant vertical vibration at 2 Hz while the machine was tasked to clear debris from a quarry blasting site. Despite the high vertical energy at this frequency the lateral vibration still dominated the r.m.s. magnitude. There is scope to reduce this vibration using a suitably suspended seat that has the ability to isolate from as low as 2 Hz, again without floor data it is not possible to determine how well the current seat is working.

The articulated truck had a vertical vibration component centred around 2.2 Hz, and the dump truck had vertical vibration lower than this centred around 1.6 Hz. There is scope to attenuate the vertical vibration for the articulated truck using an appropriate

suspension seat but unfortunately this would not be possible for the dump truck due to the limits of current suspension frequency isolation. This is not too concerning for this machine as the dump truck did not expose the operator to very high magnitudes. Both of the motor graders had vertical vibration components centred around 2.2 Hz, however MG2 had significantly more vertical energy at this frequency compared to MG1. MG2 had an old mechanical suspension seat fitted to the cab whereas MG1 had an air suspension seat, therefore suggesting that improvements could be made with selection of a seat with better attenuating properties above 2 Hz.

4.6.3 Comparison of Worst Axis across Machine Types

The lateral direction was the worst axis of vibration for 83% of the articulated truck measurements this supports the second hypothesis '*lateral vibration will dominate the exposure profile for articulated trucks*'. Only one of the machines had dominant vibration in the fore-and-aft direction. The primary task for these machines involves moving from one site location to another, often over relatively poorly maintained routes. Operators are exposed to roll motion due to differing profiles for each side of the machine which is transformed to lateral vibration due to the distance from the centre of rotation. The terrain at site 4 was uneven due to the poor weather conditions; the routes being muddy and waterlogged. At site 6, the trucks travelled only on well maintained concrete roads, this is reflected in the lower vibration magnitudes experienced at this site. The truck at site 2 travelled only on well maintained concrete roads; this is also reflected in the lower vibration magnitudes experienced in this machine.

All of the dump trucks produced the highest amount of vibration in the vertical axis, most likely due to the relatively good haul roads meaning that the machine did not roll and the generally steady speeds at which the machines were driven, therefore not inducing fore-and-aft components in the vibration. The findings for the dump trucks are in support of the third hypothesis '*vertical vibration will dominate the exposure profile for bulldozers; dump trucks; and rollers*'; however, this is not the case for the bulldozers or for the roller machines. The vertical direction was dominant in the vibration emission for two of the rollers and the lateral vibration was dominant axis for the third roller, the small sample size for these machines influenced the overall percentage and therefore no firm conclusions can be made. For the bulldozers only 37% had dominant vibration in the vertical direction and the remaining 63% had dominant vibration in the fore-and-aft direction.

The fore-and-aft axis was the worst direction of vibration for all of the excavators, for 75% of the tracked loaders, and 71% of the wheel loaders. This is not unforeseen considering all these machines carry out tasks involving loading or impacting parts of the machine (the bucket or blade) in the fore-and-aft direction and / or repeated acceleration and deceleration. The findings for the excavators and tracked loaders support the fourth hypothesis 'fore-and-aft vibration will dominate the exposure profile for excavators during digging tasks; wheel loaders during loading tasks; and tracked loaders during earthmoving tasks', however it is not possible to accept the hypothesis for the wheel loaders. The lateral direction dominated 29% of the wheel loader measurements. There are a number of possible factors that could have influenced this, including the possibility that machines with vibration dominated by the lateral axis may have greater amounts of travel and directional changes in their cycle. This was the case for WL1, WL6, and for WL9 during the blasting operation. Wheel Loader 5 was also required to travel long distances between the stock pile and delivery point for the granite. The lateral direction also dominated all the motor grader measurements, this is in contrast to previous findings where the vertical (NIWL, 2004; Fairlamb & Haward, 2005); fore-and-aft (NIWL, 2004); and lateral (NIWL database, 2004) directions have all dominated.

4.6.4 Whole-Body Vibration Exposure Compared with the PA(V)D

The Exposure Action Value of the Physical Agents (Vibration) Directive is 0.5 m/s² A(8) and the Exposure Limit Value is 1.15 m/s² A(8). The challenger tractor would exceed the ELV after 2 ½ hours of operation; the exposure points for this machine are 10 times higher compared with the majority of the measurements. For this reason Hyp[6] must be rejected because this machine would definitely exceed the ELV within 8-hours of operation. Risk reduction measures should start with removal of the unauthorised attachment on the machine and immediately consider the use of an alternative machine for the task, for example a roller machine produces less vibration (refer to Table 4.7) performing a similar task and possibly costs less money to purchase and maintain. One of the bulldozers and one of the tracked loaders were approaching the ELV for 8-hours of operation and on the day tested they would have exceeded the ELV because they were both operating the machines for longer than 8-hours. Considering the organisational and social pressures are high in many of the industries it is likely that any additional overtime for operators of a number of the bull-dozers and tracked loaders would result in pushing their exposure above the limit value if they worked over their normal working hours. Many of the remaining machines would expose operators

to vibration that would exceed the EAV in less than 4 hours (corresponding to an emission value of ~0.70 m/s²). Over 80% of the machines would exceed the EAV within 8-hours of operation, this supports the fifth hypothesis *'over 70% of the machines will exceed the exposure action value of the Physical Agents (Vibration) Directive within 8-hours of operation'*.

The tracked loaders and the bulldozers were the worst types overall, followed by the articulated trucks. The machine group that typically produced the lowest vibration was the tracked excavators followed by the rollers and a selection of the wheel loaders. Risk reduction measures, health surveillance, training, and minimisation of the vibration exposure should be adopted for the operators driving tracked loaders, bulldozers, and articulated trucks. The trucks may be easier to control by enforcing lower speed limits and ensuring smoother access routes. It is not possible to improve road conditions for the tracked loaders and dozers because their primary task involves smoothing out terrain and earthmoving. These tasks are typically completed at low speeds. One of the operators of a tracked loader complained that the back-end of the machine (illustrated in Figure 4.9) sometimes hit the ground when the machine travelled up a gradient or during directional change. This could be one of the contributing factors to the high vibration magnitudes experienced in the fore-and-aft direction (typically below 1 , for this type of machine.

Figure 4.9 Example of tracked loader highlighting the area a driver considered to be problematic for machine operation

Vibration spectra for the tracked loaders and dozers usually show substantial vibration at frequencies below 2 Hz in the x-direction. As the W_d frequency weighting is most sensitive at such low frequencies, these components are likely to form a major contribution to the frequency weighted r.m.s. vibration magnitude as discussed previously in the power spectral section. It is difficult to isolate the operator from such low frequency components as any passive isolation mechanisms would require a very low resonance frequency resulting in large horizontal travel. Furthermore, such horizontal isolation systems for a cab or seat would also respond to other loading. For example, when the machines were operated on inclined surfaces the 'isolated' part of the system (e.g. the seat or the cab) would tend to move towards the end of the travel due to gravitational forces acting on the suspension. If the isolation were provided by a seat, then it could also prove problematic for operation of controls. For example, if an operator needed to depress the brake, the force applied would also push them back on the suspension. Finally, the suspension would also move in response to any acceleration or braking forces. Each of these constraints combines to make it impractical to use simple passive isolation systems for low frequency horizontal vibration isolation. This would also be a problem for the wheel loaders that exceeded the EAV in the current study.

The most practical methods of reducing the vibration exposure experienced in these machines are to ensure that the machine operates on as smooth surfaces as possible and to ensure that operators avoid driving the machine aggressively. Such measures are practical as operators of all machines driving over a smoothed road surface will benefit from lower vibration exposures. Training of operators is a cost effective method of reducing exposures as it does not require replacement equipment to be purchased. Re-educating operators regarding appropriate driving techniques could help to minimise their exposures, this is particularly relevant during tracking operations.

In many cases it might not be necessary to use a tracked loader for a particular task. Wheel loaders could have been used as an alternative to tracked loaders for many of the loading tasks observed in this study. Wheel loaders usually have a lower vibration emission than tracked loaders for simple loading tasks. Motor graders could also perform the smoothing tasks carried out by these machines, as they were found to expose the operators to less vibration even though they were still above the action value. Excavators could be a good alternative for bulldozers where the task involves moving large amounts of earth. If the excavators are able to perform the task from a stationary position then the vibration magnitudes will be much lower. However, if the

task requires a considerable amount of tracking then the operator of the excavator might also be exposed to higher magnitudes of vibration, as previously witnessed (Paddan et al., 1999; Paddan and Griffin, 2001).

4.6.5 Comparison of Whole-Body Vibration Data with Previously Published Data

The vibration exposures from Mansfield (2003), Cann et al. (2003) and the current study are in good agreement. The articulated trucks, dump trucks, bulldozers and wheel loaders are comparable to Mansfield's (2003) data. There are some discrepancies with the data from Cann et al. (2003), perhaps where the sample size is not sufficient to provide a representative range of exposure. The bulldozer and motor graders emissions are comparable but the dump trucks, wheel loaders and tracked loaders produced lower emissions in the current study. Cann et al. (2003) did not apply the multiplication factors to the horizontal axes therefore these values may be even higher if the worst axis happened to be in the horizontal direction. The findings from the current study have been plotted alongside the research highlighted previously and also with the more recent research, published since the completion of the study (Figure 4.10). In contrast with the previous research the dozers in the current study produced the greatest vibration in the fore-and-aft and the vertical direction. There is larger spread in the vertical data for the previous research. The maximum vibration was measured in a dozer by Scarlett and Stayner (2005a,b), they did however find a faulty seat in the machine, which would explain the high magnitude in the vertical direction.

There are similar vibration profiles for the wheel loaders from the current study and the previous research. There were only a small number of machines producing higher maximum horizontal vibration in the previous research. This is to be expected considering the range of environments and operations the machines have been measured in. The data for the excavators presents the largest discrepancy between the current study and the previous research. The current study found a spread in the vibration from 0.15 – 0.50 m/s^2, in the previous research the spread starts around 0.05 m/s^2 and finishes closer to 2.0 m/s^2. Due to the large sample of excavators recorded in the previous research it is not surprising to find a greater spread in the data. The three machines that exceeded the ELV were in the smaller category of excavators and they were all performing arduous tasks, involving removal of steel plates, earth flattening and earthmoving, i.e. all tracking tasks, similar to operations for the worst machines here. The machines at the opposite end of the scale were performing digging tasks more inline with the current study. If the comparison was only between the smaller

samples of excavators performing digging tasks (Paddan *et al.*, 1999) the discrepancies would disappear.
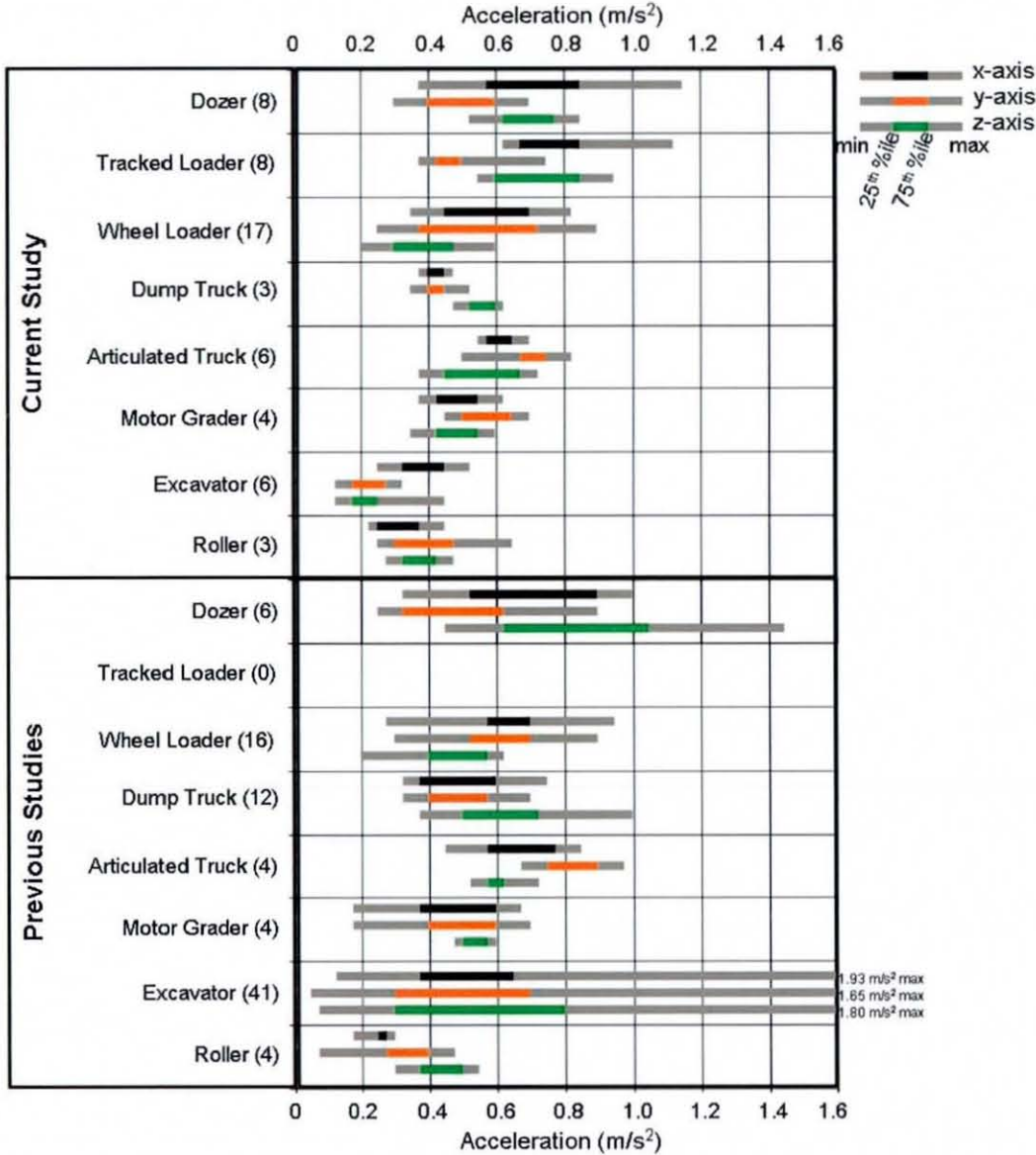
Figure 4.10 Vibration emission values across each machine category for the current study and previous research[5], including measurement from a range of operations and environments, presented as the minimum number, 25th percentile, 75th percentile and the max acceleration values within the samples measured (no. of samples are presented in parenthesis; horizontal axes include the 1.4 multiplication factor).

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[5] Paddan *et al.*, 1999; Gould, 2002; Mansfield, 2003; Mansfield & Atkinson, 2003; NIWL, 2003; Fairland and Haward, 2005; Scarlett & Stayner, 2005; Toward *et al.*, 2005; VIBRISKS, 2007.

4.6.6 Observations and Confounding Factors for the Evaluation of Risk

4.6.6.1 Effect of Task on Whole-Body Vibration Values

The majority of the machines performed repetitive work cycles, comprising of only a few different tasks. Some of the task cycles were too short in duration to split the tasks up further. For example, the wheel loaders typically had loading cycles lasting around 60 seconds, involving a load pile, phase, drive, tip, drive to pile 'V-shaped motion'; a tipping operation may only last a few seconds. Therefore the only task comparisons made between these machines were for two wheel loaders who performed different tasks during separate measurements. Wheel loader 9 clearly demonstrates how carrying out an alternative task to loading cycles can greatly increase the vibration magnitude in all three axes of vibration. Factors contributing to the increased vibration may include, extra travelling to and from the operation, faster working pace to clear the material before the next blast and the condition of the quarry floor where the wheel loader was operating. This machine would only carry out this task occasionally with the remaining time spent on the primary task of loading aggregate lorries. Regardless of the task frequency, the blasting operation would still need to be included in the overall daily vibration exposure, especially as it is subjecting the operator to higher vibration magnitudes. This is likewise for WL4 carrying out two distinct tasks. Higher vibration magnitudes are produced when the machine is loading a train compared with loading a crusher machine. One possible explanation for this is the time pressure placed on the operator to complete loading of rail wagons as soon as possible, this in combination with the increased frequency of directional change could alter the vibration profile of the machine. This operator carries out this task at least twice a day so it would be important to include this task in the daily exposure calculation.

There was no clear trend observed between the different tasks performed by the tracked loaders. Loading, and levelling produced similar vibration magnitudes, these magnitudes increased slightly during the tracking operation for two of the machines. The largest difference between tasks was observed in both the articulated and rigid dump trucks. The smallest vibration magnitudes were experienced during the loading operation, the most severe magnitudes occurred during travelling. The fore-and-aft vibration magnitudes increased further when the machines travelled unloaded. The travelling operations dominate the vibration exposure therefore they should be the main focus of concern when implementing a risk reduction plan; this may include targeting the condition and maintenance of the access roads the machines use.

4.6.6.2 Seat and Cab Design

The operators driving the tracked machines (bulldozers and tracked loaders) adopted poor postures in order to maintain good visibility. Although mirrors or CCTV systems were provided in some of the machines, operators were observed looking over their shoulders to the rear of the machine during reversing manoeuvres and for extended periods of time in the bulldozers. It is possible that this is a problem of non-compliance with training, failure to use visibility aids or poorly specified, poor matching of the machine to the task or a constraint in the design of the machine. These non-neutral postures adopted by the operators may subject them to additional harm while they are being exposed to high magnitudes of vibration. This would need to be taken into account during a health risk assessment; currently there is no guidance on how this should be accounted for. The biomechanical models used to determine the human response to vibration have mainly focused on the upright posture. Research is needed in this area to gain understanding of how the twisted postures interact with the vibration exposure to ensure the risks are managed effectively.

The field study also identified discrepancies between the range of seats used and the types of armrests mounted to them. Many of the armrests and controls were not adjustable for the operators and vibration was felt through both of them, Kittusamy (2000) found similar issues. The seating design is also very different from the typical seats used in laboratory settings to test human responses to vibration. Biomechanical data show a change in frequency resonance with variations in posture. However, there is little biomechanical data that has been obtained using seats with backrests and few known studies reporting the effect of armrests on biomechanical responses to vibration. Further work investigating the effect of seating design on biomechanical responses is required. Currently, it is not possible to understand the dynamics and interactions between the different amounts of contact with the seat and how this can influence the outcome of the health risk. Additionally it is important to consider the possible safety implications from the relative movement with the controls and issues with visibility.

4.6.6.3 Organisational and Social Issues

The crusher machine discussed in Section 4.5.6.2 produced extremely high vibration in the vertical direction. Although this is not an off-road machine and is only exposed to the operator intermittently it still needs to be highlighted because of the severe health implications it could pose to the operator. Griffin (1990) reviewed the history of studies

conducted on vibrating platforms, some of them on construction workers. It was concluded that such platforms can present a host of vascular and health disorders (p.749). Considering this machine can expose the operator to magnitudes at the limit value of the PA(V)D with four hours exposure a day, action needs to be taken to ensure the person operating the machine is not then exposed to vibration from other sources throughout their working day. The crusher should have a good maintenance record because this could help to reduce the frequency of problems with the machine and therefore limit the operator's exposure.

Conversations with the operators highlighted the issues of overtime and the general safety culture within some of the organisations. Many of the operators' remained in their machines all day, even during break times. Some of the machines were working far away from any facilities so the time needed to travel to the canteen would reduce their actual break period. Ideally the operators' would take some time out of their machines so they can have a break from being sat in the same posture for most of the day. The work durations highlighted in Section 4.5.4 do not include times when the operators work overtime. Health risk assessments should take account of the periods when operators work overtime and consideration should be given to the frequency of overtime. This could significantly alter the control measures and health surveillance required for an operator. Some of the operators in this study could be pushed over the ELV if they were taking on regular overtime.

4.7 Limitations of the Study

The field study has high external validity; unfortunately this is gained at the expense of the internal validity. Due to the nature of the trials environment it was not possible to alter the operations or request any re-runs of the machines. The experimenter and equipment had to be as "stealth like" as possible. This did ensure the data captured was as true to the real working environment and conditions of the operators as was physically possible. The sample size of some machine types was too small to gain additional understanding to the nature of that particular machine. In some cases the machines were very rare so the chances of finding additional numbers were extremely difficult. The tracked loaders, for example, were not operating at the typical sites first visited, in order to locate these machines industrial help was required.

Measurements were only recorded on the seat in the machines. In order to cover the range of machines targeted for the study it would not have been viable to measure on the floor, seat and backrest. If there was more time to complete the study recordings of

WBV at the feet would have been taken to increase the understanding of the seat dynamics.

Ideally measurements would have been for the whole of the working day. Nonetheless, throughout the testing period every effort was made to ensure measurement durations were sufficient to provide an accurate representation of the vibration exposure experienced throughout a working day, in all types of machine. Preferably the measurement durations should be no shorter than one hour, on occasions this was not possible to achieve this minimum duration. Extraneous factors influenced how long measurements could last in each machine. For example, the last three sites were visited in one day this greatly restricted the amount of time that could be spent at each site. The amount of time and resources available were maximised to ensure reliable measures were obtained.

The emission values combined with the operating hours provide a useful estimate of the exposure profile. However, they fail to account for the many times when operators are stationary in their machines or times when they are away from the machine sorting out problems. This makes it difficult to apply the emission values across a range of environments for health risk assessments. One alternative would be to use the number of work cycles performed as a measure for the exposure limits. Using the HSE points system this could prove to be a viable solution for exposure estimates. One problem with this is the amount of variability experienced between different work cycles (Kittusamy, 2000; Rehn, 2004). The next chapter will address this issue by quantifying the amount of variability between work cycles, in order to determine how many cycles would constitute a reliable measure.

The overall aim of the thesis was *to determine the variability between humans, machines and task environments in order to provide knowledge to inform improvements in methods of risk management for whole-body vibration exposure'*. The findings from this chapter very much follow the practioners' philosophy. In order to consider a more in-depth development of the methods used the consideration of the variability inherent to whole-body vibration measurement and assessment needs to be taken account of.

The evaluation of risk can be largely influenced by the selection methods used for measuring whole-body vibration. The amount of variability between daily operations and between different sites is still unknown. There is a body of evidence to suggest large variability exists, yet no substantial proof to quantify this variability. The next

chapter aims to determine how much variability there is between the same models of machines operating at different sites and over different days.

4.8 Conclusions

The tracked machines produced some of the most severe vibration profiles out of all the machines. The wheel loaders also produced high magnitudes in certain cases, as did the trucks in the lateral axis. The tracked machines expose operators around the action value of the vibration directive but with the addition of operators adopting twisted postures and awkward static postures these risks are likely to be elevated. The wheel loaders and trucks can be managed with smoother ground surfaces, operator training and restriction on speed to help reduce the vibration exposure, whereas the tracked machines primary job is to smooth the ground at an already slow pace. Due to the nature of the work in these machines and the limited engineering solutions provided for fore-and-aft vibration it is important to understand how the risks can be managed.

- **The WBV emission data support Hyp[1] *'Machines with crawlers performing tracking tasks will produce the greatest whole-body vibration emission'*:** The machines fitted with crawlers and performing tracking tasks produced the greatest whole-body vibration emission. Bulldozers and tracked loaders exposed their operators to high magnitudes of vibration (0.63 – 1.12 m/s^2 r.m.s). The challenger tractor produced the most severe vibration magnitudes out of all the machines.

- **The articulated truck data support Hyp[2] *'Lateral vibration will dominate the exposure profile for articulated trucks'*:** The lateral direction was the worst axis of vibration for 83% (5 out of 6) of the articulated truck measurements. The remaining machine had the dominant axis in the fore-and-aft direction.

- **The dump truck data support Hyp[3], but the bulldozers and rollers do not support Hyp[3] *'Vertical vibration will dominate the exposure profile for bulldozers, dump trucks and rollers'*:** All three dump trucks had dominant vibration in the vertical direction. Only 37% (3 out of 8) bulldozers had dominant vibration in the vertical direction, the remaining 63% had dominant vibration in the fore-and-aft. The lateral direction was the worst axis of vibration for 83% (5 out of 6) of the articulated truck measurements. Two of the three rollers had dominant vibration in the vertical direction, however due to the small sample size firm conclusions cannot be drawn.

- The excavators and tracked loaders support Hyp[4], but the wheel loaders do not support Hyp[4] *'Fore-and-aft vibration will dominate the exposure profile for excavators during digging tasks, wheel loaders during loading tasks, and tracked loaders during earthmoving tasks'*: The fore-and-aft axis was the worst direction of vibration for all of the excavators (6 out of 6), for 75% (6 out of 8) of the tracked loaders, and 65% (11 out of 17) of the wheel loaders. The remaining 35% of the wheel loaders had dominant vibration in the lateral direction. During these measurements the machines were involved in more travelling during their cycles.

- **Over 80% of the machines would exceed the EAV within 8-hours of operation, this supports Hyp[5]** *'Over 70% of the machines will exceed the exposure action value of the Physical Agents (Vibration) Directive within 8-hours of operation'*: All of the bulldozers, tracked loaders and articulated trucks would exceed the EAV in half a days work (4 hours). Eight of the nine wheel loaders would also exceed the EAV after half a days work. Health risk assessments should help to minimise the exposure in these machines and they should take into account the twisted postures adopted by the operators of the bulldozers and tracked loaders.

- **One machine would exceed the ELV within 8-hours of operation, this does not support Hyp[6]** *'No machines will exceed the exposure limit value of the Physical Agents (Vibration) Directive within 8-hours of operation'*: The challenger tractor would exceed the ELV after 2-hours of operation. The most likely cause of this high exposure is the unauthorised "hex" attachment used to flatten the ground. Risk reduction measures should start with removal of the unauthorised attachment and selection of an alternative machine with lower vibration emissions, (for example, rollers can perform the same task with a significantly lower emission below the EAV).

- Operators can also be exposed to severe vibration from additional vibrating machines throughout their working day. Crusher machines regularly become jammed and require attendance from operators. Standing on the machine exposes the operator to the highest magnitudes of vertical vibration. It is important to take into consideration the exposure to other sources of vibration when conducting a health risk assessment.

- Observations during the field trials highlighted concerns over the typical back and neck postures adopted by the operators. Twisted postures featured

130

regularly for the operators of the bulldozers (including prolonged and static) and tracked loaders. Some machines did not have armrests on the seats and even the machines with armrests failed to provide adjustments for the operators. There is little guidance on the interactions between these postures and the vibration and no known biomechanical data to support any assumptions on the interactions.

Chapter 5 - Study 1 Part B

Determination of the variability in whole-body vibration measurements of earth-moving machines

This chapter discusses a field study designed to establish how much variability exists in the measurement of emission values for whole-body vibration experienced in earth-moving machines. Although previous research has acknowledged variability exists, often the quantification of the variability has been ignored. The aim of this study was to determine how much variability exists between work cycles and daily cycles in order to establish how the measurement of vibration can influence the assessment of risk. The research focused on characterising features of whole-body vibration exposure among earth-moving machinery operators throughout a range of industry sectors and types of machines. Research was carried out under real operating conditions to investigate the magnitudes of occupational exposure to whole-body vibration and to determine the causes of variability found between measurements. It is important to determine the amount of variation that could potentially affect the outcome of a health risk assessment.

5.1   Introduction

Machine manufacturers are required to reduce vibration emissions for operators to the 'lowest level' under the EU Supply of Machinery (Safety) Directive (89/392/EEC), and are also required to provide purchasers with emission values. Despite the requirement for machinery suppliers to provide emission data, there is no methodology clearly defined as to how to provide such data. There are still very few harmonised WBV test codes and little experience in their ability to produce numbers that can adequately describe the potential vibration exposure risk (Coles, 2003). Currently there are some generic methods of measuring vibration for a machine model that are repeatable, including EN1032 (2003) and EN13059 (2002); however they are often not representative of the vibration emissions experienced at different work sites. Generic values for WBV emission are difficult to produce. Under real operating conditions the constantly varying conditions of the ground surface and the wide variety of tasks that are carried out by machines means that the operating conditions vary from site to site and from day to day.

Previous literature has discussed the variation inherent to whole-body vibration measurements. However, there has been little attempt to quantify this variability from

vibration measurements performed in real operating conditions. Often it is not practicable to measure vibration over the entire working day therefore a sample of each operating task is collected. A large array of variables can alter the accuracy of a vibration measurement in its extrapolation to a daily dose measure, e.g. variability in driving style, road surface, loading (Mansfield *et al.,* 2003).

Paddan (2000) investigated the influence of measurement duration on the vibration magnitudes in an armoured fighting vehicle. Findings showed that measurements for 1-minute period were 6% different compared to a 10-minute period, the error reduced to less than 1% for measurement over 5-minutes. The study only measured vibration for 10-minutes yet more recent studies have shown that the minimum measurement time should be no less than 10 minutes in duration, with the ideal time of at least 30 minutes duration (Mansfield and Atkinson 2003 & Mansfield *et al.,* 2003). These studies are all in agreement that the longer the duration of r.m.s. measurement, the better the probability of the vibration value being close to the true daily exposure. Marjanen (2006) investigated long term continuous measurements of WBV in order to determine whether short term measurements can give an overall picture of the daily exposure of a machine or work phase. The results highlighted significant differences in daily exposure durations and vibration magnitudes and was especially evident when the work required flexible hours. The daily exposure period showed large variability especially for the wheel loader, the main reason for this was the rapid change in winter conditions which determined the usage of the loader.

The research on measurement duration has provided greater understanding of the inaccuracies that can result from inappropriate sampling methods. As it is usually not possible to measure for full days, it is important to use a sampling strategy that takes account of the likely variability in acceleration found throughout the vibration exposure. European Standard EN14253 (2006) states that the number of work cycles over which measurements are made shall be sufficient to show that the average value obtained is representative of the vibration from the operation throughout the day. One way to determine the extent of the uncertainty in the measurement is to calculate the variation found between loading cycles. Pinto *et al.* (2005) measured the amount of uncertainty in vibration A(8) values in a range of different machines. One of the findings suggested a large proportion of the variability was attributable to differences between loading cycles. However, the amount of difference between loading cycles was not discussed in the study.

There have been attempts to measure the variation in loading cycles, Rehn *et al.* (2005) quantified the variability in loading cycles for forwarder machine operators. The results highlighted large amounts of variability for the whole-body vibration exposures, therefore suggesting that different conclusions could be made regarding a health risk assessment. A breakdown of the loading cycle found that operators were exposed to the highest vibration magnitudes during travelling tasks and while the vehicles were travelling empty. The variation between measurements while travelling empty equated to 36% coefficient of variation. The variation was largely dependent upon forwarder model and terrain type. This was contrary to travelling with a load (48% coefficient of variation), the type of forwarder and operator was found to be the most important predictors for variation. However, it is important to also consider that a percentage of the variation could be due to the difference in measurement durations. Some measurements for travelling were only 16 seconds in duration, with the longest measurement of 892 seconds.

Kittusamay (2000) suggests that the relative variance is more dependent on differences in the specific tasks performed rather than the equipment being used or the operator using the equipment. This was based on the findings from a sample-to-sample study of 13 specific tasks. Of these tasks 54% had a coefficient of variation below 10% and the remaining 46% had coefficients of variation ranging from 12.7% to 48.8%. These studies had different methodological approaches which could account for the different conclusions drawn from the results. Rehn *et al.* (2005) focused on variation in 3-axes of vibration for 11 forwarder machines (forestry log transportation) with 11 operators and broke down the tasks into travel empty, travel loaded, loading and unloading. Kittusamay (2000) focused on variation in the vertical direction for 3 backhoe loaders, 4 excavators and 1 loader with 8 operators and broke down the tasks into low/high idling, chip concrete, digging, riding, smoothing rocks and loader tasks. Considering that most machines will be assigned to individual tasks based on the ability of that machine it is probable that they will also produce different amounts of variation within their work cycles. A larger scale study is needed to understand and characterise the differences between machine categories and their related tasks.

Changes in road surface and road roughness are likely to impact the amount of variability experienced between work cycles for operators exposed to vibration. Paddan (2003) investigated the effects of road surface on the vibration magnitude of 21 work vehicles including, 10 cars, 4 vans, 6 lorries and 1 mini bus. For the 5 axes of vibration investigated including z-floor, x-, y- and z-seat and x-backrest the vibration magnitudes

for concrete were on average 23% higher than travelling over tarmac. Von Gierke *et al.* (1991) presented typical vibration levels and frequency content encountered in a range of military and heavy vehicles over three types of terrain, including; rough terrain, cross country and concrete. The relationship showed that as terrain becomes rougher the range of the vibrations frequency content decreases and the acceleration value increases. If the machines task involves travelling over a variety of different terrain then there is likely to be an increased amount of variability between work cycles.

5.2 Hypotheses

It is important to acknowledge the variation inherent to whole body vibration exposure to help understand how this variation will affect health risk assessments. Most people have only typically measured for short periods of time, with small sample sizes for each machine set and very few studies looking at the day-to-day variability. There is a big question of whether individual samples can be representative of the work performed throughout the day and the rest of the week. The aim of the study is to determine how substantial the variability is between vibration measurements of work cycles and daily cycles in earth-moving machines. The criteria used to determine if the amount of variability was low, moderate or high was established from previous research on measurement duration (Mansfield *et al.*, 2003; Mansfield and Atkinson, 2003). The criteria were derived from the acceptable error margins according to ISO 8041 (1990). If the coefficient of variation falls below 12.5% then it is considered to have low variability, if it falls between 12.5% and 25% then it is considered to have moderate variability and if it falls above 25% then it has a high amount of variability and therefore the chances of making an incorrect assessment would be greater.The hypotheses for this study are:

Hyp[1]: Vibration magnitudes from one day will be above the 25% error margin for the magnitudes experienced at other times during the working week.

Hyp[2]: Vibration profile from one machine will not be within a 25% error margin for a similar machine working in another environment or site.

Hyp[3]: Vibration magnitudes from one work cycle will exceed the 25% acceptance level for the amount of variability found within a machines emission for a particular task.

Hyp[4]: Variation between work cycles will be dependent on machine type

5.3 Experimental Method

The experimental method was designed to answer the hypotheses addressing the variability between days, work cycles, work tasks and work sites. Measurements of whole-body vibration were made on 43 earthmoving machines during January to November 2004. Repeat measurements were taken on 7 different types of machines, this made 61 whole-body vibration measurements in total. Machine groups included wheel loaders, tracked loaders, skid steer loader, bulldozers, motor graders, articulated dump trucks, off-highway dump trucks, excavators, material handler, compacter, rollers and challenger (tracked tractor). These machines were targeted across the range of sites to test the hypothesis that measurements from one type of machine would not be representative for the same type of machine operating at a different site. Industry sectors in the UK were targeted from granite quarries to construction; this ensured a representative sample of typical vibration environments was covered. In total 10 different sites were visited to collect data. The breakdown of sites and machines are presented in Chapter 3. Details of the machines operations and terrain characteristics are presented in Chapter 4 and Appendix A3.

5.3.1 Machines and Operator Characteristics

The machines and operators that took part in the study are described in Chapter 4 Table 4.1. Pictures of the machines are provided in Appendix A4. The study was designed so that minimal interference was caused to the operators who were required to perform their daily work tasks. In order to achieve this equipment set-up was completed as fully as possible before approaching the machine and operator. The equipment was set-up in the machine during break times or periods of inactivity. Information about the machine and the operator was also collected during these times.

5.3.2 Experimental Procedure and Analysis

Measurement durations varied depending on the operation of the machine. The average measurement duration was 131 ± 67 minutes (range 22 - 326 minutes). However, in common with many types of earth moving machines, the work usually required some waiting time where the machine was stationary (e.g. waiting for another operator to suitably position a lorry; queuing at a site bottleneck).

The vibration measurements were conducted according to ISO 2631-1 (1997) and the assessment according to the Physical Agents (Vibration) Directive (2002). Two sets of instrumentation were used, one for real time acceleration and one for averaged

metrics. Both instruments had a tri-axial accelerometer fitted to the seat pan in a flexible disc beneath the ischial tuberosities (presented in Chapter 3). The accelerometer measured vibration in 3 translational axes; the fore-and-aft (x-axis), lateral (y-axis), and vertical (z-axis) direction. The first set of instrumentation was a Biometrics DataLogger with anti-aliasing filters, it recorded the raw data sampled at 500Hz. The data was downloaded to a PC for post-analysis using software developed in LabVIEW, and compliant with ISO 8041 (1990). During the analysis process the raw acceleration signals were frequency weighted according to ISO 2631-1. Weighting W_k was used in the vertical direction and weighting W_d was used in the horizontal directions. The Larson Davis meters conditioned the vibration signal and logged the r.m.s. data every 10 seconds, with the vibration dose values integrated over 1-minute periods. In the vertical direction, weighting W_k was used (frequency range 0.5 – 80 Hz); in the horizontal directions, weighting W_d (0.5 – 80 Hz) was used.

Vibration dose values (VDV) were also calculated during the processing and analysis of the data. VDV has been suggested to present a more reliable measure of the risk exposed to operators. However, there has been much debate about the validity of using VDV and during the course of the PhD the r.m.s. has been the preferred metric for the assessment of risk. Furthermore VDV is a function of exposure duration and therefore not suitable for cycle variation. The PA(V)D has been implemented into UK legislation using the r.m.s. and also widely across Europe. For this reason the thesis has only focused on the assessment of r.m.s.

Systems with integrated global positioning (GPS) were used to log the speed of each machine during their measurement period. This system did not always produce a signal in certain machines. This may be due to the location of these machines especially at a quarry face where the reception of satellites becomes limited. Video data was also collected for every measurement and written notes were taken. It also enabled information to be recorded about the typical postures adopted by the machine operators This allowed for identification of any distinct tasks encountered during the operating cycle, e.g. loading versus hauling. This enabled comparison of such tasks to help identify tasks that altered the amount of variability during a work cycle. In order to test the hypotheses and determine how much variation exists in whole-body vibration measurements, all data collected were split up into work cycles across the full measurement duration.

The analysis process used video footage and the written notes concerning the movement of each machine to extract acceleration data for each work cycle. The

frequency weighted r.m.s. was calculated for each axis of vibration and for every cycle. In total 2686 work cycles were individually analysed.

The coefficient of variation in Equation 5.1 was calculated to determine the variability found between work cycles and between days, in the three axes of vibration.

$$C_v = \frac{\sigma}{\mu}$$

Equation 5.1

Where μ is the mean and σ is the standard deviation

The Total$_{r.m.s.}$ value in Equation 5.2 was calculated by combining the data obtained within each work cycle to produce an overall vibration emission value:

$$Total_{r.m.s.} = \sqrt{\frac{1}{T} \sum_{n=1}^{n=N} a_{wn}^2 t_n}$$

Equation 5.2

where T is the sum of all of the vibration exposure times over all cycles, a_{wn} and t_n are the frequency-weighted r.m.s. and exposure time for cycle n, and N is the number of cycles.

5.4 Results

In order to test the hypotheses formulated for this study repeat measurements were recorded over different measurements or different days. The analysis determined if one measurement could be representative for the vibration experienced throughout the working week, the findings are discussed in 5.4.1.

Throughout the data collection period repeated work cycles were measured to allow for comparisons between the individual r.m.s. values. Section 5.4.3 discusses the variability found between the individual work cycles and the total r.m.s. value for every machines' work cycles, this does not include any waiting periods between work cycles. The results have been broken down and discussed in each machine category, as presented in Chapter 4 Table 4.1. Section 5.4.3.8 discusses the overall findings for the amount of variability found between work cycles for whole-body vibration measurements.

5.4.1 Day-to-Day Variability of Whole-Body Vibration Emission Values

Repeat measurements were made at four of the sites on a variety of machines; this included four wheel loaders, two tracked loaders, two articulated trucks, one motor grader and one excavator. The coefficient of variation for each machine and the r.m.s. values for the daily measurements are presented in Figure 5.1.

The average daily variability ± the standard deviation for all the machines is 12 ± 10 (range 0.3 – 32) for the x-axis, 14 ± 11 (2.9 – 31) for the y-axis, and 16 ± 12 (1.2 – 33) for the z-axis. The machines with the greatest amount of daily variation across all three axes are WL3 and WL4. Wheel loader 9 and EX1 both exhibit large daily variation in two directions of vibration and AT3 and TL2 exhibit large daily variations in one axis. Two measurements were carried out on day 1 for WL9; one of the measurements was carried out during a different operation to the machines typical task operation (as discussed previously in Chapter 4). Wheel Loader 4's task operation also varies between days, one day the operator is required to load the train wagon and the second day they are required to load the crusher machine. One of the articulated trucks had variation less than 10% between measurement days, the other one AT3 was not as consistent between measurements. On the second day not only did the vibration magnitude change the direction of dominant vibration also changed from the y-axis to the x-axis.
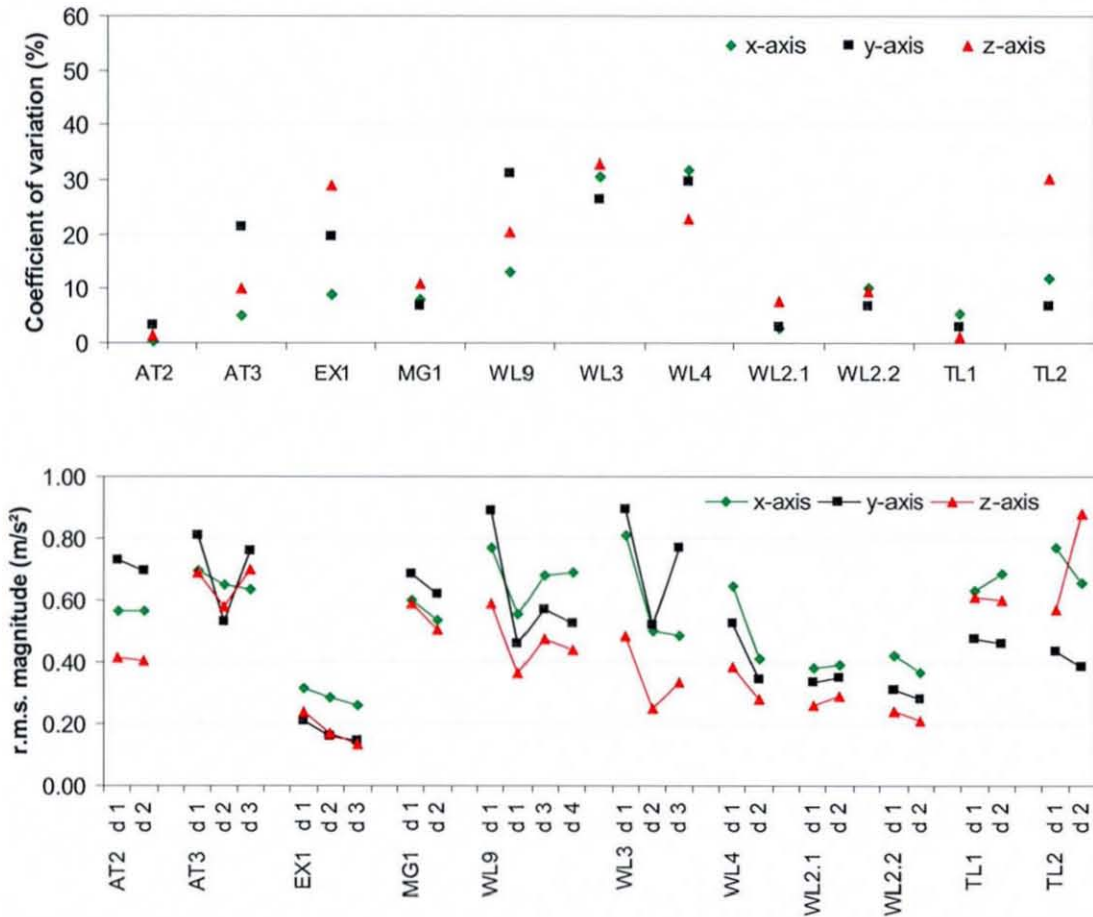
Figure 5.1 Daily variation of frequency weighted r.m.s. for articulated trucks (AT), excavator (EX), motor grader (MG), wheel-loaders (WL) and tracked-loaders (TL).

5.4.2 Site-to-Site Variability of Whole-Body Vibration Emission

A large selection of the machine types investigated throughout the project were in operation at a variety of different sites. On some occasions repeat measurements were carried out over a number of days for these machines (as described in Section 5.4.1). The machine groups that were investigated at a variety of sites have been plotted in Figure 5.2, the worst axis for the frequency weighted r.m.s magnitude is presented.

The motor graders had higher magnitudes of vibration at site 4 compared with site 6, this may be the result of different types of terrain at the two sites. At site 4 the terrain was muddy and the motor grader was operating in wet / waterlogged conditions. At site 6 the two motor graders in operation were working in a confined area where the terrain consisted of concrete roads and lime/superficial ground. The average speeds were similar for all the motor graders; this suggests the terrain could be the main cause of this difference, especially as the dominant axis is the lateral axis.

Articulated trucks created the highest vibration magnitudes at site 6, followed by site 4. This is not surprising as the operating speeds for both of these machines were higher than the machine tested at site 2. The worst axis in all but one case was the lateral direction.
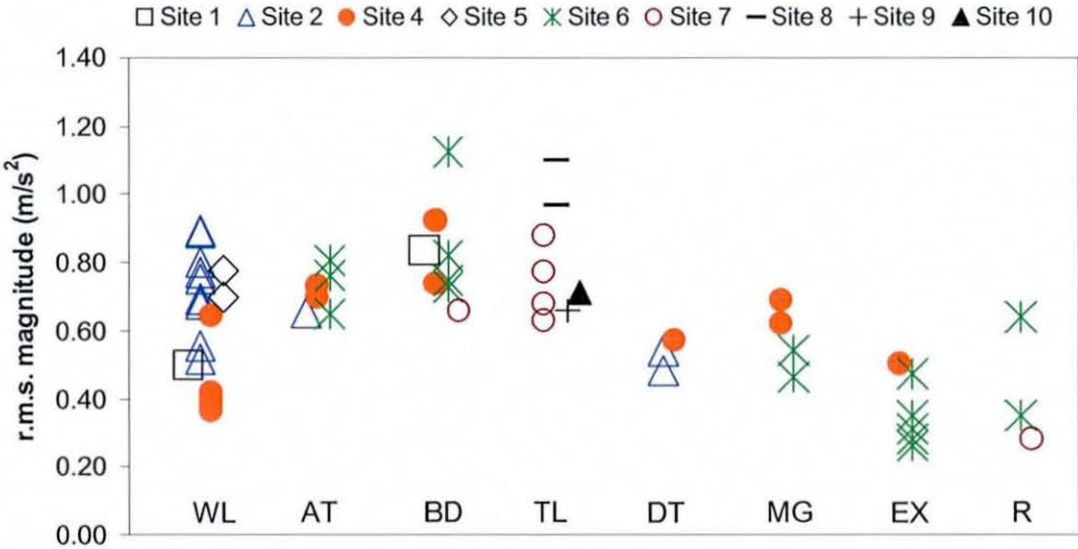
Figure 5.2 Comparison of machines frequency weighted r.m.s. vibration magnitudes produced at different sites (presented as worst axis of vibration magnitude for each machine).

One interesting observation in the tracked loader data is the consistently higher vibration magnitudes found at site 8 compared with site 7, 9 and 10. Two types of tracked loaders were being operated at site 8 comprising a 953C and a 963B both of which were operated by the same driver. It is impossible to determine the reason why the vibration magnitudes are higher at this site but one possible explanation could be the operator driving style considering it is the same operator driving both machines. Alternatively it could be related to the conditions of the site and the task operation. The loaders were travelling in a small area, this required the machine to frequently change direction and as it was operating on a range of gradients, this could have influenced the vibration magnitudes.

5.4.3 Inter-cycle variation in earth-moving machines

This section discusses the findings for the variation between work cycles for all the machines measured during the field study. Firstly the bulldozers will be discussed in detail and the tracked loaders and the wheel loaders. Following this will be a discussion of the trucks, motor graders and excavators. The section will finish with a

discussion of the miscellaneous machines and rollers, these are the machines that appeared less frequently around the sites investigated. The individual machines will be referred to using the assigned numbers presented in Chapter 4 Table 4.1. i.e. bulldozer D85EX will be dozer 1 or BD1.

5.4.3.1 Work Cycle Variation Observed in Bulldozers

The bulldozers' primary task involved moving material consisting of granite, clay, coal or superficials. The findings for the work cycles have been summarised in Table 5.1. All dozer machines performed the same type of task during data collection; this involved moving earth to level the ground surface. However, the types of materials being moved varied between different sites and between different areas of the same site. The material consisted of granite, clay, coal or superficials.

Table 5.1 Inter-cycle variation of the frequency weighted r.m.s. values in bulldozers

Machine Type	ID	Site (day)	r.m.s. (m/s^2)			C of V (%)			No. of cycles
			a_{wx}	a_{wy}	a_{wz}	x	y	z	
Bulldozers	BD1	6 (m1)	1.29	0.59	0.61	17	23	13	207
Bulldozers	BD2	6 (m1)	0.85	0.51	0.51	22	29	12	158
Bulldozers	BD3	1 (m1)	0.39	0.41	0.85	26	22	10	60
Bulldozers	BD4	7 (m1)	0.60	0.35	0.73	31	23	17	78
Bulldozers	BD5	6 (m1)	0.60	0.36	0.82	23	27	13	115
Bulldozers	BD6	6 (m1)	0.78	0.63	0.70	20	20	20	138
Bulldozers	BD7	4 (m1)	0.71	0.56	0.68	34	38	25	73
Bulldozers	BD8	4 (m1)	0.94	0.71	0.83	14	12	16	12

There is no discernable trend in the amount of variability between work cycles of different dozer machines. The smallest machines (<10000 kg) BD1 and BD2 both produce the largest amount of variability in the lateral axis. The medium sized machines (>10000 kg, <20000 kg) have the largest amount of variability in the fore-and-aft direction and the larger machines (>20000 kg) vary in the dominant axis of variation. One reason for the smallest machines displaying the greatest amount of variability in the lateral axis could be due to the lighter weight influencing the occurrence of side-to-side sway. The axis with the largest amount of variability is not the same as the axis with the worst magnitudes of vibration. The only machine with corresponding worst axes for vibration and variability is BD6, however the variability is constant across all three axes so there is no dominant axis for variability.

The machines with the greatest amount of variability are BD4 and BD7. Both of these machines' work cycles have large amounts of variation due to the changing characteristics of the terrain they are travelling on. The terrain conditions and gradient changes as the machine moves between different sections of the site. Dozer 7 provides a good example of how sampling error can occur while performing a health risk assessment. Appendix A7 shows a breakdown of each work cycle for this machine, the figure clearly highlights the periods when there are larger vibration magnitudes. During this time the machine was moving large sections of rock on a very steep gradient. Closer inspection of the video showed the operator of this machine is driving quickly / aggressively up and down the slope, this could be a factor influencing the high vibration magnitudes. Periods of large vibration magnitudes can also clearly be identified in the work cycles for Dozer 4 in Appendix A7. During these periods the machine was moving large rock particles towards an embankment.

5.4.3.2 Work Cycle Variation Observed in Tracked loaders

The tracked loaders' primary task involved levelling the ground, however, three of the machines were also involved in loading material into aggregate lorries. Machines were also required to travel between site locations. The data have been summarised in Table 5.2. In total, 369 cycles were individually analysed. BD3 and BD4 were operated by the same individual. Repeat measurements were made on two of the tracked loaders (machines 1 and 2) over a two day period.

Table 5.2 Inter-cycle variation of the frequency weighted r.m.s. values in tracked loaders

Machine Type	ID	Site (day)	r.m.s. (m/s²) a_{wx}	a_{wy}	a_{wz}	C of V (%) x	y	z	No. of cycles
Tracked loader	TL1	7 (m1)	0.79	0.57	0.72	8	12	6	6
Tracked loader	TL1*	7 (m2)	0.83	0.57	0.75	9	14	9	12
Tracked loader	TL1	7 (m3)	0.80	0.54	0.70	9	9	6	7
Tracked loader	TL2	7 (m1)	0.85	0.45	0.56	17	20	11	13
Tracked loader	TL2	7 (m2)	0.79	0.47	0.69	17	16	13	91
Tracked loader	TL3	8 (m1)	1.12	0.76	0.97	12	15	8	29
Tracked loader	TL4	8 (m1)	1.03	0.68	0.88	14	14	13	58
Tracked loader	TL5	9 (m1)	0.61	0.33	0.48	17	20	18	26
Tracked loader	TL5*	9 (m2)	0.76	0.50	0.55	8	15	10	6
Tracked loader	TL6	10 (m1)	0.66	0.54	0.85	6	16	12	26
Tracked loader	TL6*	10 (m2)	0.75	0.47	0.71	12	14	11	45

Work cycles involve levelling the ground apart from those marked with a * for the machines carrying out loading cycles.

The dominant axis of variability was primarily the lateral axis with a mean coefficient of variation of 15% (range 9-20%), however, the fore-and-aft direction produces similar amounts of variability in a number of measurements with a mean coefficient of variation of 12% (range 6-12%). The vertical direction produced the lowest overall with a mean coefficient of variation of 11% (range 6-18%). The largest variation between work cycles was 20%, this was observed in two measurements, TL2 on day 1 and TL5. For most machines, the most severe axis did not correspond to the axis with the most variation in the data. In the most severe axis, the mean coefficient of variation was 12% (range 8-17%).

The machine with the lowest level of variability between work cycles was TL1. Repeat measurements were conducted on this machine over a two day period. The levelling operation on both days showed the smallest amount of variability, followed closely by the loading cycle operation. The variability may be this small during the levelling operation as the task was very consistent in terms of length travelled, number of directional changes and the terrain characteristics.

Table 5.3 provides an example of the data obtained for individual loading cycles for one of the tracked loaders performing a loading task. The ID numbers represent each separate cycle performed by the machine. Three aggregate lorries visited the site

during the measurement resulting in three sets of loading cycles (e.g. 1a, 1b, 1c, 1d, represents 4 loading cycles for lorry 1). Cycles varied in duration from 36 to 65 seconds and tended to take longer for the first lorry than for the other two. The worst axis of vibration usually occurred in the x-direction, but for three cycles, the worst axis occurred in the z-direction whilst loading lorry 3. In these cases, the magnitudes that were measured in the x-direction were only slightly lower than those in the z-direction. The reason for the increase in dominant axis is unknown, although it is possible that it is due to the loader operating on a different loading pile with a change in the surface roughness.

Table 5.3 Example of individual loading cycles for tracked loader. Loading cycles are labelled to represent cycles required to load each of three aggregate lorries: '1', '2' and '3' represent each lorry; 'a'-'d' represent each cycle required to load the lorry.

Loading cycle	r.m.s. magnitude (m/s^2)			Worst axis	Duration (s)
	x-axis	y-axis	z-axis		
1a	0.88	0.53	0.72	X	55
1b	0.83	0.54	0.72	X	65
1c	0.78	0.57	0.66	X	53
1d	0.85	0.66	0.69	X	62
2a	0.81	0.52	0.78	X	59
2b	0.93	0.63	0.88	X	38
2c	0.75	0.41	0.73	X	36
2d	0.96	0.70	0.78	X	55
3a	0.72	0.47	0.74	Z	38
3b	0.86	0.55	0.72	X	41
3c	0.73	0.53	0.74	Z	43
3d	0.79	0.60	0.86	Z	45
Total$_{r.m.s.}$	0.83	0.57	0.75	X	590
C of V (%)	9	14	9		

5.4.3.3 Work Cycle Variation Observed in Wheel Loaders

The wheel loaders' primary task involved loading material into aggregate lorries / crusher machines or distributing material between different sections of a site (granite, clay, coal or scrap metal). The loading cycles tended to be short in duration (usually 60 - 90 seconds) for most types of wheel loaders performing this type of task. Summary data for individual work cycles are presented in Table 5.4.

Table 5.4 Inter-cycle variation of the frequency weighted r.m.s. values in wheel loaders

Machine Type	ID	Site (day)	r.m.s. (m/s²)			C of V (%)			No. of cycles
			a_{wx}	a_{wy}	a_{wz}	x	y	z	
Wheel Loader	WL1	2 (m1)	0.77	0.84	0.51	15	20	16	97
Wheel Loader	WL2.1	WL2 Op1	0.39	0.33	0.26	18	13	11	42
Wheel Loader	WL2.2	WL2 Op2	0.43	0.31	0.24	25	16	18	11
Wheel Loader	WL2.1	WL2 Op1	0.40	0.36	0.30	20	19	17	18
Wheel Loader	WL2.2	WL2 Op2	0.36	0.28	0.26	12	10	9	12
Wheel Loader	WL3	2 (m1)	0.73	0.75	0.42	16	28	24	32
Wheel Loader	WL3	2 (m2)	0.51	0.52	0.26	15	25	14	44
Wheel Loader	WL4	4 (m1)	0.73	0.60	0.43	11	17	12	94
Wheel Loader	WL4	4 (m2)	0.53	0.45	0.35	14	15	15	50
Wheel Loader	WL5	1 (m1)	0.46	0.39	0.26	13	21	14	77
Wheel Loader	WL6	5 (m1)	0.77	0.54	0.39	18	24	17	92
Wheel Loader	WL7	5 (m1)	0.84	0.65	0.51	18	21	13	34
Wheel Loader	WL8	2 (m1)	0.75	0.79	0.41	35	45	35	29
Wheel Loader	WL9	2 (m1)	0.82	0.96	0.63	21	20	30	28
Wheel Loader	WL9	2 (m2)	0.69	0.53	0.42	15	20	18	78
Wheel Loader	WL9	2 (m3)	0.71	0.49	0.41	13	18	19	57
Wheel Loader	WL9	2 (m4)	0.70	0.50	0.45	14	23	19	49

The average amount of variation between work cycles is 19 ± 7% (9 – 45% coefficient of variation) for all the machines combined and across the three axes of vibration. The worst axis of vibration was predominantly the fore-and-aft direction (71% of the machines), with the remaining 29% exhibiting the highest magnitudes of vibration in the lateral direction. The worst axis of variation between work cycles did not follow the same pattern as the direction of dominating vibration. Around 65% of the machines had the greatest amount of variability between work cycles for the lateral axis, 23% for the fore-and-aft and the remaining 12% have the most variability in the vertical axis. Eight of the wheel loaders had corresponding worst axis of vibration and worst axis of

variation. On average the lateral axis produced the greatest amount of variability between work cycles 20.9 ± 7.6% (range 10 – 45%), compared with the fore-and-aft direction 17.2 ± 5.8% (range 11 – 35%) and the vertical axis 17.7 ± 6.6% (range 9 – 35%).

Wheel Loader 8 was found to exhibit the greatest amount of variation between individual work cycles. Further investigation showed that the high variation was associated with the elevated vibration magnitudes when the machine was travelling at faster speeds; this was verified using the GPS data (presented in Appendix A8). The variation between work cycles would substantially reduce if these travelling periods were not measured in an assessment, for example Table 5.5 highlights the differences for vibration magnitudes and variation between work cycles when the machine is measured with the travelling periods and without the travelling periods.

Table 5.5 Comparison of frequency weighted Total$_{r.m.s.}$ and coefficient of variation for wheel loader 8 with and without travel.

Machine Type/ ID		Total$_{rms}$ (m/s^2)			Coefficient of Variation (%)		
		x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
Wheel Loader 8	With travel	0.75	**0.79**	0.41	35	**45**	35
Wheel Loader 8	Without travel	**0.60**	0.59	0.32	20	**29**	14

5.4.3.4 Work Cycle Variation in Articulated and Dump Trucks

Both the articulated and dump trucks carried out delivery cycles ranging in duration from 7 minutes up to 28 minutes. The primary task for both the articulated and dump trucks was transportation of material (granite, clay or superficial). The data have been summarised in Table 5.6.

Table 5.6 Inter-cycle variation of the frequency weighted r.m.s. values in trucks

Machine Type	ID	Site (day)	r.m.s. (m/s^2)			C of V (%)			No. of cycles
			a_{wx}	a_{wy}	a_{wz}	x	y	z	
Articulated	AT1	2 (m1)	0.64	**0.77**	0.65	**10**	7	9	8
Articulated	AT2	4 (m1)	0.58	**0.75**	0.42	**5**	4	**5**	5
Articulated	AT2	4 (m2)	0.56	**0.71**	0.40	**6**	6	**6**	5
Articulated	AT3	6 (m1)	0.70	**0.81**	0.70	**9**	6	7	6
Articulated	AT3	6 (m2)	**0.67**	0.55	0.60	9	**15**	10	5
Articulated	AT3	6 (m3)	0.64	**0.77**	0.70	**10**	9	8	4
Dump Truck	DT1	2 (m1)	0.39	0.40	**0.48**	5	**6**	4	9
Dump Truck	DT2	2 (m1)	0.47	0.51	**0.55**	8	7	7	19
Dump Truck	DT3	4 (m1)	0.43	0.37	**0.56**	11	10	**12**	13

There appear to be no clear trends for the amount of variation observed in each axis. The worst axis of vibration for the articulated trucks is predominantly the lateral (y-axis), this is not the case for the worst axis of variation. This suggests that vibration measurements carried out on these types of machines under similar conditions have a low level of variability between work cycles. The highest amount of variation was observed in the lateral axis for AT3, measurement 2, the dominant axis of vibration for this particular measurement was the fore-and-aft, so ultimately this would not affect a health risk assessment.

5.4.3.5 Work Cycle Variation Observed in Motor Graders

The motor graders' primary task involved smoothing access roads to help maintain their condition for all transport vehicles. The data have been summarised in Table 5.7. There is no dominant axis for the amount of variability observed between work cycles. The highest variation is found in the lateral (y-axis) for grader 1 on day 2, this is also the dominant axis of vibration. This is an interesting finding when compared to the same machine at the same site operating on a different day. One explanation for the increase in variation for the lateral direction from day 1 to day 2 is the deterioration of the terrain conditions. Substantial rainfall between the two days resulted in a temporary grounding of all the machines operating on the site. Operations were resumed mid-morning but the conditions were still not ideal, the main track linking the coal face and the site yard was considerably more waterlogged. This in effect would cause the muddy track to become churned up and thus substantially increase the irregularity of the terrain surface. Although the variability increased, the magnitude of the vibration in the y-axis decreased. This is likely to be due to the reduced speed that occurred due to the poorer road conditions (the reduction in speed was confirmed using the GPS data).

Table 5.7 Inter-cycle variation of the frequency weighted r.m.s. values in motor graders

Machine Type	ID	Site (day)	r.m.s. (m/s²)			C of V (%)			No. of cycles
			a_{wx}	a_{wy}	a_{wz}	x	y	z	
Motor Grader	1	4 (m1)	0.61	0.70	0.60	8	5	12	7
Motor Grader	1	4 (m2)	0.54	0.63	0.51	12	22	11	8
Motor Grader	2	6 (m1)	0.44	0.54	0.44	18	9	15	14
Motor Grader	3	6 (m1)	0.38	0.49	0.35	13	10	18	12

5.4.3.6 Work Cycle Variation Observed in Excavators

The excavators' primary task involved loading material into aggregate lorries or a crusher machine, apart from excavator 1, the primary task of this machine was to spread earth evenly across the ground. The data is summarised in Table 5.8. There was no dominant axis for the amount of variability observed between work cycles: the vertical axis produced the greatest amount of variability in four of the machines investigated. The amount of variability was considerably higher in all three axis compared with the other machine groups. Two excavators EX1 (day 3) and EX2 exhibited the greatest amount of variability in the vertical axis (over 50%). As this was not the worst axis of vibration, the variability would become irrelevant when performing a health risk assessment. One characteristic that these two measurements have in common is that both the machines performed more tracking (i.e. driving on tracks) than the other machines. Excavator 4 also had a large amount of variation greater than 50%, however, this was in the lateral not vertical axis. This machine spent the majority of its work operation in a stationary position, however, it was required to move sideways from time to time when a new section of earth needed to be excavated.

Table 5.8 Inter-cycle variation of the frequency weighted r.m.s. values in excavators

Machine Type	ID	Site (day)	r.m.s. (m/s²)			C of V (%)			No. of cycles
			a_{wx}	a_{wy}	a_{wz}	x	y	z	
Excavator	EX1	6 (m1)	0.39	0.21	0.20	21	32	37	56
Excavator	EX1	6 (m2)	0.37	0.20	0.20	29	30	29	69
Excavator	EX1	6 (m3)	0.43	0.25	0.30	24	24	57	14
Excavator	EX2	6 (m1)	0.50	0.32	0.41	26	35	52	30
Excavator	EX3	6 (m1)	0.39	0.33	0.24	26	26	26	58
Excavator	EX4	4 (m1)	0.50	0.23	0.17	36	52	30	150

5.4.3.7 Work Cycle Variation in Rollers and Miscellaneous Machines

This section presents the roller machines and the miscellaneous machines that do not fit into a specific category. The data sets for the work cycles have been summarised in Table 5.9.

There is no consistent trend between the three types of rollers investigated. There is a large amount of variability in the lateral axis for R1. The lateral vibration magnitude increased towards the end of the measurement. Unfortunately the GPS failed to pick up reception during this measurement, therefore these events cannot be correlated

with the speed data. However, the circumstances surrounding this measurement period may help to determine the cause of the increased vibration and variability during this time. The weather deteriorated during the measurement so all machines were required to halt operation. This usually results in the machines travelling to a set destination to park up the machine while they wait for further instruction. If this was the case then the additional travelling may be the cause of the elevated magnitudes.

Roller 2 was also operating on the same site as R1, but in a different area. This area had good satellite reception for the GPS, this meant that speed could be correlated with the data (presented in Appendix A8). The periods of elevated vibration during this measurement correlated with the speed of the machine. The variation was considerably high across all three axes for this machine. The magnitudes of vibration are also consistently higher across axes compared with the other two rollers. This was not surprising as this machine was travelling over a variety of terrain, the gradient of the terrain also changed during the measurement and the speed of the machine.

Table 5.9 Inter-cycle variation of the frequency weighted r.m.s. values in miscellaneous machines

Machine Type	ID	Site (day)	r.m.s. (m/s²)			C of V (%)			No. of cycles
			a_{wx}	a_{wy}	a_{wz}	x	y	z	
Skid Steer L	SSL1	2 (m1)	1.00	0.63	0.71	12	15	15	5
Roller	R1	6 (m1)	0.36	0.39	0.42	12	27	10	20
Roller	R2	6 (m1)	0.52	0.76	0.52	26	28	29	74
Roller	R3	7 (m1)	0.33	0.38	0.29	8	7	7	14
Material H	MH1	5 (m1)	0.41	0.38	0.27	20	21	15	5
Compactor	CP1	6 (m1)	0.44	0.72	0.28	17	18	12	56
Challenger	CL1	10 (m1)	1.66	1.06	2.11	7	7	7	16

Roller 3 had the lowest amount of variation between cycles compared with all other machines in this section apart from the Challenger. This machine was operating over a short distance, with marginal change in gradient and it consistently travelled over the same terrain.

The material handler produced higher vibration in the horizontal axes, the variation between cycles was also higher in the horizontal compared with the vertical direction. This is not unexpected as the machine is constantly handling different types of scrap metal and swinging the grapple claw at varying speeds and distances.

The skid steer loader measured at site 3 had one primary task of loading sandbags in the builders yard. The r.m.s. vibration magnitudes are lower than the skid steer loader 216 measured during the pilot study for this thesis (presented in Appendix A2) when comparing the loading cycle operation. This is not surprising as the loading cycles for machine 753 were kept within a very small area so the machine was not involved in significant amounts of travel, and any travel undertaken was done so on concrete. The skid steer loader in the pilot study was operating at a proving ground on rougher terrain with stock piles that were further apart. The skid steer loader 753, did however, produce larger horizontal vibration than the skid steer loader 216 when it was travelling (0.73 and 0.53 m/s² for the x- and y-axis). The amount of variation between cycles for this machine could be considered to be high for a machine carrying out such a repetitive task.

The Challenger produces the most severe vibration of any machine measured throughout this study; as discussed in Chapter 4. This severity remains high throughout the work cycles. The variation is small between cycles because the machine is flattening the same circular area of a field throughout the measurement period.

5.4.3.8 Work Cycle Variability Acceptance for Machine Categories

The earth-moving machines have been categorised into their respective groups in order to analyse the differences found between them. Figure 5.3 presents the individual variability and vibration magnitudes experienced in each machine.

The machines have been categorised into three groups depending on whether they have low, moderate or high variability between work cycles, these are presented in Table 5.10. The dump trucks and articulated trucks fell within the lowest variation category (below 12.5%) and at the other end of the scale in the high category were the excavators (above 25% variation). The wheel loaders come into the moderate category for variation although there were a small number of these machines that had very high amounts of variation between measurements. However, due to the large sample set collected the majority of wheel loaders are within the 12.5 – 25% range.

Table 5.10 Mean inter-cycle variation for machine type

Variation Category	Machine Type	Coefficient of Variation (%) mean ± stdev (range)		
		x-axis	y-axis	z-axis
0 - 12.5% (Low)	Dump trucks	8 ± 3 (5 – 11)	8 ± 2 (6 – 10)	8 ± 4 (4 – 12)
	Articulated trucks	8 ± 2 (5 – 10)	8 ± 4 (4 – 15)	8 ± 2 (5 – 10)
12.5 - 25% (Medium)	Motor graders	13 ± 4 (8 – 18)	12 ± 7 (5 – 22)	14 ± 3 (11 – 18)
	Tracked loaders	12 ± 4 (6 – 17)	15 ± 3 (9 – 20)	11 ± 3 (6 – 18)
	Wheel loaders	17 ± 6 (11 – 35)	21 ± 8 (10 – 45)	18 ± 7 (9 – 35)
Over 25% (High)	Rollers	15 ± 9 (8 – 26)	21 ± 12 (7 – 28)	15 ± 12 (7 – 29)
	Bulldozers	23 ± 7 (14 – 34)	24 ± 8 (12 – 38)	16 ± 5 (10 – 25)
	Excavators	27 ± 5 (21 – 36)	33 ± 10 (24 – 52)	39 ± 13 (26 – 57)

Note: variation category is selected based on at least 75% of the measurements falling under the category % for all three axes, x, y and z.
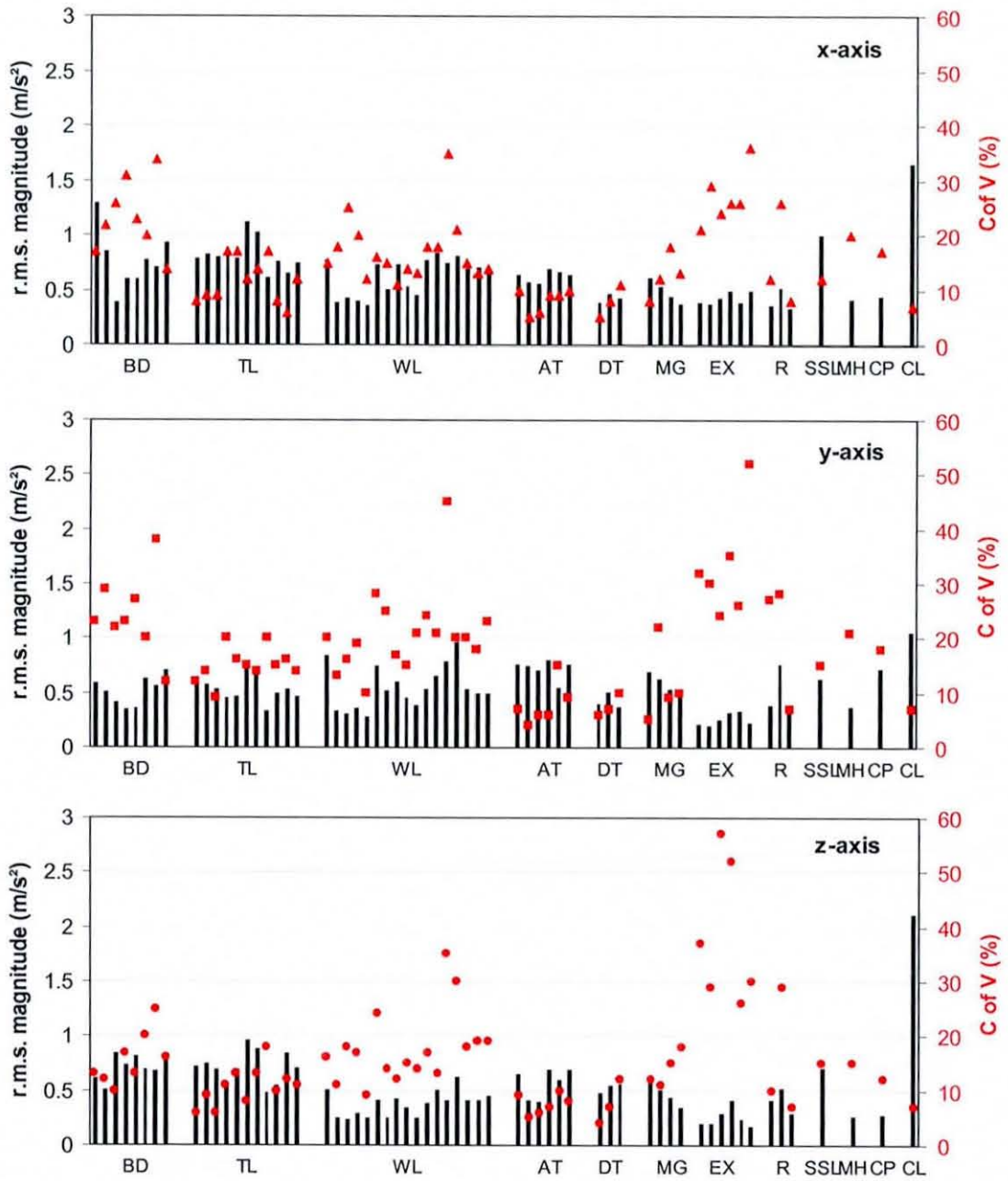
Figure 5.3 Frequency weighted r.m.s. and coefficient of variation for bulldozers (BD), tracked-loaders (TL), wheel-loaders (WL), articulated trucks (AT), dump trucks (DT), motor graders (MG), excavators (EX), rollers (R), skid steer loader (SSL), material handler (MH), compactor (CP) and challenger (CL)

5.5 Discussion

This study was not a laboratory experiment or a controlled field trial. Therefore many complications can arise and most of the measurements were at the mercy of the sites and workers driving the machines. Conditions are notably going to vary for these very reasons and that is the point of the study to determine how much variability one should expect. A large number of factors can alter the accuracy of a vibration measurement in its extrapolation to a daily dose measure. It is important to acknowledge the variation inherent to whole body vibration exposure to help understand how this variation will affect health risk assessments. The aim of the study was to determine how substantial the variability is between vibration measurements of work cycles and daily cycles in earth-moving machines. The hypotheses stated in section 5.2 have been tested and will be discussed in the following section.

The coefficient of variation has been calculated to determine the amount of variability in the data. A high coefficient of variation implies a high variability in vibration magnitude from day to day and from work cycle to work cycle. For the individual measurements 69% will occur within the range of the mean x (1 − coefficient of variation) and mean x (1 + coefficient of variation). Although most measurements occur within the range encompassed by ± 1 standard deviation of the mean, more than one quarter will occur outside this range, assuming a normal distribution of measurements.

5.5.1 Day-to-Day Variability of Whole-Body Vibration Emission Values

The findings from the day-to-day variability study support the first hypothesis, '*Vibration magnitudes from one day will be above the 25% error margin for the magnitudes experienced at other times during the working week*'. These findings are comparable to the results of Marjanen (2006). Only 27% of the machines investigated for day-to-day variability had coefficient of variations below 10% in all axes (under the 12.5% lower limit). Five out of the 11 machines measured had at least one axis exceeding the 25% upper limit. Many of which had the greatest amount of variability in the axis with the greatest amount of vibration. Kittusamy (2000) suggested that the variance is more dependent on differences in the specific task performed rather than the equipment being used. There is also evidence of this here; however it could also be argued that certain machines are more adaptable to a greater variety of tasks, therefore resulting in more variance. This appears to be the case for the wheel loaders, some of their

daily tasks changed depending on the requirements at that time, resulting in greater variation between the daily vibration profiles.

Articulated truck 3 had a large amount of variation between days in the lateral axis. The most likely explanation for this is on one of the days this machine was carrying a different type of load. The load characteristics may have altered the lateral stability of the machine. Excavator 1 produced large variations for both the lateral and vertical axes, this may be the result of greater amounts of travel on day 1 compared with the other two days.

One of the measurements for wheel loader 9 was carried out during a different operation to the machines typical task operation. If the change in task operation was disregarded for the purpose of this daily variation study then the variability between days would significantly reduce from 13%, 31%, and 20% to 11%, 10%, and 13% for the x-, y- and z-axis, respectively. This suggests that when the machine is involved in normal loading operations the variability between daily measurements is within an acceptable range. Wheel Loader 4's task operation also varies between days, one day the operator was required to load the train wagon and the second day they are required to load the crusher machine.

Wheel Loader 3 was measured on three separate occasions. It is interesting to find the highest vibration magnitudes occur during the first measurement, especially as the investigators witnessed the driver of this machine conducting exaggerated movements once the vibration test equipment had been fitted. The operator of this machine expressed his dislike for this particular model and is suspected of intentionally increasing the severity of the measurement by driving aggressively. By the second and third measurement he may have developed some immunity to the presence of the investigators as reported previously by Stayner (2005).

The tracked loader 953 also exhibited a large amount of variation in the vertical direction. This machine was carrying out the same type of levelling operation on both days, however, on the first day this machine was operating on a very steep gradient and on the second day it was on flat terrain.

Although some of the measurements were found to be very repeatable (e.g. AT2 or TL1) it is not possible for a class of machine to be characterised as typically having that amount of variability between measurements as the same type of machines were also found to have little repeatability (e.g. TL2). In addition there were three instances

where the dominant axis of vibration changed between the measurements (for WL9, AT3 and TL2), this also suggests there is still lots of uncertainty that cannot be quantified with such a small data set. There needs to be more research in this area looking at larger data sets over larger numbers of repeat measurements.

5.5.2 Site-to-Site Variability of Whole-Body Vibration Emission

The results from the site-to-site variability cannot validate the second hypothesis 'vibration profile from one machine will not be within a 25% error margin for a similar machine working in another environment or site'. Generally the trends observed in each machine category were similar across all the sites investigated. Articulated trucks produced r.m.s. values around the $0.60 - 0.80$ m/s² at the three sites investigated (9% coefficient of variation). The dump trucks produced vibration magnitudes around $0.50 - 0.60$ m/s² (9% coefficient of variation). The truck data may be closely correlated as the tasks carried out by these machines were very similar across the different sites. There is a substantial spread in the data for wheel loaders so in terms of the wheel loaders the hypothesis could be accepted for these machines (29% coefficient of variation), however the spread appears to be more related to the task within a site compared with across different sites. The majority of wheel loaders were carrying out loading tasks, however, the variety of the loading tasks, load carried and distance travelled varied substantially between measurements. The excavators also had substantial spread in their data (28% coefficient of variation), the majority of these machines were measured at one site and so the comparison between different sites is not substantial enough to draw any conclusions. Bulldozers, tracked loaders and motor graders all had similar amounts of variability between the machines (BD 18% c of v; TL 20% c of v; MG 17% c of v).

There is no one site that typically produces vibration magnitudes higher than any other. The only exception was Site 8, this site, however, only used tracked loaders therefore it is hard to judge the condition of the site based on such a small sample of machines. The main concern regarding the range of sites visited is the potential that only large sites with a well established safety and maintenance system were visited. This is problematic when trying to obtain a full representation of the different operating environments for this sample of earthmoving machines.

5.5.3 Inter-Cycle Variation in Earth-Moving Machines

The machine group with the least variation between work cycles was the articulated and off-highway trucks. All of the machines had less than 15% difference between work cycles for the r.m.s. magnitude. Following this trend only three tracked loaders, one wheel loader, one roller machine, one motor grader and the challenger produced similar amounts of variation between cycles. The remaining machines exhibited higher amounts of variability between each work cycle. This suggests that measurement durations in the majority of machines should be long enough to account for this variability. The machine group with the highest amount of variation between work cycles was the tracked excavators. All of the excavators measured during this project fall below the action value of the Physical Agents (Vibration) Directive once an A(8) value is calculated from the emission value. Therefore the high amount of variation observed between work cycles is effectively less important as these machines will not be targeted for a vibration health risk assessment. However, in times when there is the likelihood of measurement in these machines consideration needs to be given to the variability to ensure many work cycles are recorded. The excavators in this study were not involved in tracking but for times when they are, there could be similar amounts of variation, unfortunately without further measurements this is still an unknown.

The rollers, bulldozers and excavators variability between work cycles supports the third hypothesis *'vibration magnitudes from one work cycle will exceed the 25% acceptance level for the amount of variability found within a machines emission for a particular task'*. The excavators in particular were found to vary substantially between excavation loading cycles. However the remaining machines did not exceed the variability limit of 25%; the motor graders, tracked loaders and wheel loaders typically had variation between the range 12.5 – 25%, whereas articulated trucks and dump trucks fell below 12.5%.

The wheel loaders were found to have a greater spread in variation compared to other machines in the moderate category, however this is partly due the large number of measurements taken on these types of machine. The majority of wheel loaders were carrying out loading tasks, however, the variety of loading tasks, load carried and distance travelled varied substantially between measurements. The machine with the largest amounts of variation between work cycles was an extreme case compared to the remaining wheel loaders (WL8). The variation for this particular machine was largely dependent on the amount of travel involved in the work cycle. It is therefore important to encompass many operation cycles for a vibration measurement to ensure

reliable emission values are obtained for wheel loaders that have increased amounts of travel during the work cycles.

The variation between work cycles has been shown to be dependent on the type of machine being operated, these results support the fifth hypothesis 'variation between work cycles will be dependent on machine type'. The dump trucks and articulated trucks fall within the lowest variation category and at the other end of the scale are the excavators in the very high variation category. Kittusamy (2000) also found the vibration to vary significantly for excavators, from sample-to-sample. The coefficient of variation for 8 samples of an excavator digging and loading a truck exceeded 40%.

The variation observed between work cycles for some machines was found to correspond with the increased travel carried out during the task. An example of this has been presented for Wheel loader 8 where exclusion of the travelling periods highlights the change in cycle variation and vibration magnitude. This suggests that measurements of wheel loaders carrying out additional travelling during their task cycle need to be longer in duration than measurements of wheel loaders carrying out typical loading tasks with small amounts of travel and therefore small deviations of speed. The majority of the articulated and dump trucks cycle involves travelling. The fundamental difference with these machines is they are mainly operating on well-maintained roads with controlled speed limits. The high variability in cycles is present for other machines that do not usually have large amounts of travel within their tasks, such as the wheel loaders. The machines with the greatest amount of variability in their cycle are the excavators; the majority of their operation time is spent in a stationary position excavating earth or rocks.

Dozer 4 and Dozer 7 were both found to produce large amounts of variation in vibration due to the changing characteristics of the terrain. The terrain conditions and gradient change as the machines work on different sections of the sites. Dozer 7 in particular was working on very steep rocky terrain during work cycles 10 to 29. If that section was removed from the Dozer's normal operation then the variability between cycles would reduce to 21, 18 and 15% for the x-, y- and z-axes respectively.

On the second measurement for motor grader 1 there was an increase in variation between cycles for the lateral axis. Due to substantial rainfall on this day the muddy track the machine was operating on became waterlogged and churned up. This resulted in the surface becoming very irregular compared with the first days measurement. In contrast, both the challenger and tracked loader 1 produced very

small variation between work cycles, even though they were operating on rough terrain. The difference was that even though the terrain was rough both of these machines consistently smoothed and flattened the same area throughout the measurement period. This would have meant that they were being subjected to the same amount of rough terrain, with no particularly irregular gradients or rocky areas.

Findings from the inter-cycle variation clearly support the notion of measuring for a longer duration as highlighted previously by Mansfield *et al.* (2003). The amount of variation experienced throughout the range of earth-moving machines highlights the importance of conducting a task analysis prior to doing the measurement. Operators may often neglect to inform the investigator of times when they might be operating on different types of terrain. They may consider the task they perform to remain constant throughout the day, and fail to remember the times when the terrain or material might alter in characteristics. For example, if they are earthmoving on flat terrain or moving larger rock particles like dozer 7, the investigator would need to ensure this activity is included in the assessment. Therefore a variety of specifically formulated questions should be asked to ensure a thorough overview of the daily working operations is provided.

5.5.4 Limitations of the study

Like the previous study this one has high external validity; unfortunately gained at the expense of the internal validity. All the limitations about the field study discussed in Chapter 4 are also relevant to this one. The sample size of some machine types was too small to gain sufficient understanding of the nature of the variability experienced between work cycles.

Ideally measurements would have been for the whole of the working day. Nonetheless, throughout the testing period every effort was made to ensure measurement durations were sufficient to provide an accurate representation of the vibration exposure experienced throughout a working day, in all types of machine. Preferably the measurement durations should be no shorter than one hour, on occasions this was not possible to achieve this minimum duration. Extraneous factors influenced how long measurements could last in each machine. For example, the last three sites were visited in one day this greatly restricted the amount of time that could be spent at each site. The amount of time and resources available were maximised to ensure reliable measures were obtained. This subsequently reduced the number of work cycles that could be measured for some models of machines.

Ideally the true source of the variation found between the work cycles would be identified. Due to the nature of the study depending on the quantification of the 'true' variability it was not possible to manipulate the work environment to be able to control any of the variables. It was also not possible to determine the variability between A(8) exposures because the duration was often limited. Consideration of this type of variability should be explored in future research.

5.6 Conclusions

Throughout the study evidence has presented itself to suggest that operator behaviour and driving style can have an impact on the vibration exposure of earthmoving machines. In many cases earthmoving machines produced similar trends of vibration magnitudes when operating in a range of different environments, from granite quarries and open cast coal mines to airport construction sites. The amount of variability between work cycles was similar within each machine category. The specific conclusions for this study are:

- **The results from the day-to-day variability support Hyp[1]** *'vibration magnitudes from one day will be above the 25% error margin for the magnitudes experienced at other times during the working week';* vibration magnitudes measured from one day were not consistently representative of the vibration profile experienced throughout the working week. The findings clearly demonstrate the necessity to take measurements on more than one day. The largest variability occurred due to the type of task being undertaken. Where substantial changes in emission or worst axes of vibration occurred from day-to-day these were due to task or material changes.

- **The results from the site-to-site variability for most of the machines do not support Hyp[2]** *'vibration profile from one machine will not be within a 25% error margin for a similar machine working in another environment or site;* generally the trends observed in each machine category were similar across all the sites investigated. Although there was substantial spread in the data for wheel loaders there appeared to be just as much spread within the same site. Excavators were mainly measured at one site so even though there was 28% variation, this was more related to the machine and task than the site.

- **The rollers, bulldozers and excavators variability between work cycles supports Hyp[3]** *'vibration magnitudes from one work cycle will exceed the*

25% acceptance level for the amount of variability found within a machines emission for a particular task'; excavators in particular were found to vary substantially between excavation loading cycles. However the remaining machines did not exceed the variability limit of 25%; the motor graders, tracked loaders and wheel loaders typically had variation between the range 12.5 – 25%, whereas articulated trucks and dump trucks fell below 12.5%.

- **The results from the inter-cycle variation support Hyp[4] *'variation between work cycles will be dependent on machine type'*;** variation between work cycles was shown to depend on the type of machine being operated. As highlighted in the previous bullet point.

- Machines with the greatest amount of travel in a work cycle do not necessarily have the greatest amount of variability. The machines with the greatest amount of travel in their work cycles are the articulated and dump trucks, yet they have the lowest amount of variability between cycles. The fundamental difference with these machines is they are mainly operating on well-maintained roads with controlled speed limits. The machines with the greatest amount of variability in their cycle are the excavators; the majority of their operation time is spent in a stationary position excavating earth or rocks.

- Variation between work cycles was high when the terrain type was irregular. Dozers exhibited periods of elevated vibration magnitudes due to the changing characteristics of the terrain this increased the variability substantially between work cycles and could be managed through appropriate training. The weather impacting terrain also increased the variability between work cycles for a motor grader. Rain created a waterlogged track that became churned up resulting in increased irregularity of the surface causing greater variation in the lateral vibration.

Chapter 6 - Study 2

Influence of twisted posture on the biomechanical response to vertical vibration

This chapter discusses a laboratory study designed to incorporate the ergonomic risk factors identified in the field study presented in Chapter 4 and 5. Operators of earthmoving machines, particularly the tracked loaders and dozers, were found to adopt non-neutral twisted postures while being simultaneously exposed to high magnitudes of vertical and fore-and-aft vibration. This study aimed to establish if adopting twisted postures could change the biomechanical response to whole-body vertical vibration. The methodology was validated with previous research; this ensured the study design could be developed to incorporate the more realistic conditions for the field environment, as presented in Chapter 7.

6.1 Introduction

Operators of earthmoving machines are regularly exposed to a range of occupational hazards. The nature of their working task can expose them to unsafe magnitudes of whole-body vibration and shock, in conjunction with a variety of postural constraints. This has been highlighted by the previous study described in Chapter 4, the study identified concomitant risk factors for the operators: driving in postures with elements of twisting in the back and neck whilst simultaneously exposed to whole-body vibration. Twisted postures are clearly a widespread problem in many industries yet relatively little is known about the interactions of these postures with vibration exposure. Magnusson and Pope (1998) determined that forklift drivers, farmers and construction workers are all exposed to long periods of twisted posture. Furthermore Kittusamy and Buchholz (2001) found operators adopted a twisted or flexed trunk posture for 25% of their excavating work cycle, in addition to having a flexed or twisted neck for 22% of the cycle. In underground mining, operators of load-haul dump vehicles have been observed adopting asymmetric postures throughout their work cycle, whilst also exposed to relatively high magnitudes of whole-body vibration. One operator in particular had his neck twisted >40 degrees for 93% of a 60 minute work cycle (Eger *et al.*, 2006).

Subjective ratings of discomfort have been shown to increase whilst driving with twisted necks or backs compared with driving in a forward upright posture (Wikström,

1993). Discomfort could be the first indication of more serious problems for drivers exposed to bent twisted postures considering they have been found to have a greater risk of developing musculoskeletal disorders and low back pain (Kittusamy and Buchholz, 2004; Hoy et al., 2005).

Vibration exposure has also been associated with back pain, yet previous research has failed to address both vibration and postural factors in combination. One way to develop the understanding of the combined effects of whole-body vibration and posture on the human body is to consider vibration transmission through the body. The transmissibility of the human body can indicate the biomechanical response to whole-body vibration (Paddan and Griffin, 1998). Seat-to-head transmissibility and investigation of the rotational movement of the head can also provide an indication of the level of disturbance an operator may experience while operating earthmoving machines. Rotational head movements particularly in the pitch direction can hold most interest for activity disturbance, due to the flexion/extension of the neck having the greatest impact on vision (Griffin, 1990).

Many studies have been performed to investigate the apparent mass in a forward facing posture (e.g. Fairley and Griffin, 1989; Mansfield and Griffin, 2000; Mansfield and Griffin, 2002; Rakheja et al., 2002; Wang et al., 2004) and the transmissibility of vibration from the seat to the head for subjects exposed to translational whole-body vibration (WBV) (e.g. Paddan and Griffin, 1988a, 1988b, 1993, 1994 and 1996; Matsumoto and Griffin, 1998). One consistent finding across studies is that seated subjects' fundamental resonance frequency exists in the region around 4 - 5 Hz for vertical vibration exposure. Although the findings are consistent it has been suggested that 'caution should be exercised in the interpretation of any single curve showing an 'average' transmissibility of a group of subjects (Paddan and Griffin, 1994): sitting posture and individual differences in body dimensions including height and weight have explained most of the variation in seat-to-head transmissibility (Messenger and Griffin, 1989) as opposed to differences within an individual's transmissibility. Paddan and Griffin (1994) found the median data for 12 subjects to differ greatly from the transmissibility of some of the subjects. For a back-off (no backrest contact) condition inter-subject variation was found to be up to 18 times greater than intra-subject variability. A similar relationship could be expected in the current study considering the subjects will also be in a back-off position.

The amount of variation found in the transmission of vibration due to postural changes has been explored by a number of researchers (e.g. Paddan and Griffin, 1988a;

Messenger and Griffin, 1989; Kitazaki and Griffin, 1998; Hinz *et al.*, 2002; Howarth, 2003). However, none of these studies have attempted to reflect the typical 'twisted posture' adopted during operation of many earthmoving machines. One more recent study of apparent mass assessed static and dynamic postures, including a twisted posture that could typically be observed in operators of earthmoving machines (Mansfield and Maeda, 2005). The authors evaluated the apparent masses in the range of posture conditions for subjects exposed to vibration. In a dynamic twisting posture, including a continuous arm motion task, the peak in the apparent mass was attenuated, indicating a different biomechanical response was experienced in the moving posture. It was suggested that the change in biomechanical response was due to either the extended arms acting as a passive vibration absorber or that the twisting action interfered with the usual acceleration-muscle feedback system. The authors found a small but significant increase for the resonant frequencies in the twisted static posture compared with the back-off upright posture. The relationship reversed at frequencies above 10 Hz however no statistical analysis was presented for such frequencies. The twisted static posture and back-off upright posture are the most comparable postures to the ones in the current study; therefore one might predict a similar relationship in transmissibility.

To date there have been no specific studies looking at the variations in seat-to-head transmissiblility for participants adopting a twisted posture as opposed to the 'standard' upright forward facing posture. Ergonomic postural tools like Rapid Upper Limb Assesment (RULA) tell us that twisted postures contribute to increased risk for musculoskeletal disorders, yet the understanding of the interactions with vibration transmission are still unknown. Using the findings from a number of studies reporting the effects of head angle, pelvic angle and back postures one could hypothesise the possible changes in transmissibility in such a posture (Messenger and Griffin, 1989). The studies found an 'anatomically correct forward facing sitting posture' increased the transmission of vibration to the head at higher frequencies but minimized the transmissibility at lower frequencies. If the curves of the spine are bent or twisted one might observe the converse: i.e. increases in low frequency head motion but reductions in the transmission of high frequencies. Likewise with an 'upright' posture the back will be straight and this posture tends to give less head motion at low frequencies but transmits much more vibration at high frequencies.

6.2 Hypotheses

It is important to understand the interactions between vibration exposure and twisted postures to improve understanding of the biomechanical responses of the human body. The aim of this study is to improve understanding of how twisted postures interact with the vibration exposure to help guide future work for the effective management of WBV risks. A secondary aim of the study was to validate the methods used with previous single-axis findings from the research literature, in order to apply the methods for use in a multi-axis study. The hypotheses for this study are:

Hyp[1]: The apparent mass modulus will be greater at frequencies below 10 Hz while seated in a twisted posture compared to an upright posture.

Hyp[2]: The apparent mass modulus will be lower at frequencies above 10 Hz while seated in a twisted posture compared to an upright posture.

Hyp[3]: Inter-subject variability will be more than four times greater than intra-subject variability for seat-to-head transmissibility.

Hyp[4]: Vertical and pitch seat-to-head transmissibility will be greater at frequencies below 10 Hz while seated in a twisted posture compared to an upright posture.

Hyp[5]: Vertical and pitch seat-to-head transmissibility will be lower at frequencies above 10 Hz while seated in a twisted posture compared to an upright posture.

6.3 Experimental Method

6.3.1 Subject Characteristics

Fourteen male subjects and one female subject participated in the experiment. Subjects had a mean age of 23.4 σ 1.2 yrs, a mean stature of 170 σ 10 cm and a mean weight of 66.4 σ 11.4 kg.

6.3.2 Experimental Procedure and Analysis

Subjects were exposed to 60 seconds of vertical random vibration within the frequency range 1-20 Hz. The magnitude of the vibration was set to 1.0 m/s^2 r.m.s. (root mean square, unweighted). The vibration magnitude was based on the vertical vibration magnitudes found in the tracked bulldozers and loaders discussed in Chapter 4 and 5. Vibration was generated using a multi-axis shaker and measured using a Bruel and Kjaer 4326A triaxial accelerometer amplified using a Nexus charge amplifier. Subjects sat on a wooden rigid seat, in two different postures: 'upright' forward facing posture and 'twisted' non-neutral posture. In both conditions the hands rested on the lap and there was no backrest contact. In the 'upright' condition, subjects were instructed to sit in a relaxed upright posture facing straight ahead. In the 'twisted' condition, subjects were instructed to look over their right shoulder in the coronal plane (Figure 6.1). Both postures required the subjects to focus on a marker, positioned either at the front of the seat, or the rear of the seat. The trials were repeated 3 times for each posture condition and the order of test conditions was randomised using a Latin-square design.

Figure 6.1 Two postures adopted during the experiment; upright (forward facing) posture and twisted posture, without backrest support.

6.2.2.1 Apparent Mass Experimental Method

The force at the seat was measured using a Kistler force plate. The influence of the mass of the plate was removed using the mass cancellation technique in the frequency domain; the apparent mass of the unloaded force plate was subtracted from the subjects' apparent mass. Force and acceleration signals were acquired by Pulse (Version 8) data acquisition system. Data was acquired at 512 samples per second via anti-aliasing filters set at 170 Hz. Coherence, phase and apparent mass were recorded through the data acquisition system.

Apparent masses (M(f)) were calculated using the cross spectral density (CSD) method, presented in Equation 6.1.

$$M(f) = \frac{CSD_{force-acceleration}(f)}{PSD_{acceleration}(f)}$$

Equation 6.1

Where:

CSD (f)   is the cross spectral density between the acceleration and the force

PSD (f)   is the power spectral density of the acceleration at frequency f

To enable direct comparisons of subjects' apparent masses the sitting weight of each subject at 1.0 Hz was averaged for the twist and upright posture. The apparent mass was then divided by the mean value in order to normalise the data.

6.2.2.2 Seat-to-Head Transmissibility Experimental Method

Subjects held a bite-bar tightly in their mouth comprising accelerometers mounted on the left and right side and at the back of the head. The accelerometers measured the vibration at the head in the fore-and-aft, lateral and vertical directions. Seat-to-head transmissibilities were calculated in order to determine the ratio of the input acceleration at the seat (vertical vibration) and the output acceleration at the head (fore-and-aft, lateral and vertical vibration). The ratio gives a measurement of the extent to which the vibration has been attenuated or amplified by the spinal system. If the ratio is greater than 1 then the vibration has been amplified. Calculations of roll (lateral bending of the head) and pitch (flexion/extension of the head/neck complex) motion at the head were also completed (refer to Section 3.6.2.2). Calculations of yaw motion could not be completed due to technical difficulties. Seat-to-head transfer

functions were calculated using the cross-spectral density method, presented in Equation 6.2:

$$T(f) = \frac{CSD_{Seat\text{-}head}(f)}{PSD_{Seat}(f)}$$

<div align="right">Equation 6.2</div>

Where:

CSD (f)   is the cross spectral density between the seat and head acceleration

PSD (f)   is the power spectral density of the seat acceleration at frequency f

6.4   Results

This section presents the findings for the apparent mass measurements and the seat-to-head transmissibility while seated in an upright and a twisted posture. The intra- (within) and inter- (between) subject variability are also discussed in the following section. The Wilcoxon matched-pairs statistical test was used to determine if there were any significant differences between the different postures adopted and the different methods used. Statistical significance was accepted at $p<0.05$.

6.4.1   Apparent Mass

6.4.1.1   Intra- and Inter-Subject Variability

Intra-subject variability was small between the three repeat trials for the apparent mass; only slight changes were evident at higher frequencies (

Figure 6.2). Conversely, inter-individual differences were large in both posture conditions (Figure 6.3). The variability was reduced partially with the normalised apparent mass (Figure 6.4), nevertheless clear differences can be observed for the magnitude at peak resonance, the heavier subjects tended to have a larger magnitude response, with peak magnitudes ranging between 44.9 – 122.3 kg. Coherence was high across all frequencies, suggesting that there was good correlation between the force and acceleration.
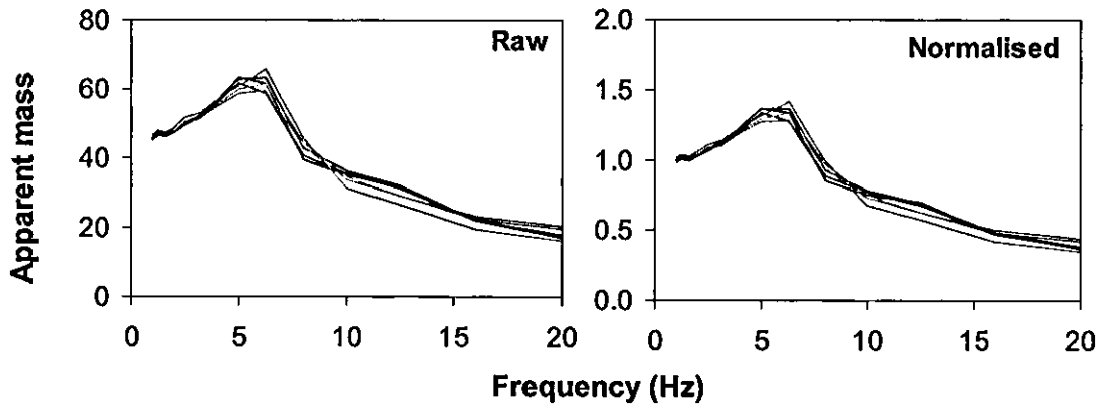
Figure 6.2 Intra-individual variability for 3 repeat trials for apparent mass, example of one subject exposed to random vertical vibration (1-20 Hz, 1.0 m/s² unweighted r.m.s) and seated in a upright (black line) or twisted posture (grey line).
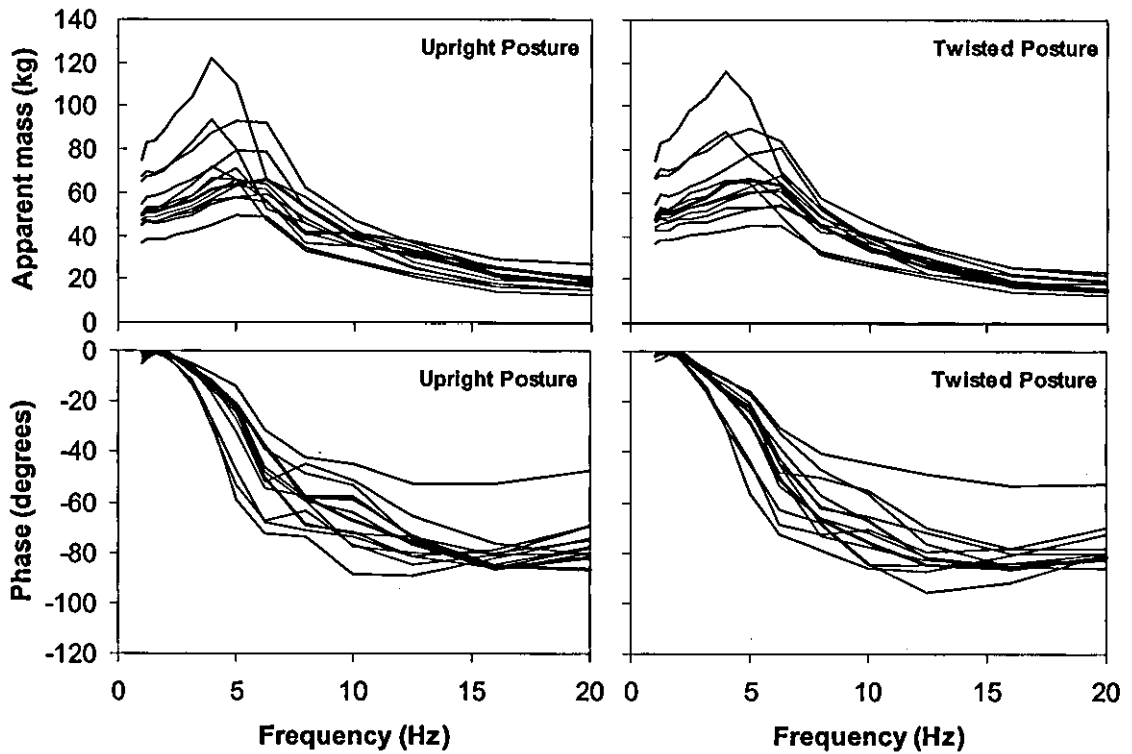
Figure 6.3 Individual apparent mass and phase data for 14 subjects exposed to random vertical vibration (1-20 Hz, 1.0 m/s² unweighted r.m.s) and seated in an upright or twisted posture.

169
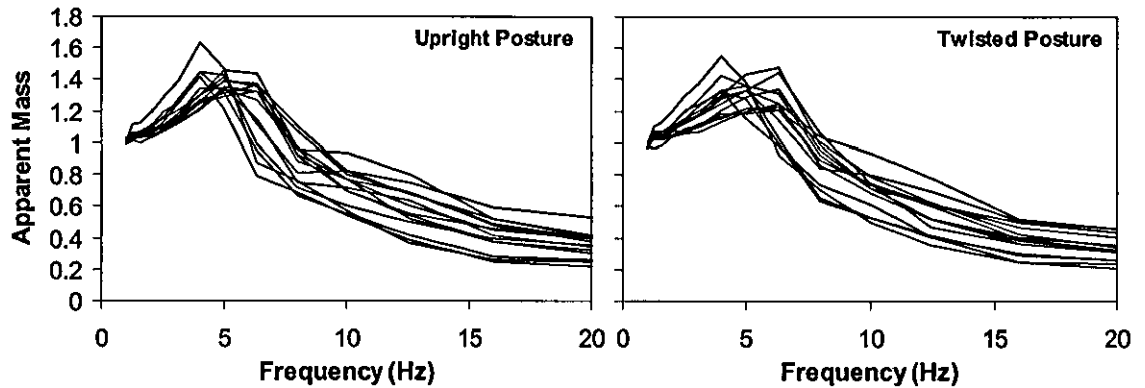
Figure 6.4 Normalised apparent masses for 14 subjects exposed to random vertical vibration (1-20 Hz, 1.0 m/s² unweighted r.m.s) and seated in an upright or twisted posture.

6.4.1.2 Influence of Posture on the Apparent Mass

Subject 8 was excluded from the apparent mass data due to technical difficulties experienced during the measurement. Therefore the following analysis is based on the remaining 14 subjects, including 13 males and 1 female (subject 7). The individual comparisons between vertical normalised apparent mass in an upright and a twisted posture are presented in Figure 6.5. The female had a very similar response to the male subjects, in both postures. It is typical for females to have a smaller body mass and stature compared to males, however, in this instance a number of the male subjects were of a similar height and weight.

There is a small observable pattern between the two posture conditions. The twisted posture condition tends to produce a lower magnitude response at some frequencies, compared with the upright posture. This is particularly evident around the peak response and at frequencies higher than 10 Hz. The median apparent mass of all the subjects maintains the pattern observed in the individual data, subjects had a peak resonance between 4 – 6.3 Hz for both postures (Figure 6.6). Statistical pairwise comparison was performed at 1/3 octave-band frequencies between 1-20 Hz; the findings are superimposed onto Figure 6.6. Statistical differences between the two postures were found at 2, 4, 5, 12.5 and 16 Hz. The difference between postures is no greater than the difference observed between different subjects.
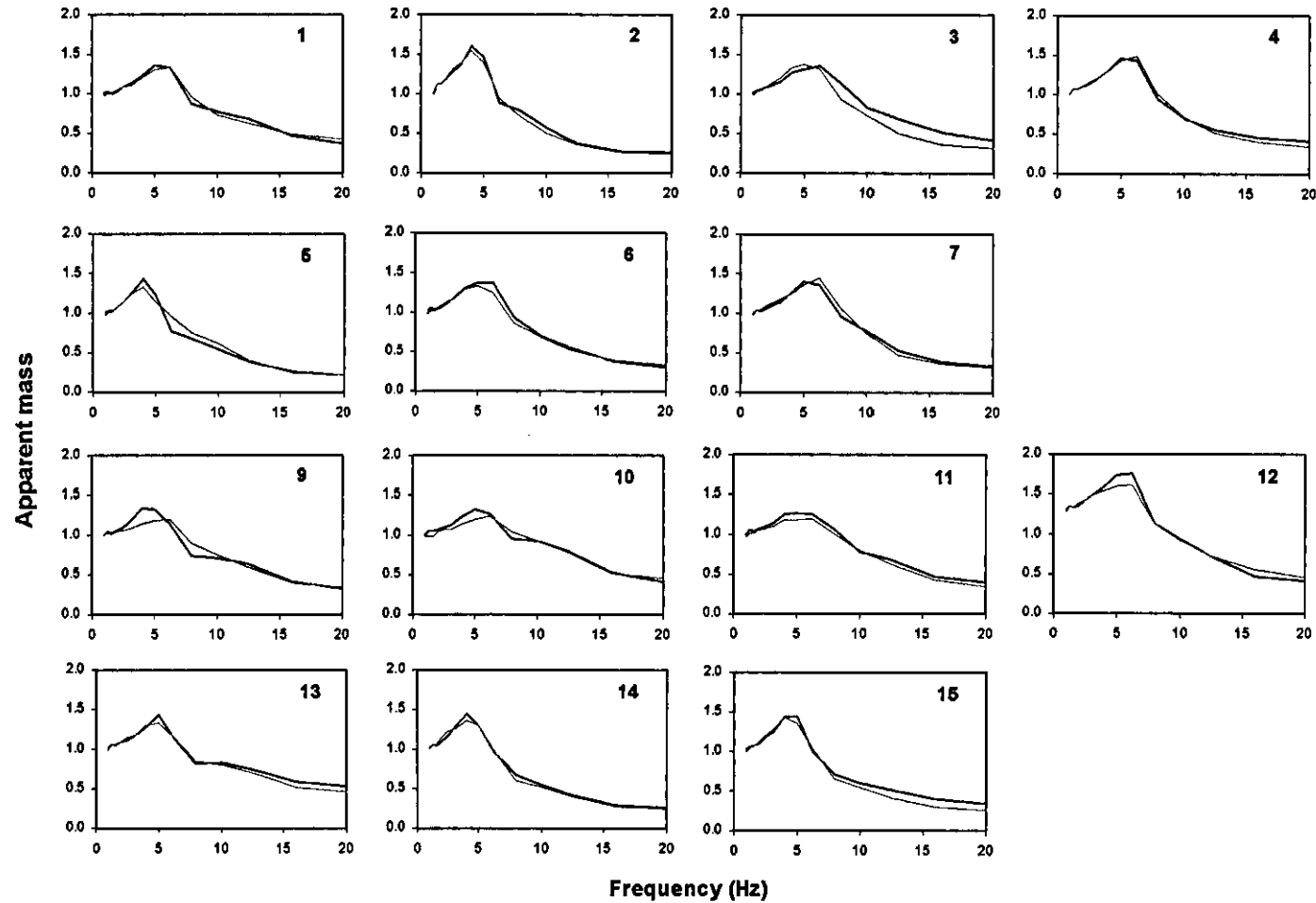
Figure 6.5 Individual apparent masses for 14 subjects exposed to random vertical vibration (1-20 Hz, 1.0 m/s² unweighted r.m.s) and seated in an upright (black line) or twisted posture (grey line).
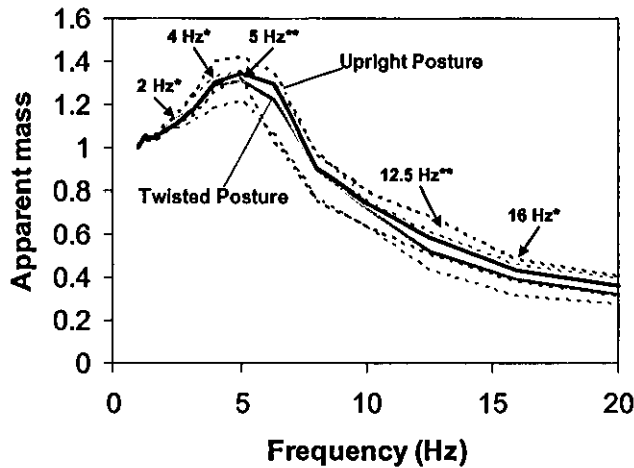
Figure 6.6 Median normalised apparent masses for 14 subjects exposed to random vertical vibration (1-20 Hz, 1.0 m/s² unweighted r.m.s). Pairwise statistical comparison between postures are presented as; * ($p < 0.05$); ** ($p < 0.005$).

6.4.2 Seat-to-Head Transmissibility

6.4.2.1 Intra- and Inter-Subject Variability

Intra-subject variability between the three repeat trials for both posture conditions is presented in Figure 6.7. There were a few discrepancies at certain frequencies around the resonant peak and at higher frequencies. Subjects' mean values of the three trials were taken forward for the overall analysis, therefore taking account of any deviations between the three repeats. Despite the small discrepancies there were clearly separate patterns in the transmissibility curves while seated in an upright compared to a twisted posture.
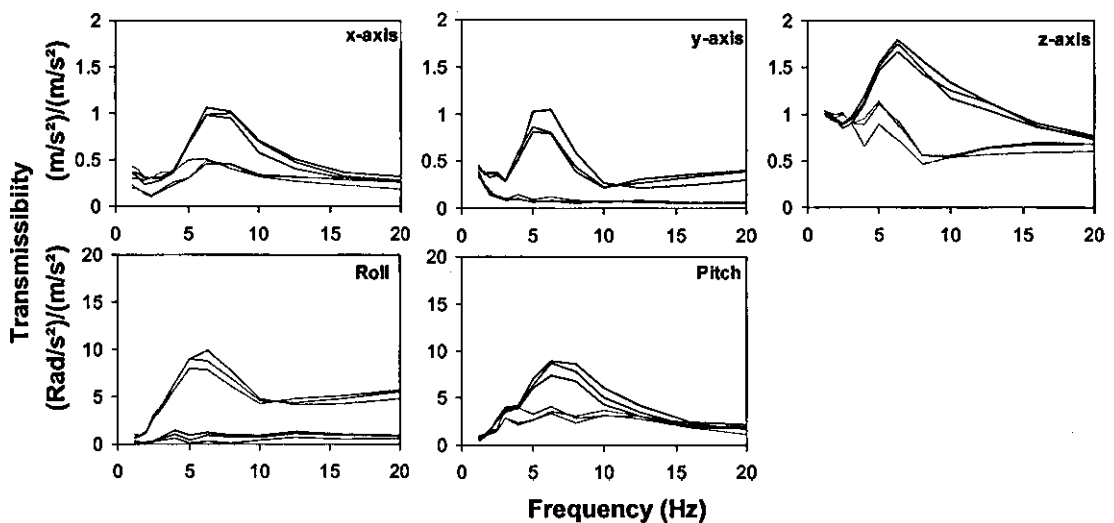
Figure 6.7 Intra-individual variability for 3 seat-to-head transmissibility trials, example of subject exposed to random vertical vibration and seated in a upright (black line) or twisted posture (grey line).

172
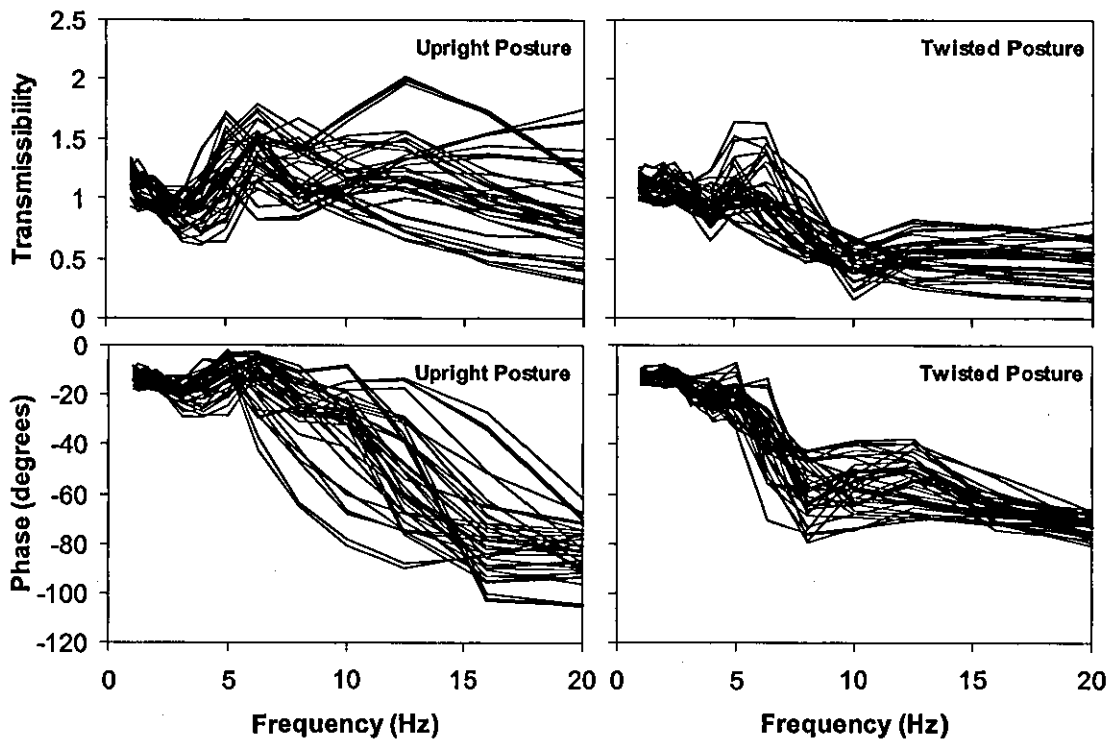
Figure 6.8 Transmission by modulus for vertical seat-to-head vibration of 14 subjects with 3 repeat trials seated in an upright posture and twisted posture.

Inter-subject variability was higher in the upright posture compared with the twisted posture for the vertical transmissibility and phase (Figure 6.8), and for the fore-and-aft motion at the head (Figure 6.10). The opposite is true for the lateral and roll motion: the twisted posture produced greater variability compared with the upright posture. Variability between subjects was high for pitch motion at the head; the amount of variability was similar across postures. Subjects in an upright posture produced a peak in the transmissibility of vertical vibration between 4 - 6.3 Hz with the exception of subject 1 who had a second peak in transmissibility at 12.5 Hz for all three trials (Figure 6.9). The anomaly is not present for the twisted posture condition where all subjects had a peak in transmissibility between 5 - 6.3 Hz.
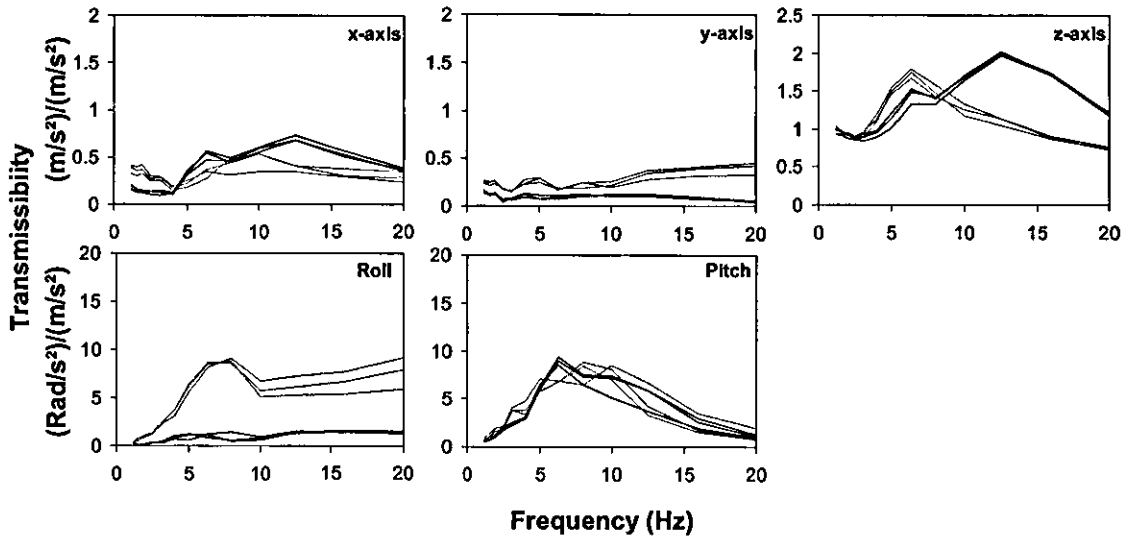
Figure 6.9 Seat-to-head transmissibility over three repeat trials for Subject 1, black lines denote upright posture and grey lines the twisted posture.
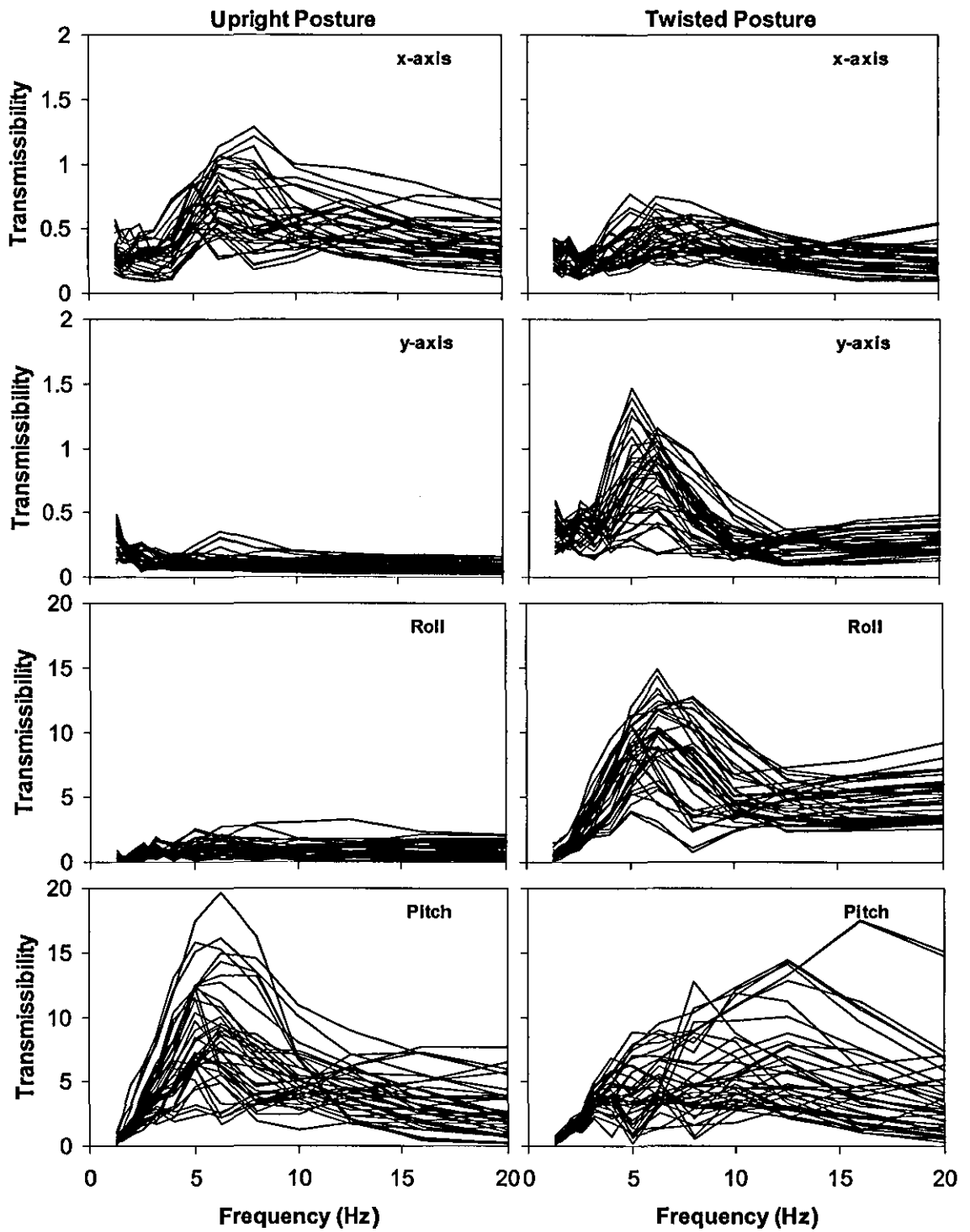
Figure 6.10 Transmission by modulus for fore-and-aft, lateral, roll and pitch motion at the head of 14 subjects with 3 repeat trials seated in an upright posture and twisted posture.

6.4.2.2 Influence of Posture on the Transmissibility

Most individuals had the highest resonance response in the vertical direction while seated in an upright posture; however, there were a few exceptions. Subjects 4 and 9 had a marginally higher resonant peak while seated in the twisted posture (presented in Appendix A9). Additionally 8 out of 14 subjects' initial peak in the twisted posture was slightly higher compared with the initial peak in the upright posture. The primary resonant peak was in the same 5 – 6.3 Hz range for the twisted posture and the upright posture.

Figure 6.11 shows differences between postures for the horizontal and rotational axes of vibration. For a rigid system, seat vertical to head vertical transmissibility would equal 1.0 at all frequencies. Seat vertical to head horizontal transmissibility would equal 0.0 at all frequencies. Observations, however, of Figure 6.11 show that both the fore-and-aft (x) and lateral (y) axes have transmission values greater than zero. This is the result of cross coupling in the system as the human body is a flexible, non-rigid system. Transmissibility in the vertical (z) axis is greater than 1 at the peak frequency for both the upright and the twisted postures. This amplification is sustained in the upright posture even at higher frequencies; the twisted posture presents a distinctly different pattern where less amplification is experienced after the peak frequency of 5 Hz.

Near the principal resonance for the fore-and-aft and pitch motion at the head the upright posture was higher compared with the twisted posture. Subject 15 had the greatest increase in pitch motion out of all the subjects. Two subjects (S13 and S14, presented in Appendix A9) contradicted the trend by having greater pitch motion with the twisted posture. The lateral and roll motion at the head produced a more consistent pattern, both measures were higher in all subjects while seated in a twisted posture. Both measures changed from being close to zero, with no clear frequency dependence in the upright posture to a system with a clear peak at about 6 to 8 Hz in the twisted posture (Figure 6.11). This represents an 88% increase in transmission to the lateral axis and roll motion at the head while seated in a twisted posture.
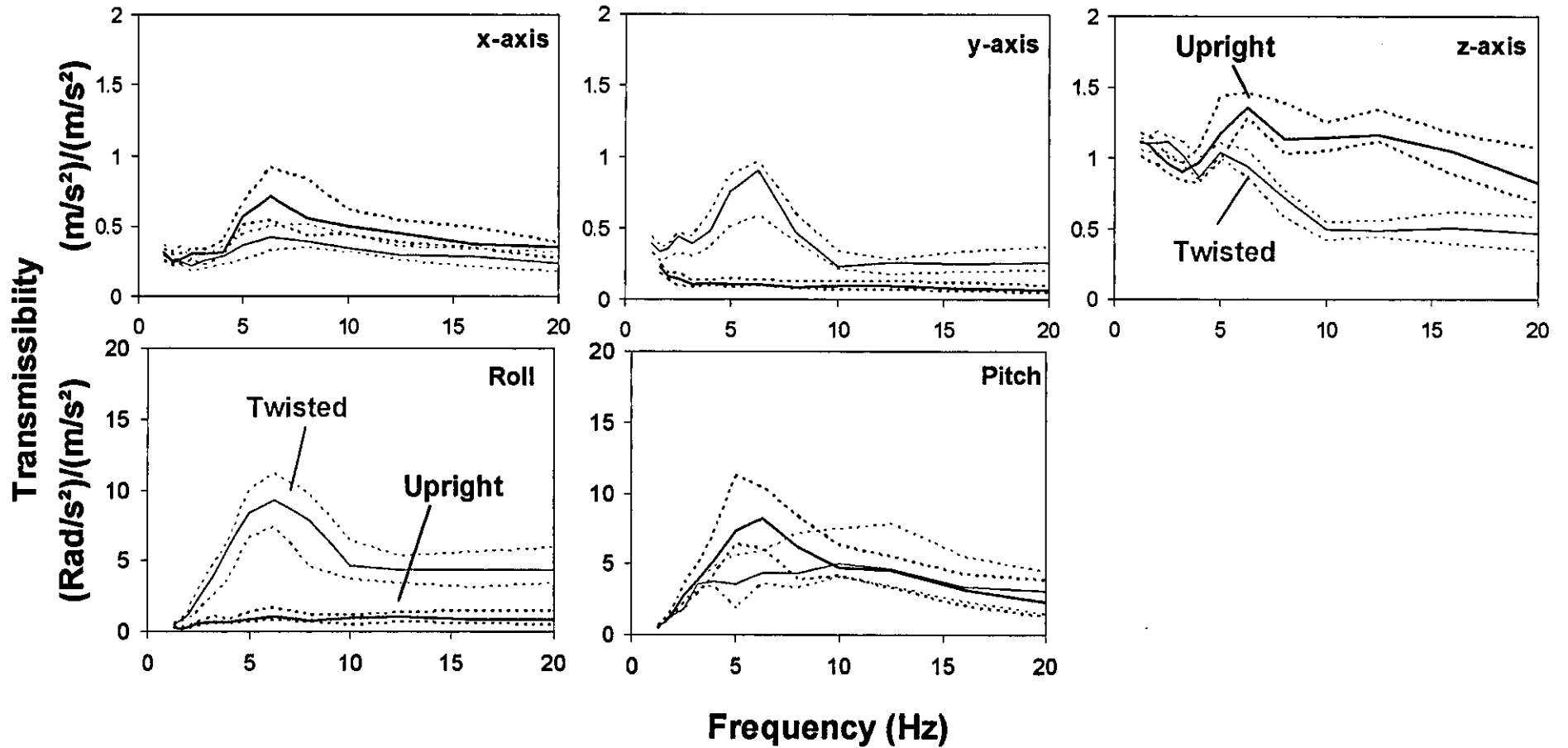
Figure 6.11 Transmissibility of vibration from the seat to the fore-and-aft (x), lateral (y) and vertical (z) directions at the head, with roll and pitch motion of the head/neck. Values are presented as median (solid line) and upper and lower quartiles (dashed lines) of 14 subjects. Black lines denote upright posture and grey lines the twisted posture.

Table 6.1. Pairwise statistical comparison of transmissibility response in the translational and rotational axes, seated in upright forward facing posture vs. twisted posture

Frequency (Hz)	x-axis	y-axis	z-axis	Roll	Pitch
1.25	.	.	.	**	.
1.6	.	**	.	**	.
2.0	.	**	**	**	.
2.5	*	**	**	**	**
3.15	.	**	**	**	.
4.0	.	**	.	**	*
5.0	**	**	.	**	**
6.3	**	**	*	**	*
8.0	**	**	**	**	.
10	**	**	**	**	.
12.5	**	**	**	**	.
16	**	**	**	**	.
20	**	**	**	**	.

. (p > 0.05); * (p < 0.05); ** (p < 0.005) Wilcoxon

Pairwise statistical comparisons of posture at different frequencies are presented in Table 6.1. For the horizontal x-axis transmissibility was significantly higher for the upright posture at all frequencies from 5 Hz and above, and at 2.5 Hz. The opposite was true for the lateral axis; the twisted posture was significantly higher at all frequencies apart from 1.25 Hz. In the vertical direction the twisted posture was significantly higher at 2.0, 2.5 and 3.15 Hz and the upright posture was significantly higher at frequencies between 6.3 and 20 Hz. The rotational axes exhibited different results, significantly higher roll motion at the head was found at all frequencies while seated in a twisted posture; compared with the pitch motion where seated in an upright posture resulted in significantly higher transmissibility, but only at 2.5 Hz, 4.0 Hz, 5.0 Hz and 6.3 Hz.

6.4.3 Comparison of Apparent Mass and Seat-to-Head Transmissibility

Figure 6.12 compares the median vertical transmissibility curves for the apparent mass and the seat-to-head transmissibility. There is greater correlation between the different methods for the twisted posture transmissibility curves as opposed to the upright posture curves. The increased transmission for the seat-to-head data at higher frequencies suggests this method can provide more information about the changes in posture between the two conditions, whereas very small differences are found using the apparent mass method.
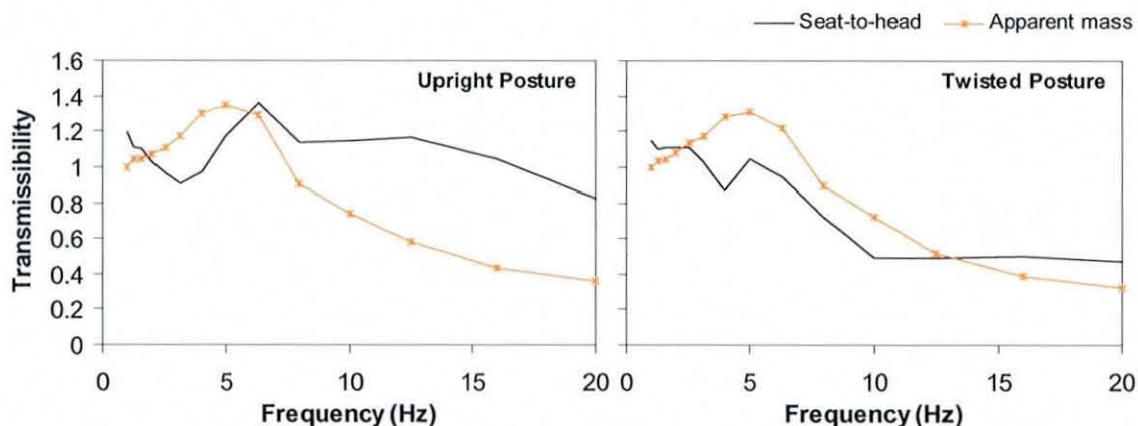
Figure 6.12 Comparison of median seat-to-head transmissibility and median apparent mass vertical response, for an upright and twisted posture.

6.5 Discussion

Evidence from expert opinion suggests non-neutral postures adopted by operators may subject them to additional harm while they are being exposed to high magnitudes of vibration. The biomechanical models used to determine the human response to vibration have mainly focused on the upright posture and therefore cannot be applied to situations where the torso and neck are twisted. Any forces causing injury from WBV will not be well predicted by biomechanical models incapable of representing the appropriate body motions and the effects of body posture (Kitazaki and Griffin, 1998).

This study aimed to firstly; '*improve understanding of how twisted postures interact with the vibration exposure to help guide future work in the effective management of WBV risks*', and secondly; '*validate the methods used with previous single-axis findings from the research literature, in order to apply the methods for use in a multi-axis study*'. The study was designed in order to test the hypotheses outlined in Section 6.2. They will be accepted or rejected in the following sections.

6.5.1 Apparent Mass

The characteristics of the apparent mass curves in the upright posture are comparable with previously reported measurements, there was a clear peak resonance between 4 – 6.3 Hz. Seated in a twisted posture also produced a clear peak in the range 4 – 6.3 Hz, and subsequently any differences in vibration transmission were found to be small between postures. The first hypothesis '*The apparent mass modulus will be greater at frequencies below 10 Hz while seated in a twisted posture compared to an upright posture.*' was rejected based on the findings. The magnitudes at resonance and at frequencies around the peak were significantly higher for the upright posture not the

twisted posture: Unlike the findings reported by Mansfield and Maeda (2005), they reported no significant difference between the magnitudes at resonance for a twisted posture and a back-off upright posture and small but significant increase in the resonance frequency for the twist condition. The second hypothesis '*The apparent mass modulus will be lower at frequencies above 10 Hz while seated in a twisted posture compared to an upright posture*' could only account for certain frequencies and not all frequencies above 10 Hz, and it was also apparent that inter-subject variability was greater than any differences that were found between postures.

One possible explanation for the discrepancy between the previous study (Mansfield and Maeda, 2005) and the current study could be the difference in vibration magnitude. The current study used higher vibration magnitudes compared with the previous study; this could have resulted in greater non-linearity in the subject's biomechanical response and subsequently altered the dynamics in the two postures. In addition different subjects were used and therefore they could have generated different responses to the vibration input while adopting a more conservative twist.

Although the trends in apparent mass were significant, they were small, and less than the differences observed between subjects.

6.5.2 Seat-to-Head Transmissibility

For the seat-to-head data it was hypothesised that '*Inter-subject variability will be more than four times greater than intra-subject variability for seat-to-head transmissibility*'. This third hypothesis was accepted based on the findings that variation between subjects was much greater than the variation within individual subjects. There was also greater variability in the vertical transmissibility while seated in an upright posture compared to the twisted posture. Previously upright 'back off' postures have been found to vary greatly between subjects (e.g. Messenger and Griffin, 1989; Paddan and Griffin, 1994). It could be that adopting a controlled twisted posture limits the spinal position as it is more constrained to that specific posture as opposed to an upright posture where the spinal curvature can move more freely and therefore more likely to vary between subjects.

The fundamental resonance frequencies for the vertical seat-to-head transmissibilities fall mainly between 5 – 6.3 Hz for both postures. The peak in transmissibility could suggest there is a spinal response at that frequency. However Griffin (1990) suggests '*the peak could be caused by the combined interactive movements of several parts of*

the body, for example; pitch motion of the head, movement of the viscera, bending motion of the spine and so forth'. Pg.334

Subject 1 had an atypical biomechanical response to vertical vibration compared with all the other subjects. Their body produced a second peak in the transmissibility curve while seated in the upright posture. Individual data presented in a study by Paddan and Griffin (1988a) also found a few subjects had a second large peak in transmissibility between 10 -15 Hz. Messenger and Griffin (1989) found correlations between spinal angles (excluding the upper thoracic region) and vertical transmissibility. One subject in particular produced a comparable transmissibility curve to Subject 1 in the current study. The subject had large peaks in transmissibility up to 20 Hz, the largest differences between body angles for this subject compared with the remaining 7 subjects were found around T12 and L2 in the middle to lower spine. The subject had an additional $10°$ of curvature at T12 and L2, thus suggesting greater lordosis of the lower thoracic and higher lumbar spine. Spinal morphology was not measured in this study and so this possibility cannot be confirmed. However, these previous investigations show that it is not unusual to find individuals with non-standard seat-to-head transmissibilities, and illustrates a possible limitation of the standard technique of averaging responses across multiple subjects.

The fourth Hypothesis was rejected; *'Vertical and pitch seat-to-head transmissibility will be greater at frequencies below 10 Hz while seated in a twisted posture compared to an upright posture'.* The twisted posture did produce higher vibration at very low frequencies but overall subjects seated in an upright posture had a significantly greater transmission of vertical vibration from the peak up to 20 Hz and significantly more pitch motion around the peak resonance. This does, however, partially validate the fifth Hypothesis; *'Vertical and pitch seat-to-head transmissibility will be lower at frequencies above 10 Hz while seated in a twisted posture compared to an upright posture.'* The hypothesis could only be accepted based on the vertical data and not the pitch motion at the head. The largest increase in transmission from sitting in an upright posture to a twisted posture was found in the lateral axis and roll movement at the head. The twisted posture was significantly higher at all frequencies from 1.6 Hz and above, for both the lateral and roll axes.

The increased forces and moments created during the twisted posture could place additional stress on the spinal column, as the stabilisation of the head-neck complex becomes more difficult. The cervical spine can withstand the highest axial compressive loads and sustain the highest load (and strain) magnitudes when it is in

the straight neutral position (White and Panjabi, 1990). Sitting in a normal upright posture with the head in the neutral position causes a low load on the cervical spine; the load movement is balanced by muscle forces and tension of the passive structures. The more the head departs from neutral, the more the load increases (Thuresson, 2005). Therefore in the neutral position the head and neck will be more adapted to loading, especially in the pitching motion of the head, as observed during ambulation (Woodman and Griffin, 1996). This could mean that while the spine is rotated away from the neutral position there may be a greater impact on the structures even with a lower vibration transmission. Considering the increased vibration transmission experienced in this posture it would be detrimental to ignore this hazardous working posture in relevant standards and during a vibration risk assessment.

Considering the complex motion of the neck during the twist condition it is likely the x-axis values have transposed to the y-axis and in addition roll motion appears as pitch motion. This makes individual interpretation of either roll or pitch a challenge. The magnitudes of head vibration produced by pitch and roll vibration may be expected to depend greatly on the location of the centre of rotation. Barnes and Rance (1975) rotated subjects about their upper lumbar vertebrae and found that there was amplification of the vibration over the range 2-8 Hz. This was attributed to the translational vibration produced at the neck by the rotation of the body.

In the neutral position the centre of mass of the head occurs anterior to the atlanto-occipital joint and therefore vertical vibration generates rotation motion in the fore-aft plane, which is the direction where the neck has the greatest range of motion. This can be observed in Figure 6.11. Even after rotation of the head as in this study, the centre of mass of the head remains anterior to the base of the neck, due to the associated shoulder rotation, and therefore vertical vibration again induces loading in the (seat) fore-aft plane. In the twisted condition, this corresponds with roll of the head and this explains the difference in response between the postures. Furthermore, lateral rotation of the neck (roll) is an axis with a smaller range of motion and therefore mechanical limits would be reached sooner than if the motion was pure pitch (McGill *et al.*, 1999).

6.5.3 Comparison of Apparent Mass and Seat-to-Head Transmissibility

The findings for the apparent mass and seat-to-head transmissibility both demonstrated an increase in magnitude at the resonant frequencies while seated in an upright posture compared to a twisted posture. In spite of this change between

postures it is difficult to draw solid conclusions from the apparent mass due to inter-subject variability accounting for a larger difference. The seat-to-head transmissibility, on the other hand, did show a clear difference between postures in comparison to the inter-subject variability. The change in transmission was maintained across the frequency range of interest.

It is interesting to note that many previous studies have only utilized one of the biomechanical responses identified in this paper; Wang et al. (2004) used the apparent mass to assess a variety of postural conditions. Although this information may prove to be beneficial to seat designers, the understanding of the relative changes in body movements while seated in the different postures cannot be realized by measuring apparent mass alone.

It is clear that although apparent mass has a higher degree of repeatability compared to seat-to-head transmissibility the preferred method to use in the following study is seat-to-head transmissibility. It has a greater application for understanding the mechanisms of vibration transfer to the movement of the head and cervical spine. Before it is taken forward the method needs to be validated with previous research, this has been done in the following section.

6.5.4 Validation with Previously Published Research

The seat-to-head transmissibility data from the current study have been validated with previous research from Paddan and Griffin (1993, 1996) for all the translational and rotational axes (excluding yaw motion) and with the findings from a review of 46 studies on the vertical transmissibility from the seat to the head (Paddan and Griffin, 1998). There was good correlation across the studies, especially when considering the differences in experimental design and subjects (presented in Figure 6.13). The main discrepancies occurred in the vertical and pitch axes. Both of these axes produced the greatest movement out of all the translational and rotational axes for all the studies. Yaw head motion could not be measured in the current study, yet previous research suggests that this axis is not of great concern, as can clearly be seen in the figure.
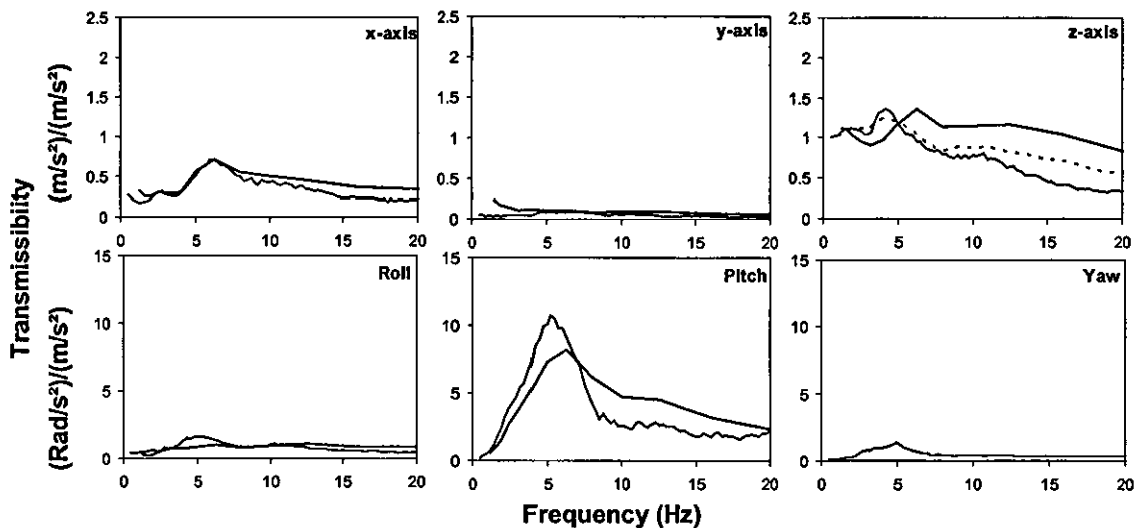
Figure 6.13 Comparison of current studies seat-to-head transmissibility with previously published data. Black line is the median values for the current study; grey solid line is the median for Paddan and Griffin, 1993, 1996; red dashed line is the median value from the review by Paddan and Griffin of 46 studies vertical transmissibility, 1998.

6.5.5 Limitations of the Study

This study was not without limitations, especially concerning the inherent problems with laboratory experiments. One female was used in the mix of subjects; ideally a more balanced study of males and females would be performed to provide more understanding of gender influence. The next study aims to address this by including at least 10 males and 10 females to determine if any gender differences exist. The postures were trying to simulate typical driving positions of the operators observed in the field study, there are many other postures that the operators adopted but it was not feasible to assess all of them so the worst case posture was chosen. In addition the seat used in the study was typical of the seats used in previous research, this allowed for validation with such research. However, it failed to account for the interactions operators have with a typical vehicles suspension seat and armrests. Only vertical vibration input was used to be able to validate with previous research that measured single axis input. It is anticipated that the next study will be able to simulate a more accurate representation of the operators seating and multi-axis vibration exposures.

6.6 Conclusions

Seat-to-head transmissibility and apparent mass produced resonance frequencies in the range 4 - 6.3 Hz. The hypotheses were tested:

- **The first hypothesis 'The apparent mass modulus will be greater at frequencies below 10 Hz while seated in a twisted posture compared**

184

to an upright posture.' was rejected because the magnitudes at the peak resonance and at frequencies around the peak were significantly higher for the upright posture not the twisted posture;

- **The second hypothesis '*The apparent mass modulus will be lower at frequencies above 10 Hz while seated in a twisted posture compared to an upright posture*'** could only account for certain frequencies and not all frequencies above 10 Hz, and it was also apparent that inter-subject variability was greater than any differences that were found between postures.

- **The third hypothesis '*Inter-subject variability will be more than four times greater than intra-subject variability for seat-to-head transmissibility,*'** was accepted. Variation between subjects was much greater than the variation within individual subjects. There was also greater variability in the vertical transmissibility while seated in an upright posture compared to the twisted posture.

- **The fourth Hypothesis was rejected; '*Vertical and pitch seat-to-head transmissibility will be greater at frequencies below 10 Hz while seated in a twisted posture compared to an upright posture'.*** The twisted posture produced higher vibration at very low frequencies but overall subjects' seated in an upright posture had a significantly greater transmission of vertical vibration from the peak up to 20 Hz and significantly more pitch motion around the peak resonance.

- **The fifth Hypothesis; '*Vertical and pitch seat-to-head transmissibility will be lower at frequencies above 10 Hz while seated in a twisted posture compared to an upright posture,'*** could only be accepted based on the vertical data and not the pitch motion at the head. The largest increase in transmission from sitting in an upright posture to a twisted posture was found in the lateral axis and roll motion at the head. The twisted posture was significantly higher at all frequencies from 1.6 Hz and above, for both the lateral and roll axes.

- The findings highlight concerns of the increased loading placed on the spinal units during vibration exposure whilst seated in a twisted posture. The findings underpin the importance of taking into account different

postural conditions when modelling the human response to vibration. Seat-to-head transmissibility was the preferred method for increasing understanding of the biomechanical response to vibration while seated in different postures. The method has been validated with previous research and it will be taken forward into the next study discussed in Chapter 7.

Chapter 7 - Study 3 Part a

Influence of twisted posture, arm support and multi-axis vibration on seat-to-head transmissibility

The previous chapter found differences between an upright and twisted posture in biomechanical responses to vibration. It also highlighted the most suitable method for assessment of human response to vibration (seat-to-head transmissibility) and validated the method with previous research. This has enabled the method to be taken forward into this study, designed to increase the external validity of the findings. This study aimed to recreate the typical postures, upright and twisted, with and without armrest support on a typical suspension seat used in industry, while being exposed to multi-axis vibration. The study was designed to compare the biomechanical response to vibration under these different conditions, but also to compare performance measures and subjective workload. The biomechanical data are presented in this chapter and the performance and workload part of the study are presented in Chapter 8.

7.1 Introduction

Chapter 6 confirmed the seat-to-head transmissibility provided the most useful information for the explanation of how the body responds to the vibration input in two different postures. In the upright posture there was greater transmission to the vertical and pitch direction, however, adopting a twisted posture while being exposed to vertical vibration resulted in large increases in movement at the head for the lateral axis and roll motion at the head. The postures in the current study will be very similar to those in Chapter 6, therefore it is predicted that the underlying mechanisms influencing the transmissibility of vibration in each posture will be the same as in the previous study; this study therefore should validate the results presented in Chapter 6.

Many questions still exist as to how the vibration in just one axis can accurately predict the response to the multi-axis vibration typically experienced in earthmoving machines and how additional vibrating parts can influence the human response, including the use of armrests and a backrest. Standards have largely been produced based on inconclusive evidence from laboratory studies that typically use the same protocol of rigid seat, vertical vibration and sinusoidal vibration: standards also do not specifically address the vibration in the head and upper quarter (Frey Law *et al.*, 2006). Chapters 4 and 5 highlighted the need to address such issues with the field observations

identifying a range of postures typically adopted by the machine operators that are currently not accounted for in biomechanical models.

The machines investigated in chapter 5 suggest there are high magnitudes of vibration transmitted through the seat to the operator; it can therefore be assumed that the vibration transmitted through the backrest and armrests is also significant. The comparison between upright and twisted posture in this study is likely to be comparable to the previous studies findings, however the inclusion of a backrest and armrests may change the response, particularly in the upright posture. Providing a backrest has been shown to increase the vibration transmissibility at frequencies above 5 Hz, with no backrest contact there is typically a resonance around 4 – 5 Hz and with a backrest the resonance frequency increases to around 6 -7 Hz (Paddan and Griffin, 1988a, 1988b, 1993, 1994 and 1996).

Excessive exposure to vibration through the seat has been found to degrade health and performance, however, the transmission through armrests is less well understood (Wilder *et al.*, 2006). It is likely that shoulder muscles may fatigue more quickly during exposure to seated vibration when the arm is not supported as compared with the use of an armrest (Magnusson and Pope, 1998), furthermore providing an armrest may reduce the effect of vibration on the hand-arm system for frequencies below 10 Hz (McLeod and Griffin, 1983). Contrary to this, it has been suggested that armrests may increase the vibration transmitted to the hand-arm system which in turn may promote muscle fatigue and compromise successful operation of the machine. One motion capture study found large increases in head-trunk relative motion due to the use of armrest controls. The study raised concerns of the likelihood of armrest controls contributing to the injury risk: '*while armrests may reduce arm and shoulder fatigue and reduce the effect of the vibrating trunk mass on the lower back, they may do so at the expense of increased motion at the neck and shoulders*' (Wilder *et al.*, 2006). Based on the limited number of studies it is predicted that the current study will find increases in vibration transmission to the head with the use of armrests.

The previous study, in chapter 6, only included one female in the subject pool, although differences were not observed between the one female and the male subjects it is important to confirm if this relationship is maintained in a larger sample of females. One study found 18 men and 18 women had similar median transmissibility curve shapes over the frequency range 1-100 Hz. However the women had significantly less vertical head motion at 2.5 Hz and significantly more vertical head motion at 40, 50 and 63 Hz (Griffin *et al.,* 1982a). Males typically have a taller stature and sitting height,

therefore creating more contact with the backrest and greater transmission at the lower frequencies from 1.25 – 5 Hz and lower transmissibilities than women at frequencies between 5 – 100 Hz (Griffin and Whitham, 1978). No previous studies have looked at potential differences between the biomechanical responses of males and females seated in twisted postures.

7.2 Hypotheses

The study is designed to improve the understanding of vibration transmission through the body in different postural positions using a more realistic simulated environment compared with Study 2. The aim of this study is to recreate the typical postures observed in the field trials; upright and twisted, with or without armrest support, to determine male and female biomechanical responses to dual-axis vibration while seated on a typical suspension seat used in industry. The hypotheses for this study are:

Hyp[1]: Differences between upright and twisted posture transmission of vibration to vertical (z) and pitch axes will follow the same pattern as the previous study.

Hyp[2]: Transmission of vibration to the lateral (y) and roll axes will follow the same pattern as the previous study, they will both be greater while seated in a twisted posture compared to an upright posture at all frequencies above 1.6 Hz.

Hyp[3]: Armrests will increase vibration transmission to the vertical (z) and pitch axes at the head in the frequency range of interest (1-5 Hz).

Hyp[4]: In an upright posture males will have a larger resonant peak than females in the vertical (z) and pitch direction.

Hyp[5]: In a twisted posture there will be no differences between males' and females' resonant peaks in the vertical (z) and pitch direction.

7.3 Experimental Method

The experiment used a repeated measures design to investigate different sitting postures (upright and twisted), with different arm postures (with and without armrests) under exposure to multi-axis whole-body vibration. Ethics approval was obtained from the Department of Human Sciences Ethics Committee at Loughborough University, further details are provided in Chapter 3 Section 3.2.

7.3.1 Subject Characteristics

Participants were screened for any previous history of back problems and other medical conditions. Twenty-one participants from Loughborough University took part in the study, including students and research staff. This cohort included 11 males and 10 females, from a range of different nationalities. Table 7.1 presents the mean and standard deviations for the males and females characteristics.

Table 7.1 Subject characteristics for height, weight and age

	Height (cm)	Body Mass (kg)	Age (years)
Males	179.5 ± 6.6 (169 – 190)	82.9 ± 10.1 (70 – 107)	23.6 ± 3.1 (19 – 29)
Females	168.1 ± 8.5 (156 – 182)	60.2 ± 8.2 (50 – 73)	27.2 ± 6.4 (21 – 35)
Total	174.1 ± 9.4 (156 – 190)	72.1 ± 14.7 (50 – 107)	25.3 ± 5.2 (19 - 35)

Values are presented as the mean ± standard deviation with range in parentheses

7.3.2 Experimental Procedure and Analysis

The four posture conditions adopted by the subjects comprised: (1) Upright Posture, With Armrests (UPWA); (2) Upright Posture, No Armrests (UPNA); (3) Twisted Posture, With Armrests (TPWA) and (4) Twisted Posture, No Armrests (TPNA) (Figure 7.1). The posture conditions were randomised using a Latin-square design. For the upright posture subjects were instructed to sit in a relaxed upright posture facing the monitor directly in front of the seat, with their back in contact with the backrest. For the twisted posture subjects were instructed to look over their right shoulder in the coronal plane to face the monitor screen placed at 135° to the mid-sagittal plane (Figure 7.1).

Subjects were exposed to 3 minutes of random vibration with an unweighted magnitude of 1.4 m/s² in the x-direction and 1.1 m/s² in the z-direction (at the seat

surface). Acceleration measurements were acquired at a sampling rate of 500 Hz and processed in LabVIEW using in-house software, along with Power Spectral Densities. The vibration spectrum was nominally flat from 1 to 20 Hz at the seat base but was affected by the dynamics of seat, as can be observed in Figure 7.2. The frequency band and magnitudes were chosen based on the dominant frequencies found in the field investigation (Chapter 4 and 5) for the tracked earth-moving machines (dozer and tracked-loaders), which are those with the highest vibration magnitudes combined with regular twisting.

Figure 7.1 Postures used during the experiment: top left corner – upright posture, no armrests; right corner – upright posture with armrests; bottom left corner – twisted posture, no armrests, right corner – twisted posture with armrests.

The air suspension seat used during the trial is typical of the seats found in bulldozer and other tracked machines. Subjects were required to have the lap belt secured throughout the trial. The height of the seat was adjusted according to the subject's weight; this procedure was completed before every trial. For the twisted sitting

condition, the angle of the head and neck was monitored using a dual-axis goniometer (SG110, Biometrics Ltd), to ensure subjects maintained the correct posture.

During the 1st minute of vibration exposure subjects held a bite-bar tightly in their mouth (for a total of 60 seconds) comprising accelerometers mounted on the left and right side and at the back of the head. The accelerometers measured the vibration at the head in the fore-and-aft, lateral and vertical directions. Seat-to-head transmissibilities were calculated in order to determine the ratio of the input acceleration at the seat (vertical vibration) and the output acceleration at the head (fore-and-aft, lateral and vertical vibration). Calculations of roll and pitch motion at the head were also completed. Seat-to-head transfer functions were calculated using the cross-spectral density method, the equations are presented in Chapter 3 Section 3.6.4.
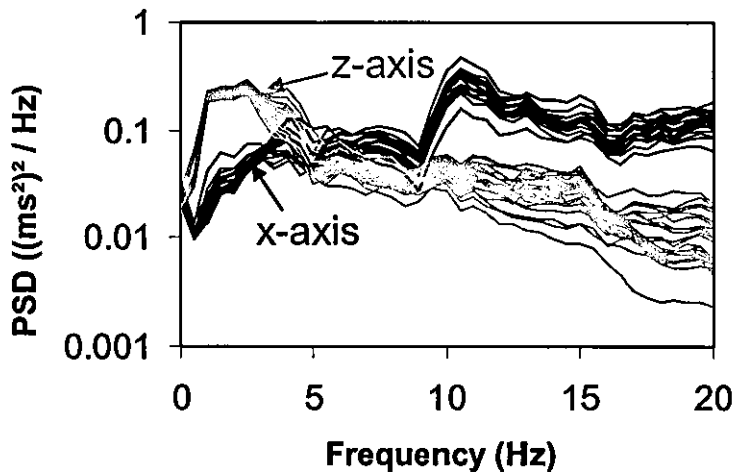
Figure 7.2 Power spectral density of vertical and fore-and-aft acceleration measured on a suspension seat for 21 subjects (frequency resolution 0.5 Hz).

7.4 Results

The Wilcoxon matched-pairs statistical test was used to determine if there were any significant differences between the different postures adopted. The Mann Whitney U statistical test was used to determine if there were any significant differences between males and females. Statistical significance was accepted at $P<0.05$. The following section discusses the differences found.

7.4.1 Inter-Subject Variability

Inter-subject variability was greatest while seated in an upright posture, and smallest while seated in a twisted posture with no armrests. There may be least variability in the TPNA condition as the influence of body size was reduced due to less backrest contact

in that posture and due to the absence of armrest contact (Figure 7.3). Greater inter-subject variability for the upright posture was also observed in the previous study presented in Chapter 6.
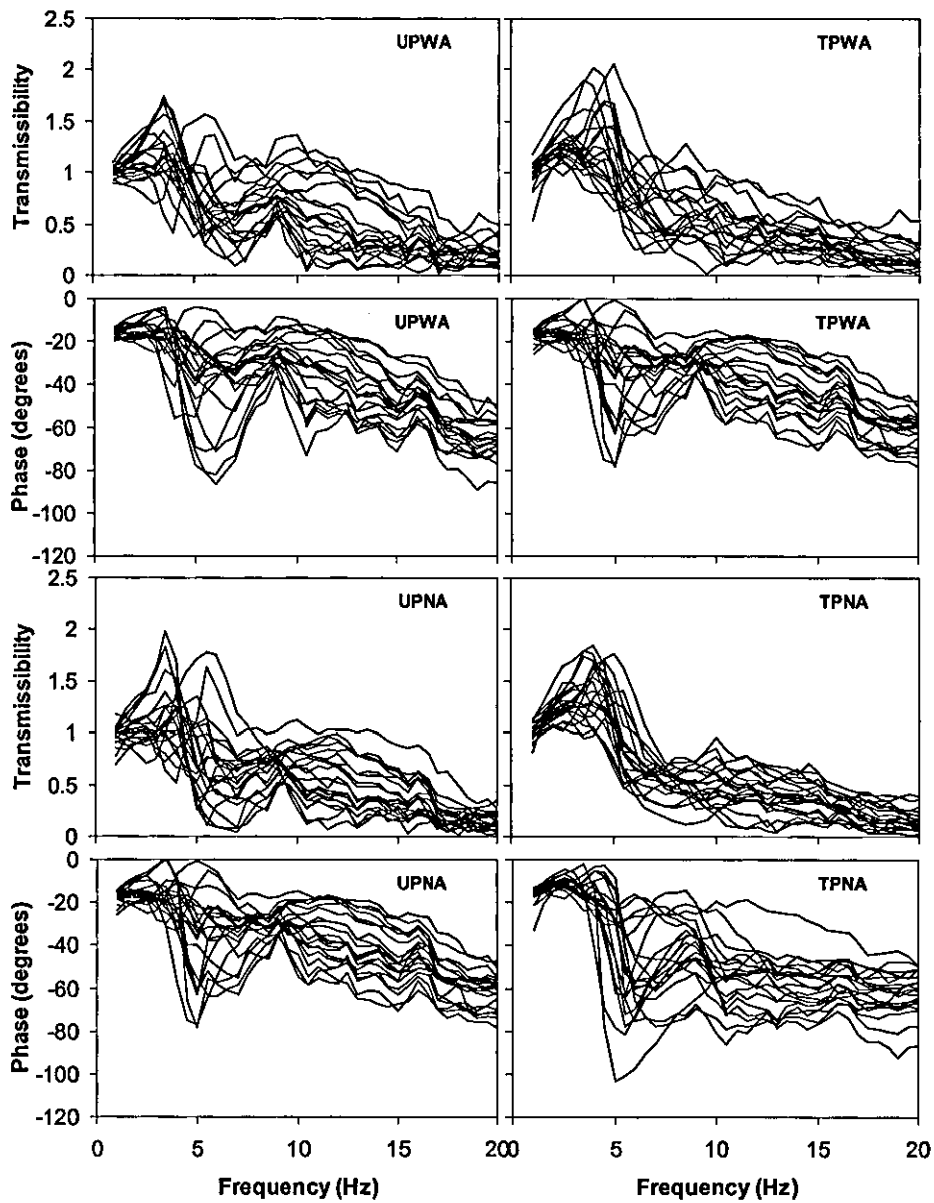
Figure 7.3. Variability between subjects for the transmissibility of vertical vibration from the seat to the vertical (z) axes at the head, in the four posture conditions, Upright Posture With Armrests (UPWA), No Armrests (UPNA) and the Twisted Posture With Armrests (TPWA), and No Armrests (TPNA).

7.4.2 Influence of Posture on Seat-to-head Transmissibility

The following section has been divided into two sections to enable clear presentation of the findings for the influence of torso and neck posture (7.4.2.1), and for the findings of armrest support (7.4.2.2).

7.4.2.1 Effects of Torso and Neck Posture

Comparisons between the upright posture and the twisted posture have highlighted differences in the transmissibility of vibration to the translational and rotational axes at the head. Figure 7.4 and Table 7.2 identifies where the main differences arise for the four posture conditions.

Figure 7.4 Transmissibility of vertical vibration from the seat to the translational and rotational axes at the head. Values are presented as the median of 21 subjects. Black lines denote upright posture and grey lines the twisted posture.

194

Table 7.2 Pairwise statistical comparison of seat-to-head transmissibility response in the translational and rotational axes, Upright Posture vs. Twisted Posture

Frequency (Hz)	Upright Posture vs. Twisted Posture(with armrests)					
	x	y	z	roll	pitch	yaw
1.5	+++	***	***	.	+++	.
2.0	+++	***	***	***	+++	***
2.5	.	***	***	***	+++	***
3.0	***	***	***	***	+++	***
4.0	***	***	***	***	+++	***
5.0	***	***	***	***	+++	***
5.5	+++	***	.	***	.	***
6.5	.	***	.	***	+++	***
8.0	+++	***	.	***	+++	***
10	+++	***	.	***	+++	***
12.5	+++	***	.	***	+++	***
16	+++	***	.	***	.	***
20	+++	***	.	***	+++	***

Frequency (Hz)	Upright Posture vs. Twisted Posture (without armrests)					
	x	y	z	roll	pitch	yaw
1.5	+++	***	***	.	+++	.
2.0	+++	***	***	***	+++	.
2.5	+++	***	***	***	+++	***
3.0	+++	***	***	***	+++	***
4.0	.	***	***	***	+++	***
5.0	.	***	***	***	+++	***
5.5	+++	***	.	***	+++	***
6.5	+++	***	.	***	+++	***
8.0	+++	***	+++	***	+++	***
10	+++	***	+++	***	+++	***
12.5	.	***	+++	***	.	***
16	.	***	+++	***	.	***
20	+++	***	.	***	+++	***

*Note: . (p > 0.05); +++ (upright greater than twisted p < 0.05); *** (upright less than twisted p < 0.05). and black box highlights the frequency range of most interest*

For the supported arm condition transmissibility differences were small, but significantly less between 3-5 Hz in the upright posture compared with the twisted for the fore-aft head motion, but bigger and opposite effects were observed between 8-16 Hz. For the unsupported arm condition, trends were consistent and significant at most frequencies.

Transmissibility to the lateral axis at the head was significantly higher at all frequencies for the twisted posture when the arms were supported and unsupported. Vertical transmissibility was significantly higher for the twisted posture up to 5 Hz, for both supported and unsupported arm conditions. At higher frequencies, between 8.0 and 16 Hz, the twisted posture produced significantly lower transmissibilities, but this was only observed in the unsupported arm condition.

In the rotational axes at the head differences were also observed between the upright and the twisted posture. There was significantly greater roll motion at the head at all frequencies (excluding 1.5 Hz) while seated in the twisted posture. This relationship was observed in both supported and unsupported arm conditions. In the pitch direction the upright posture, with supported arms, produced significantly higher transmissibilities at most frequencies except 5.5 Hz and between 16 and 18 Hz. The unsupported arm conditions produced a similar relationship in transmissibility, the upright posture was significantly higher at most frequencies, apart from those between 12.5 and 18 Hz. Yaw motion at the head was significantly higher while seated in the twisted posture for all frequencies; except 1.5 Hz for the arm supported conditions, and 1.5 and 2.0 Hz for the unsupported arm conditions.

7.4.2.2 Effects of Armrest Support

The shapes of the transmissibility curves for the upright posture are similar both with and without armrests, and likewise for the twisted posture. However there are some statistical differences between the armrest conditions, they will be discussed in the following section.

The transmissibility of vibration from the seat to the head was found to vary between the two armrest conditions and differences were dependent on the interactions between the upright and twisted postures (highlighted in Figure 7.5 and Table 7.3). For the upright posture armrest support significantly increased fore-and-aft transmission at 5.0 Hz and 5.5 Hz, yet at higher frequencies it was significantly lower compared with having no armrest support (between 8.0 and 16 Hz). A different pattern was observed

196

for the twisted posture condition, armrest support significantly increased fore-and-aft transmission between 2.0 and 8.0 Hz.

Table 7.3 Pairwise statistical comparison of transmissibility response in the translational and rotational axes, With Armrests vs. Without Armrests

Frequency (Hz)	With Armrests vs. Without Armrests (Upright Posture)						With Armrests vs. Without Armrests (Twisted Posture)					
	x	y	z	roll	pitch	yaw	x	y	z	roll	pitch	yaw
1.5	.	**	.	.	.	**	.	.	.	.	.	**
2.0	++	**	.	.	.	**	**	++	.	.	.	**
2.5	.	**	**	.	.	**	**	++	.	.	++	**
3.0	.	.	.	**	.	**	**	++	.	.	++	**
4.0	.	.	.	.	.	**	**	++	++	.	.	**
5.0	++	.	.	.	.	.	**	.	.	.	++	**
5.5	++	.	.	.	.	.	**	.	.	.	++	.
6.5	.	.	.	.	.	++	**	**	.	.	++	.
8.0	**	.	.	.	**	++	**	.	.	.	++	.
10	**	.	.	.	**	++	.	**	.	.	++	.
12.5	**	**	.	.	**	++	.	.	.	.	.	.
16	**	.	**	.	**	++	.	.	.	.	.	++
20	.	.	.	.	.	++	.	.	.	.	.	.

Note: (p > 0.05); ++ (without armrests greater than with armrests p < 0.05); ** (without armrests less than with armrests p < 0.05). and black box highlights the frequency range of most interest

There were small differences between armrest conditions for lateral transmission in the upright posture. Seated in a twisted posture the lateral transmission was significantly higher for the unsupported arm condition from 2.0 – 4.0 Hz, and the supported arm condition was significantly higher at 6.5 Hz and 10 Hz. Small differences between armrest conditions were found for the vertical transmission while seated in an upright posture. However, while seated in a twisted posture the unsupported arm condition had significantly higher transmissibilities around the resonant frequency. Small differences were observed in the amount of roll transmissibility at the head, for both armrest conditions. Pitch motion was significantly higher at frequencies between 8.0 and 16 Hz for the supported arm condition, while seated in an upright posture. There was significantly higher pitching motion for the unsupported arm condition, at 2.5 – 3.0 Hz and 5.0 – 10 Hz, while seated in a twisted posture. In an upright posture yaw motion at the head was significantly higher at all frequencies except 5.0 – 5.5 Hz, while the arms were supported. In a twisted posture a similar relationship was observed at lower frequencies from 1.5 – 5.0 Hz, and at 16 Hz.
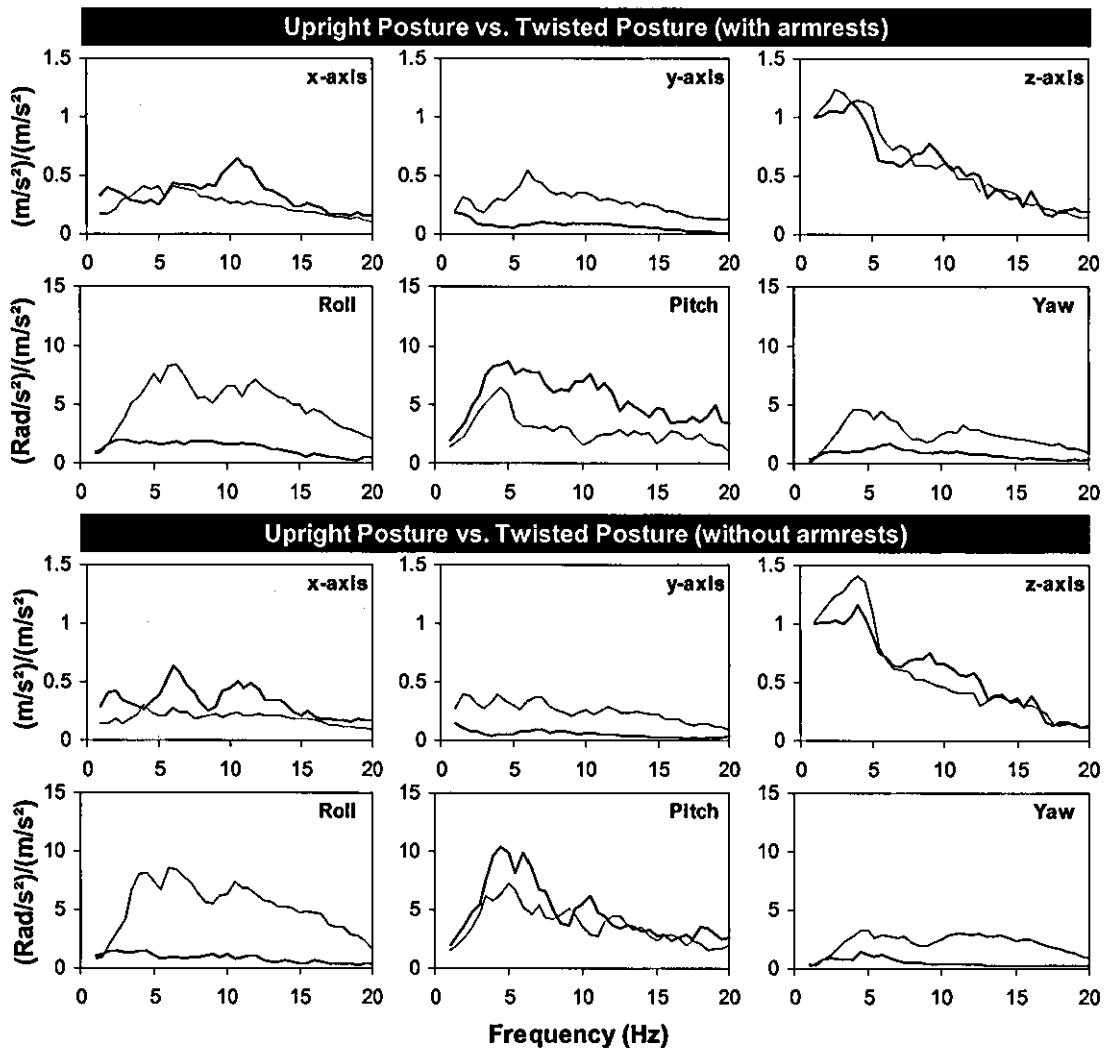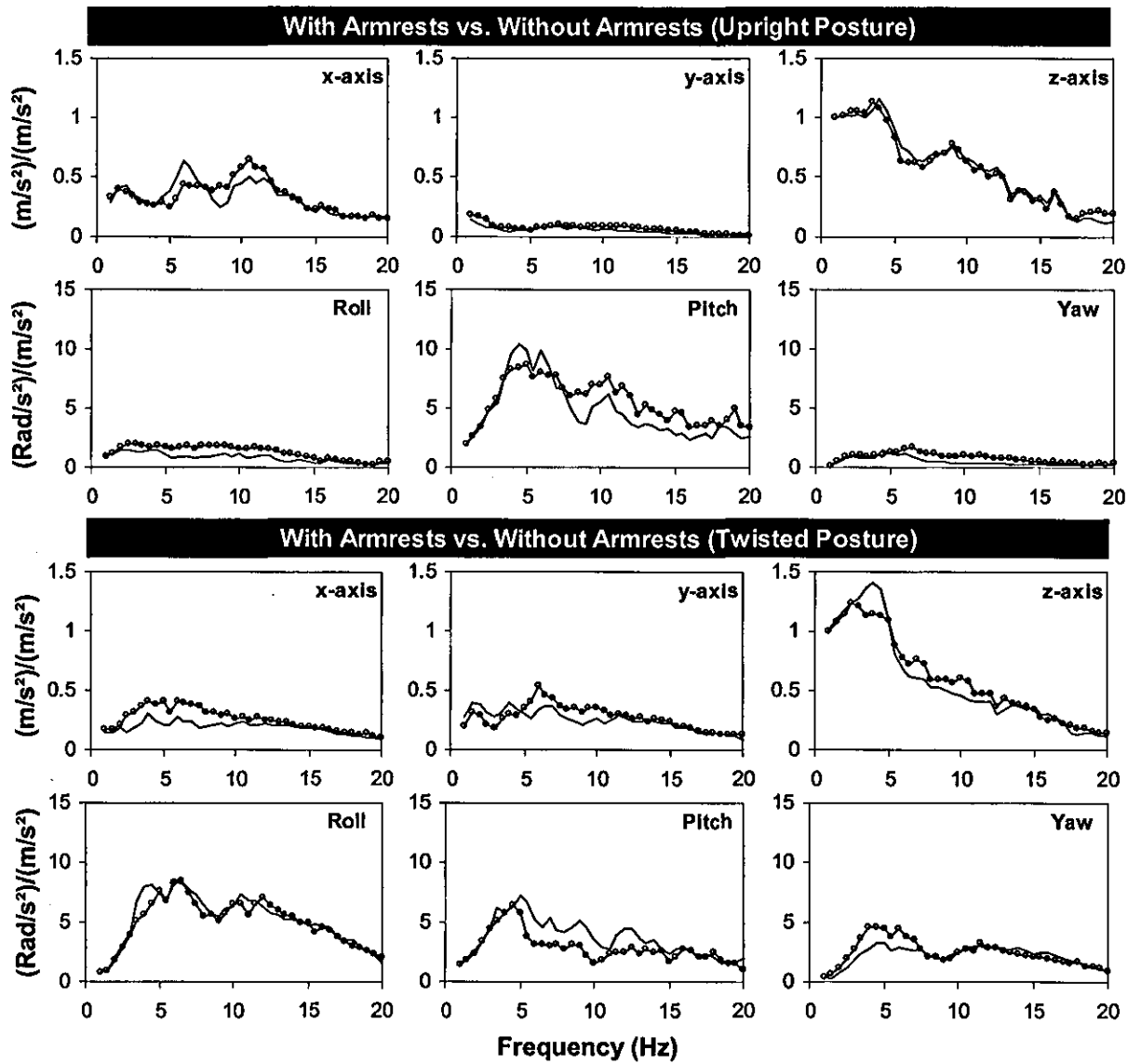
Figure 7.5 Transmissibility of vertical vibration from the seat to the translational and rotational axes at the head. Values are presented as the median of 21 subjects. Black lines denotes posture without armrests and lines with black circles denotes posture with armrests.

7.4.3 Influence of Gender on Seat-to-head Transmissibility

Out of the twenty one participants there were 11 males and 10 females. Statistical analysis was performed to determine if clear biomechanical differences existed between sexes for the transmissibility of vibration from the seat-to-the-head. Graphical comparisons are presented in Figure 7.6 and statistical comparisons are presented in Table 7.4 for the translational axes and Table 7.5 for the rotational axes. A breakdown of the individual male and female subject's biomechanical responses is presented in Appendix A10.

In the upright posture males had a greater peak resonance for vertical vibration, compared with the females (significant between 1.5 and 3.5 Hz). The males cut-off frequencies occurred around 5 Hz and descended further below the females cut-off frequencies, resulting in significantly higher curves for the females between 5.5 and 8.0 Hz in the UPWA, and from 6.5 − 8.0 Hz for the UPNA. There is no clear relationship between males and females for the lateral axis while seated in either upright posture; and the overall magnitude is insignificant compared with the vertical and fore-and-aft directions. For the x-axis differences were only found between gender for the UPWA. The males had significantly more transmission between 6.5 and 10 Hz. The largest and most noteworthy difference for the rotational movement at the head was found while seated in the UPWA, males had significantly more pitching motion at 2.5 − 3.0 Hz and also from 5.0 − 6.5 Hz.

In the twisted posture conditions findings were not consistent with the upright posture findings. No significant differences were found between males and females for the fore-and-aft direction and in the vertical direction females had a significantly higher peak resonance between 5.5 and 6.5 Hz for the posture without armrests. In the lateral direction males had significantly more transmission between 5.0 and 10 Hz while seated in the TPWA but not while seated in the TPNA condition. No clear relationship could be found between males and females for any of the rotational axes.
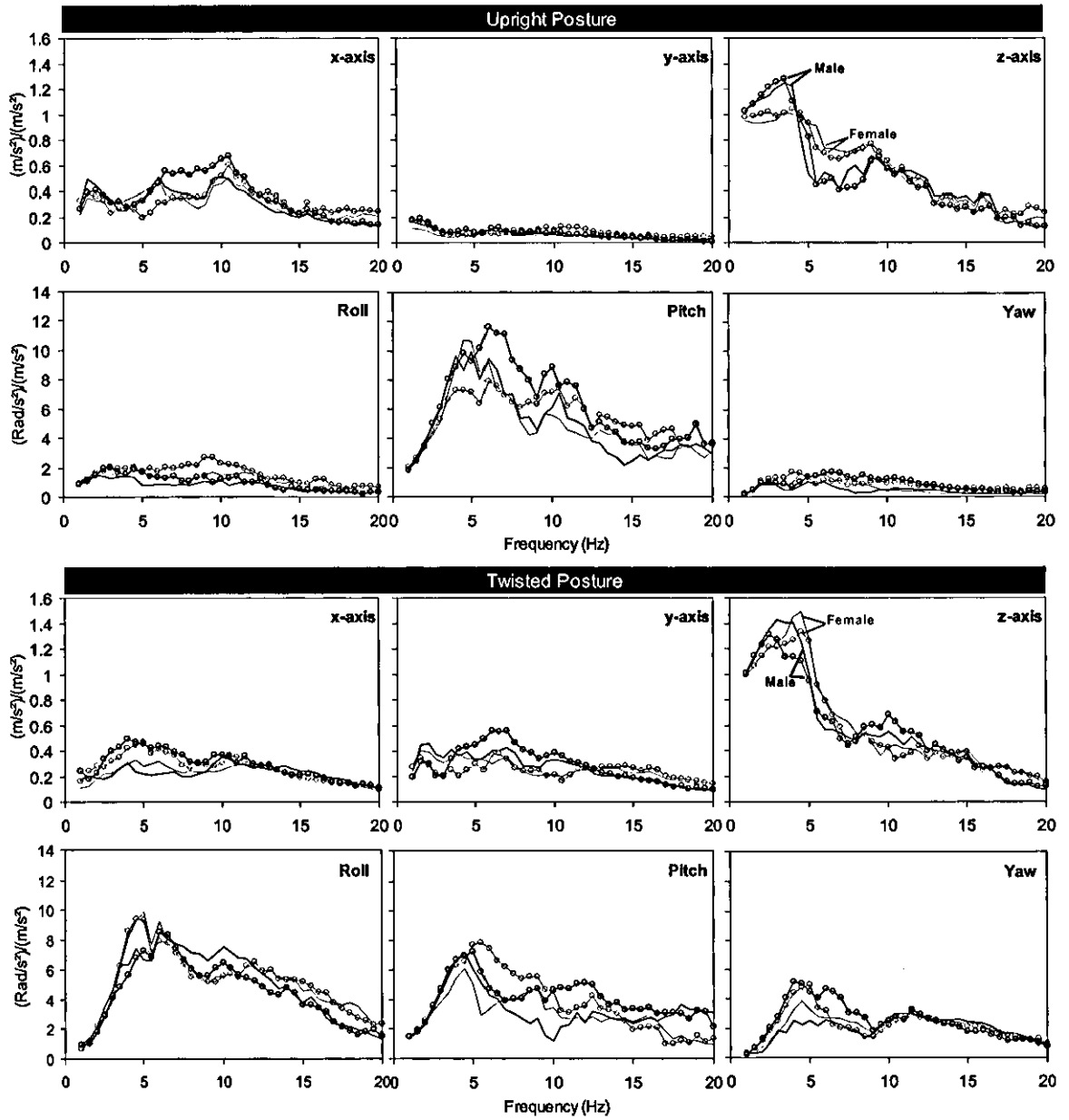
Figure 7.6 Transmissibility of vertical vibration from the seat to the translational and rotational axes at the head. Values are presented as the median of 10 females (grey lines) and 11 males (black lines). Lines with circles represent the postures with armrests.

200

Table 7.4 Pairwise statistical comparison of males vs. females transmissibility in the translational axes, seated in postures; Upright Posture with Armrests, Upright Posture, no Armrests, Twisted Posture with Armrests, and Twisted Posture, no Armrests.

Frequency (Hz)	UPWA			UPNA			TPWA			TPNA		
	x	y	z	x	y	z	x	y	z	x	y	z
1.5	.	.	++	.	.	++	.	.	++	.	.	.
2.0	.	.	++	++	.	++	.	.	++	.	.	++
2.5	.	.	++	.	.	++	.	.	.	.	.	++
3.0	.	.	++	.	.	++	.	.	.	.	.	.
4.0	.	.	.	.	.	.	.	.	.	.	.	.
5.0	.	.	.	.	.	.	.	++	.	.	.	**
5.5	.	.	**	.	.	.	.	++	.	.	.	**
6.5	++	.	**	.	.	**	.	++	.	.	.	**
8.0	++	.	**	.	.	**	.	++	.	.	.	.
10	++	.	.	.	.	.	.	++	++	.	++	.
12.5	.	**	.	.	.	.	.	.	.	.	.	.
16	.	**	.	.	.	.	.	**	.	.	.	.
20	.	**	**	.	.	.	.	.	.	.	.	.

Note: (p > 0.05); ++ (males greater than females p < 0.05); ** (males less than females p < 0.05). and black box highlights the frequency range of most interest

Table 7.5 Pairwise statistical comparison of males vs. females transmissibility response in the rotational axes, seated in four posture conditions; Upright Posture with Armrests, Upright Posture, no Armrests, Twisted Posture with Armrests, and Twisted Posture, no Armrests.

Frequency (Hz)	UPWA			UPNA			TPWA			TPNA		
	roll	pitch	yaw	roll	pitch	yaw	roll	pitch	yaw	roll	pitch	yaw
1.5	.	.	.	.	.	.	.	.	.	.	.	.
2.0	.	.	.	.	.	.	.	.	.	.	.	.
2.5	.	++	.	.	.	.	.	.	.	.	.	.
3.0	.	++	.	.	.	.	.	.	.	.	.	.
4.0	.	.	.	.	.	.	.	.	.	.	.	.
5.0	.	++	.	.	.	.	.	.	.	.	.	.
5.5	.	++	++	**	.	**	.	.	.	.	.	.
6.5	.	++	++	.	.	.	.	.	.	++	.	.
8.0	**	.	.	.	.	**	.	.	.	.	.	.
10	**	.	.	.	.	.	.	.	.	.	.	.
12.5	.	.	.	.	.	.	.	.	.	.	.	.
16	**	.	.	.	.	.	.	.	.	.	.	.
20	.	.	.	.	.	.	.	.	.	.	++	.

Note: (p > 0.05); ++ (males greater than females p < 0.05); ** (males less than females p < 0.05). and black box highlights the frequency range of most interest

7.5 Discussion

The current study was designed to improve the understanding of postural and seating influences on the transmission of vibration through the body, using a more realistic simulated environment. This study aimed to *'recreate the typical postures observed in the field trials; upright and twisted, with or without armrest support, to determine males and females biomechanical responses to multi-axis vibration while seated on a typical suspension seat used in industry'.*

Vertical seat vibration causes motion in other axes at the head although the understanding of exposure to combined axes is not as developed. This study included combined vertical and fore-and-aft vibration input at the seat. Paddan and Griffin (1988) found most of the motion at the head to occur in the mid-sagittal plane; in the fore-and-aft, vertical and pitch axes. The lateral, roll and yaw axes only produced small amounts of motion at the head. The finding is in agreement with the upright postures investigated in this study, but not with the twisted postures. The twist appears to have increased the movement in the lateral, roll and yaw axes; however this could be due to the x- and y-axes transposing and subsequently altering the rotational axes at the head (Figure 7.4). The findings are in agreement with the previous study for twisted posture. The results will be discussed in more detail in the following sections, along with discussion of the hypotheses that were outlined in Section 7.2 .

7.5.1 Effects of Torso and Neck Posture

The first hypothesis *'Differences between upright and twisted posture transmission of vibration to vertical (z) and pitch axes will follow the same pattern as the previous study.'* has been accepted and the findings have validated the previous study (Study 2 Chapter 6). Comparisons of the upright vs. twisted posture showed similar trends between 5 – 20 Hz for the two studies. Twisted posture was higher below 5 Hz for this study and higher for some of the frequency range below 5 Hz in the previous study, although there are some discrepancies. Above 5 Hz the conditions are similar the upright posture is significantly higher for both compared with the twisted. There are differences between the two studies but research suggests there can be large differences between studies (Messenger and Griffin, 1989; Paddan and Griffin, 1988a, 1988b, 1993, 1994, 1996, and1998). In the twisted posture there are more differences in the posture and differences in the seat; further research is needed to confirm the differences and to address the discrepancies at low frequency.

202

Vertical transmissibility was significantly higher for the twisted posture up to 5 Hz, for both arm postures (supported and unsupported). The upright posture was only significantly higher for the unsupported arm condition between 8.0 and 16 Hz. The pitching at the head, however, was significantly higher for the upright posture at most frequencies and for both arm postures.

The second hypothesis *'Transmission of vibration to the lateral (y) and roll axes will follow the same pattern as the previous study, they will both be greater while seated in a twisted posture compared to an upright posture at all frequencies above 1.6 Hz'* was accepted based on the findings. Adopting a twisted posture proved to significantly increase the amount of lateral and roll motion at the head at all frequencies above 1.5 Hz and for both arm posture conditions. The relationship was the same for the yaw motion at the head, although the increase in transmission from sitting in an upright to a twisted posture was not as great. Messenger and Griffin (1989) found a general trend for roll and yaw motion at the head to increase as head roll angle increased. However, pitch head motion did not change with varying head roll angle. In the vertical axis at the head transmissibility decreased with increasing head roll angle, this was particularly evident above 5 Hz. One further experiment looked at changes in yaw angle at the head (0°, 20°, 40° and 60° to the right), transmissibility increased for roll, yaw and y-axis head motion with increasing yaw angle. The studies were only based on one subject but the findings appear to explain part of the changes in transmissibility from an upright to a twisted posture, along with the explanation in Chapter 6, Section 6.5.2.

The increased vertical, lateral, yaw and roll motion at the head while seated in the twisted posture could indicate greater stresses on the neck, especially as there is still considerable amounts of head pitching. This has been previously described in study 2 (Chapter 6) *'the increased forces and moments created during the twisted posture could place additional stress on the spinal column, as the stabilisation of the head-neck complex becomes more difficult. The cervical spine can withstand the highest axial compressive loads and sustain the highest load (and strain) magnitudes when it is in the straight neutral position (White and Panjabi, 1990)'.* There is also a concern that the operator would not be able to maintain good visual performance in such a posture as the increased movement at the head combined with the awkward sitting position could adversely affect the safe operation of the machine.

The seat-to-head transmissibilities have highlighted which movements are likely to be problematic for operators of earthmoving machines, particularly for the tracked machines that this study was based on. The extent of the degradation in visual

performance can also be estimated using the transmissibility data. However, to obtain a better understanding of the influence of the conditions simulated in the current study, on the performance and workload of operators a further two dimensions were measured; the findings are discussed in the following study, presented in Chapter 8.

7.5.2 Effects of Armrest Support

The third hypothesis '*Armrests will increase vibration transmission to the vertical (z) and pitch axes at the head in the frequency range of interest (1-5 Hz)*' was rejected based on the findings. There were no clear differences for vertical transmissibility with or without armrests for the upright posture, and armrests were found to significantly reduce vertical transmissibilities around the principal resonance for the twisted posture. Pitching motion at the head was significantly increased with armrests for the upright posture in the frequency range 8.0 – 16 Hz; however in the twisted posture armrests significantly reduced the pitching motion at 2.5 – 3.0 Hz and 5.0 – 10 Hz. Considering the implications of adopting a twisted posture it appears suitable to recommend that armrests are beneficial and do not adversely increase the vibration transmission for the typical conditions simulated in this study.

Frey Law *et al.* (2006) investigated the muscle activities in the neck, shoulder and upper arm muscles during simulations of large construction equipment. Differences in muscle activity between the three arm control postures suggested the arms may behave as active dampers particularly when the control configuration is not mounted to the seat. The result of this could be an attenuation of the head and neck movement in such a posture. The authors suggest there may be a trade off between trying to reduce fatigue with armrest controls and the greater apparent muscle and joint stiffness associated with tonic muscle activity. They continue to highlight that the risk of injury may depend on the type of injury considered, for example an overuse muscle injury compared to a repetitive motion joint pathology.

Armrests and armrest mounted controls need to be considered separately when recommendations are made. Armrest controls more rigidly couple the shoulders, via the upper arms, to a vibration source and bypass the damping provided by the entire arm, potentially increasing the risk of motion-related musculoskeletal problems in the neck and upper trunk (Wilder *et al.* 2006). Consequently, the differences in vibration transmission between standard armrests (like the ones used in the current study) and more sophisticated armrests mounted with controls needs to be fully understood and is a potential area for future research.

7.5.3 Influence of Gender on Seat-to-head Transmissibility

The fourth hypothesis: *'In an upright posture males will have a larger resonant peak than females in the vertical (z) and pitch direction'* was accepted for the upright posture with armrests, the males had significantly higher resonant peaks in the vertical axis around 3.5 Hz and significantly higher peaks in the pitch direction around 6 Hz. The relationship reversed for the vertical axis between 5.5 and 8.0 Hz, where females had significantly more vertical movement. The hypothesis could not be accepted for the upright posture, no armrest condition. The vertical peak was significantly higher for the males compared with the females, however no significant differences could be found for the pitching motion at the head. Despite the difference in methodologies the findings are in agreement with previous research, women had significantly less vertical head motion at 2.5 Hz (Griffin *et al.*, 1982a) and between 1.5 and 3.5 Hz, with significantly more transmissibility at frequencies between 5.5 and 8.0 Hz (Griffin and Whitham, 1978); however, in the current study only small differences were found at frequencies above 10 Hz. The males in the current study were taller in stature (on average) compared with the females (180 ± 7 cm compared with 168 ± 9 cm). It is possible the increase in peak response for males could be attributed to the greater amount of contact with the backrest. In one study the peak magnitude response was found to be slightly greater for the highest seat height, suggesting the increased body mass supported by the higher seat could be the attributing factor (Wang *et al.*, 2004).

The fifth hypothesis: *'In a twisted posture there will be no differences between males and females resonant peaks in the vertical (z) and pitch directions'* was accepted for the twisted posture with armrests, only small significant effects were found at 1.5 and 2.0 Hz for the vertical axis and no differences were found in the pitch direction. The small significant differences were likely to be related to the shift in frequency curves for the males and females, the males tended to have a peak response at a lower frequency to females although the magnitudes were very similar. The fifth hypothesis was rejected for the twisted posture, no armrest condition in the vertical axis but accepted for the pitch direction. Females had significantly higher vertical peak responses around 5 Hz and males had significantly higher peak responses around 2.0 Hz, yet no differences could be found for pitching at the head.

One explanation for the contrast in findings between the upright and twisted posture could be the reduced backrest contact in the twisted posture changing the dynamics for males and females. Another explanation could be the variation in males and females torso-thigh angles associated with neutral body postures, the angular

characteristics are likely to influence the curvatures of the spine by influencing the extent of pelvic rotation (Webb *et al.*, 1978). There is also a tendency for hyper-lordosis among females and hypo-lordosis among males (Grandjean *et al.*, 1969). These factors could influence the changes in vibration transmission between males and females in the twisted posture, as the presence of lordotic curvatures would be less pronounced in this posture.

7.5.4 Comparison with Previous Research

It has been shown previously that including contact with a rigid backrest can have a large effect on the transmission of both vertical and horizontal vibration at the head (Paddan and Griffin, 1988a&b). Although increases in transmission were found in the current study compared to the study in Chapter 6 (Figure 7.7) the differences were not so evident compared to the differences with the current study and the vertical data from Paddan and Griffin (1993), presented in Figure 7.8. The review of 46 studies by Paddan and Griffin (1998) has been highlighted on Figure 7.7 and Figure 7.8, the data from this study is in good agreement with the current study which suggests the vertical data from Paddan and Griffin (1993) is the outlier in the research. The remaining axes from Paddan and Griffin (1993) for the lateral, roll, pitch and yaw axes are in good agreement with the current study.

The differences observed could be due in part to the type of seating used; although a backrest was used it was a cushioned backrest that is typically used in real working conditions. Therefore its dynamic response may be expected to influence the transmission of vibration in a different way to that of a rigid backrest (Messenger and Griffin, 1989). Previously 'back-on' postures have had smaller differences between subjects compared with a 'back-off' posture (Paddan and Griffin, 2004), yet the amount of inter-subject variability for the current study and study 2 were very similar. Discrepancies could also be the result of the cushioned seating system, especially as the previous research used a hard rigid seat (Paddan and Griffin, 1993).

Another key difference between the current study and previous studies is the differences between the vibration input. The current study used dual-axis vibration from the vertical and fore-and-aft direction whereas previously the studies have focused on single-axis input mainly from the vertical direction. The interactions between the two axes of vibration input could also influence the resulting human response to the vibration.

The previous study showed greater seat-to-head transmissibility for the upright posture in the vertical direction. The twisted posture however produced compatible results. The previous study showed a smaller peak during the twisted posture, but the remaining transmissibilities are very similar. There are a number of differences between the studies that could account for the discrepancies. The previous study only used one direction of vibration input and had different seating. The current study used a suspension seat and there was an additional vibration input from the fore-and-aft vibration direction, the changes could have influenced the dynamic response of the subjects. There was also differences between the subjects used, all of the subjects from study 2 were Japanese and in the current study subjects ranged in nationality and there was a greater spread of size and weight. These factors cannot be discounted as contributions to the variability between studies. As mentioned previously more work is needed to sort out the discrepancies found at low frequency, but so far the evidence for the effects at higher frequencies of sitting in a twisted posture are more convincing.
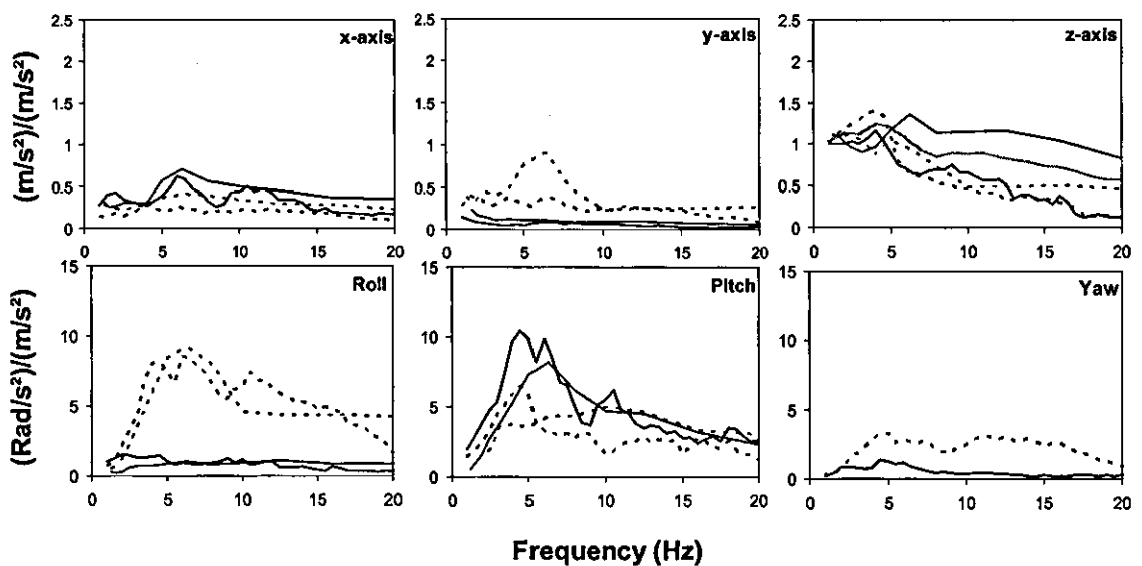
Figure 7.7 Comparison of seat-to-head transmissibility for study 2 (grey lines) and study 3a (black lines), upright (solid lines) vs. twisted posture (dashed lines) with vertical data from the review by Paddan and Griffin of 46 studies vertical transmissibility, 1998 (red hatched line).

207
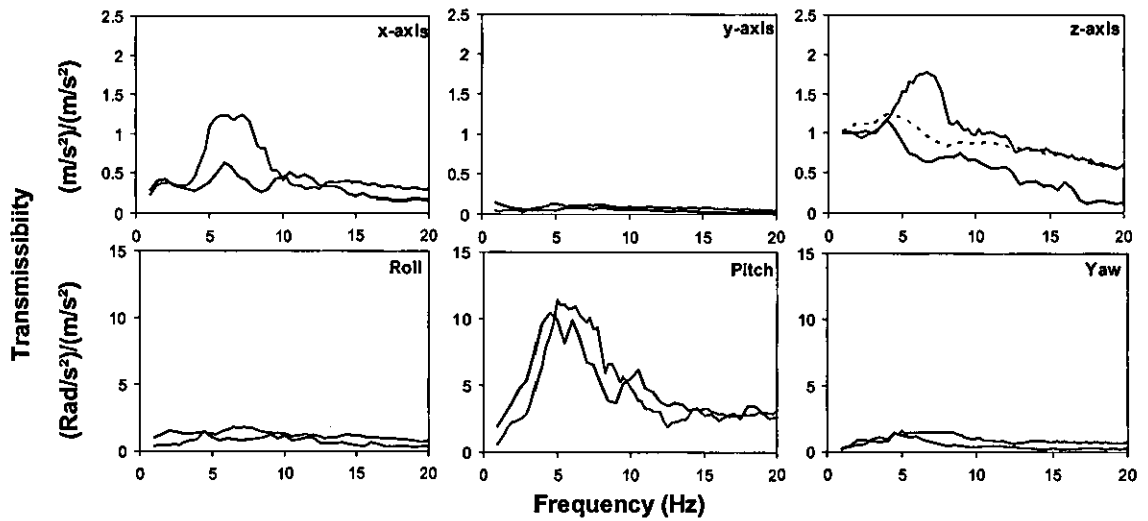
Figure 7.8 Comparison of seat-to-head transmissibility (upright posture no armrests 1-20 Hz, vertical and fore-and-aft vibration) with previously published data (upright posture, back-on, 1-25 Hz, vertical vibration from Paddan and Griffin, 1993). Black line is the median values for the current study; grey solid line is the median for Paddan and Griffin, 1993; red dashed line is the median value from the review by Paddan and Griffin of 46 studies vertical transmissibility, 1998.

7.5.5 Limitations of the Study

This study was not without limitations. It is important to acknowledge that measurements of vibration transmission to the hand-arm system were not made. Therefore the understanding of the direct vibration transmission through an armrest is limited for this study. However, the seat-to-head transmissibility can provide information on the possible mechanisms that are affected by the inclusion of armrests. Due to simulator limitations and ethical considerations, high shocks could not be simulated in the laboratory, the adoption of a non-neutral neck posture could have much severer implications for operators exposed to high shocks. Only two directions of translational vibration input were used for this study. In real operations there will be vibration input from the three translational axes; vertical, fore-and-aft, and lateral and from the three rotational axes; roll, pitch and yaw. Ultimately, it would be desirable for all inputs to be used in the laboratory, but in order to retain comparability with previous studies, only two vibration inputs were selected based on the most severe vibrations observed in the tracked machines discussed in Chapter 4 and 5.

7.6 Conclusions

The study confirmed the main findings from study 2, presented in Chapter 6. Adopting a twisted posture significantly increased the lateral and roll motion at the head, causing concern for both the potential health implications and performance decrements that operators' may experience under such conditions. The armrests provided support and attenuation at the primary resonance for the males and females seated in a twisted posture. The detailed conclusions drawn from the hypotheses are:

- The first hypothesis *'Differences between upright and twisted posture transmission of vibration to vertical (z) and pitch axes will follow the same pattern as the previous study.'* has been accepted and the findings have validated the previous study (Study 2 Chapter 6). Comparisons of the upright vs. twisted posture showed similar trends between 5 – 20 Hz for the two studies. Twisted posture was higher before 5 Hz for this study and higher for some of the frequency range before 5 Hz in the previous study, although there are some discrepancies. Above 5 Hz the conditions are similar the upright posture is significantly higher for both compared with the twisted.

- The second hypothesis *'Transmission of vibration to the lateral (y) and roll axes will follow the same pattern as the previous study, they will both be greater while seated in a twisted posture compared to an upright posture at all frequencies above 1.6 Hz'* was accepted based on the findings. The twisted posture proved to significantly increase the amount of lateral and roll motion at the head at all frequencies above 1.5 Hz and for both arm posture conditions.

- The third hypothesis *'Armrests will increase vibration transmission to the vertical (z) and pitch axes at the head in the frequency range of interest (1-5 Hz)'* was rejected. No clear differences for vertical transmissibility with or without armrests were found for the upright posture. Armrests were found to significantly reduce vertical transmission around the resonant peak for the twisted posture. Pitching motion at the head was significantly increased with armrests for the upright posture in the frequency range 8.0 – 16 Hz; however in the twisted posture armrests significantly reduced the pitching motion at 2.5 – 3.0 Hz and 5.0 – 10 Hz.

- The fourth hypothesis: '*In an upright posture males will have a larger resonant peak than females in the vertical (z) and pitch direction*' was accepted for the upright posture with armrests, the males had significantly higher resonant peaks in the vertical axis around 3.5 Hz and significantly higher peaks in the pitch direction around 6 Hz. The relationship reversed for the vertical axis between 5.5 – 8.0 Hz, where females had significantly more vertical movement. The hypothesis could not be accepted for the upright posture, no armrest condition. The vertical peak was significantly higher for the males compared with the females, however no significant differences could be found for the pitching motion at the head.

- The fifth hypothesis: '*In a twisted posture there will be no differences between males and females resonant peaks in the vertical (z) and pitch directions*' was accepted for the twisted posture with armrests, only small significant effects were found at 1.5 and 2.0 Hz for the vertical axis and no differences were found in the pitch direction. The fifth hypothesis was rejected for the twisted posture, no armrest condition in the vertical axis but accepted for the pitch direction. Females had significantly higher vertical peak responses around 5 Hz and males were significantly higher around 2.0 Hz, yet no differences were found for pitching at the head.

Chapter 8 - Study 3 Part b

Influence of driving postures and multi-axis vibration on human performance and workload

This chapter discusses an experimental study designed to investigate the effects of the combined occupational hazards; whole-body vibration and twisted posture, on performance and workload. There is little knowledge on performance during exposure to multi-axis vibration combined with constrained twisted postures. Considering the biomechanical responses changed with the addition of armrests it is important to determine if armrest support will improve or hinder performance and workload. This chapter reports a study to investigate the influence of sitting in different working postures on the visual motor reaction time (VMRT assessment) and perceived workload (NASA TLX assessment) of participants exposed to whole-body vibration in a seated posture. Twisted posture was shown to reduce task performance during seated whole-body vibration. The inclusion of armrests significantly improved the participants' ability to complete the task with a lower workload demand. This chapter demonstrates that armrest support has the potential to provide additional benefits for earthmoving machinery operators under combined environmental stressors.

8.1 Introduction

From the observations in Chapter 4 it has been highlighted that several important hazards are present for drivers of heavy earthmoving machines. Observations from the field study highlighted the need for understanding of how twisted postures and armrests interact with the operator exposed to vibration. Chapters 6 and 7 discussed the biomechanical responses to exposure of such hazards, including whole-body vibration and twisted non-neutral postures. Differences were found between subjects and between conditions. Adopting a twisted posture increased the movement at the head while exposed to vibration, and having the arms supported appeared to have some influence on the biomechanical movement at the head, although the differences were not as great as adopting a twisted posture. It was recommended that armrests will be beneficial for operators adopting a twisted posture so it is important to also find out if the armrests will be beneficial for the performance and workload of individuals.

A study by Wilder *et al.*, (2006) found large increases in head-trunk relative motion due to the use of armrest controls, with a motion capture system. This increased motion could distract the driver from their primary tasks. Considering that judgement and

decision making are always important in every day operations of heavy machines, any impairment of these processes could result in a greater chance of errors and accidents occurring. The objective of this experimental chapter is to evaluate performance and workload measures using the same vibration profile and postures investigated in the previous two chapters. It is important to determine what effects these hazards could have on performance and workload of operators as the potential for fatigue could increase which may result in injury or constitute a significant safety risk.

One study has attempted to measure performance in a real working environment, where the operators are exposed to a number of hazards including whole-body vibration exposure. Guan Tian et al. (1996) used a variety of measures including visual motor reaction time and workload to determine differences before and after work for a group of female crane operators. They found a significant decline in reaction time performance and an increased amount of errors made following work. This indicated that fatigue occurred during the course of the work; however, it failed to identify the cause of this fatigue. Many environmental hazards could have influenced the operators during the course of their shift, including vibration, posture, noise and dust.

In laboratory studies vibration has been observed both to improve and to reduce task performance. This may be because it fatigues or arouses or, because of increased task difficulty, motivates (BS6841, 1987). In 'normal upright' postures whole-body vibration has been found to impair performance, in terms of tasks requiring visual acuity and manual control (e.g. Lewis and Griffin, 1978; McLeod and Griffin, 1989; Griffin, 1990). Tracking performance has also been compromised during whole-body vibration exposure (Smith et al., 2004). Reaction time performance and mental workload have been impaired by the combined exposure to noise and vibration (Ljungberg et al., 2004). This additive effect of combined exposures would lead one to assume that performance and workload would also be impaired by the combination of sitting in a twisted posture whilst exposed to vibration. There is also evidence that motion occurring simultaneously in two axes has a considerably greater effect on vision than motion in either axis alone (BS6841, 1987). This study will replicate the previous study with a multi-axis vibration input for the vertical and fore-and-aft directions, the extent of the multi-axis effect will be dependent on the phase relationship between the two motions (BS6841, 1987). These performance tests can be enhanced by the administration of a post-hoc subjective analysis of workload. The NASA Task Load Index (NASA TLX) allows participants to perform subjective workload ratings on six sub-scales, including; mental, physical, temporal, performance,

frustration and effort (Hart and Staveland, 1988; Noyes and Bruneau, 2007). It provides a greater insight into the processes that are affected while trying to maintain performance levels.

The machines investigated in Chapter 4 and 5 suggest there are high magnitudes of vibration transmitted through the seat to the operator; it can therefore be assumed that the vibration transmitted through the armrests is also significant. Excessive exposure to vibration through the seat has been found to degrade health and performance, however, the transmission through armrests is less well understood (Wilder et al., 2006). It is likely that shoulder muscles may fatigue more quickly during exposure to seated vibration when the arm is not supported as compared with the use of an armrest (Magnusson and Pope, 1998). However, it has been suggested that armrests may increase the vibration transmitted to the hand-arm system which in turn may promote muscle fatigue and compromise successful operation of hand-operated controls. Only a small number of studies have investigated the influence of armrests. An early study by Torle (1965) found an improvement in tracking performance when the arms were supported by either a short or long makeshift armrest. A review article by McLeod and Griffin (1983) concluded that providing an armrest may reduce the effect of vibration for frequencies below 10 Hz.

Many new off-road machines have suspension seats fitted with armrests and many of these are also mounted with primary controls. However, older versions of the same machines have been found to differ in their seat configurations (presented in Chapter 4). Not all of the seats have fixed armrests or mounted controls and some of them do not have armrests, it is therefore important to understand what influence they have so recommendations for use can be given. It is possible that armrests could provide additional benefits for off-road machinery operators exposed to vibration, although their usefulness can be dependent on the ergonomic requirements of the operator. If free mobility of the trunk, shoulders and arms is required then the inclusion of armrests might be a hindrance to the operator. Previous research has shown that armrests can provide a significant amount of support for general seating (Harrison et al., 1999; 2000), but there is less understanding into whether they are beneficial for earth-moving machine operators who are required to drive over rough terrain whilst operating the machine's controls. Little consideration is given to the influence of armrests in relevant whole-body vibration standards and guidance. It is therefore important to determine what influence armrests could have on participants' performance and workload while

seated in a range of postures typically adopted during operation of earth-moving machines.

8.2 Hypotheses

The objectives of the current study were to investigate reaction time performance and perceived workload during whole-body vibration exposure while seated in upright and twisted postures, with and without armrests. The combined effect of whole-body vibration and twisted posture were assessed to determine if these stressors could have a cumulative effect on participants' ability to perform the task with a lower workload demand. Armrests were used to determine if they could be beneficial to the participants' performance outcomes.

The hypotheses are:

Hyp[1]: Vibration exposure will increase the time to respond to the visual stimulus.

Hyp[2]: Workload will increase with exposure to vibration.

Hyp[3]: Adopting a twisted posture during vibration exposure will result in a slower reaction response and highest workload demand.

Hyp[4]: Greatest number of errors will be made during vibration exposure while seated in a twisted posture.

Hyp[5]: Armrest support will improve performance during vibration exposure and reduce the workload demands.

8.3 Experimental Method

The experiment used a repeated measures design to investigate different sitting postures, (upright and twisted) with different arm support (with and without armrests) under exposure to multi-axis whole-body vibration (vertical and fore-and-aft).

8.3.1 Subject Characteristics

Participants were screened for any previous history of back problems and other medical conditions. Twenty one suitable participants from Loughborough University took part in the study. This cohort included 11 males and 10 females, from a range of different nationalities. Mean height for all the subjects was 174.1 ± 9.4 cm (156 – 190), mean weight was 72.1 ± 14.7 kg (50 – 107) and mean age was 25.3 ± 5.2 years (19 – 35).

8.3.2 Experimental Procedure and Analysis

Subjects completed a visual motor choice reaction-time task (VMRT) in four different postures; (1) upright posture with armrests; (2) upright posture no armrests; (3) twisted posture with armrests; and (4) twisted posture no armrests (illustrated in Figure 8.1). Subjects also completed a control condition with the VMRT task in a twisted posture without armrests (5), this involved sitting in the posture for 3 minutes without vibration exposure. The twisted posture was controlled by placing the screen showing the task at 135° to the mid-sagittal plane. Subjects carried out the task during a 'no-vibration' control treatment and during exposure to the vibration treatment (random signal) with a magnitude of 1.4 m/s² r.m.s in the x-direction and 1.1 m/s² r.m.s in the z-direction (at the seat surface).

Figure 8.1. Range of postures used during the experiment, upright posture (forward facing) and twisted posture (reversing), with or without armrest support.

The order of the conditions was randomised using a Latin-square design. Before starting the experiment subjects were familiarised with the procedure and allowed to practice the VMRT task. For each trial subjects completed the VMRT task with the 'no-vibration' treatment and in the 3rd (last) minute of the vibration treatment. This procedure was also followed for the 'no-vibration twisted posture' control condition, in order to test effects of the twisted posture without whole-body vibration. After each VMRT task the NASA task load index (NASA TLX) scales (Hart and Staveland, 1988) were completed by the participants in order to quantify their subjective ratings of workload (refer to Figure 8.2 for experimental design). An overall workload score was calculated from the mean ratings of all participants' over the six individual TLX workload scales.

The VMRT task was presented for 60 seconds on one of the two identical displays positioned in front, and behind to the right of the participant. The monitors showing the task were positioned at a distance of 1.1m from the participants. The programme displayed an arrow on a screen; the participant was required to respond to the arrow depending on the direction it was presented, either up, down, left or right, by pressing

the corresponding key on a keypad. The size of the arrow on the screen was large enough to ensure that participants could see the arrow clearly, even under vibration exposure. The reaction time software was validated in LabVIEW, the correlation between the reaction time software and the actual response time was $R^2 = 0.997$.

INDEPENDENT VARIABLES   **DEPENDENT VARIABLES**

POSTURE   **EXPOSURE**   **PERFORMANCE**   **SUBJECTIVE**

Upright — Armrests / No Armrests   ● No Vibration ——→ VMRT Task ------► NASA TLX

Twisted — Armrests / No Armrests   ● With Vibration ——→ VMRT Task ------► NASA TLX
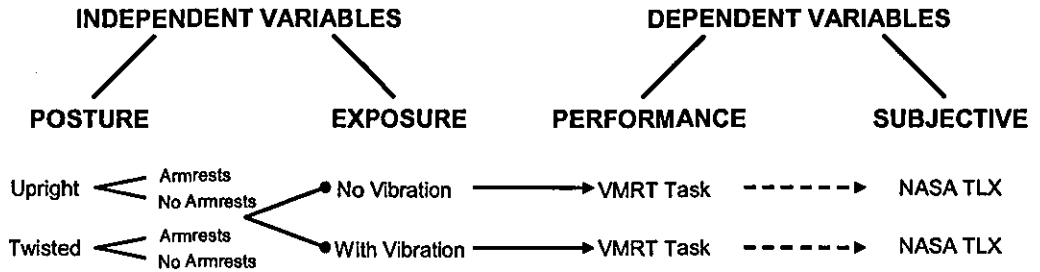
Figure 8.2 Schematic of measurement protocol for independent and dependent variables.

The air suspension seat used during the trial is typical of the seats found in the bulldozers and other tracked-type machines investigated in Chapters 4 and 5. Participants were required to have the lap belt secured throughout the trial. The height of the seat was adjusted according to their weight; this was completed before every trial. For the twisted sitting condition the angle of the head and neck was monitored using a dual-axis goniometer (SG110, Biometrics Ltd) to ensure the subjects maintained the correct posture.

The repeated measures analysis of variance (ANOVA) was used to test for any significant main effects and interactions of exposure (no-vibration control vs. vibration treatment) and posture (upright vs. twisted; with armrests vs. without armrests). The Tukey post-hoc test was used following the ANOVA to determine the exact nature of the significance between the individual conditions. Statistical significance was accepted at the 5% level ($p < 0.05$).

8.4 Results

This section discusses the findings for the performance VMRT task and perceived workload under the exposure conditions no-vibration treatment vs. vibration treatment in the four posture conditions; (1) upright posture with armrests; (2) upright posture no armrests; (3) twisted posture with armrests; and (4) twisted posture no armrests. All graphs in this section present a summary of the data for all 21 participants in this experiment. The graphs include the four posture conditions; Upright Posture No Armrests (UPNA), Upright Posture With Armrests (UPWA), Twisted Posture No

Armrests (TPNA) and Twisted Posture With Armrests (TPWA). A number of the graphs also include the Twisted Posture Control (TP-C), as appropriate, in which the participant was seated in a twisted posture for 3-minutes without vibration exposure. Statistical analysis confirmed there were no differences between males and females for reaction times, during the vibration treatment or the no-vibration treatment (Figure 8.3). Furthermore no gender differences were found for the perceived workload, therefore all data has been pooled into one group.

Figure 8.3 Mean reaction times and standard error bars for the four posture conditions: upright with armrests (UPWA); upright no armrests (UPNA); twist with armrests (TPWA); twist no armrests (TPNA) and the control, no-vibration condition for the twisted posture (TPNV). Black solid lines represent males and black dashed lines females.

8.4.1 Reaction time performance for different postures and exposure conditions

Reaction times were recorded during the 60-second VMRT task, only the reaction times generated from selecting the correct response were included in the analysis. This reduced potential errors due to manual control (psycho-motor influence) so the output more accurately reflected the posture and WBV exposure influence on cognitive function. Figure 8.4 presents the findings for the four different postures investigated with and without vibration; it also shows there was no postural fatigue effect on reaction time, for the twisted posture in the control condition.
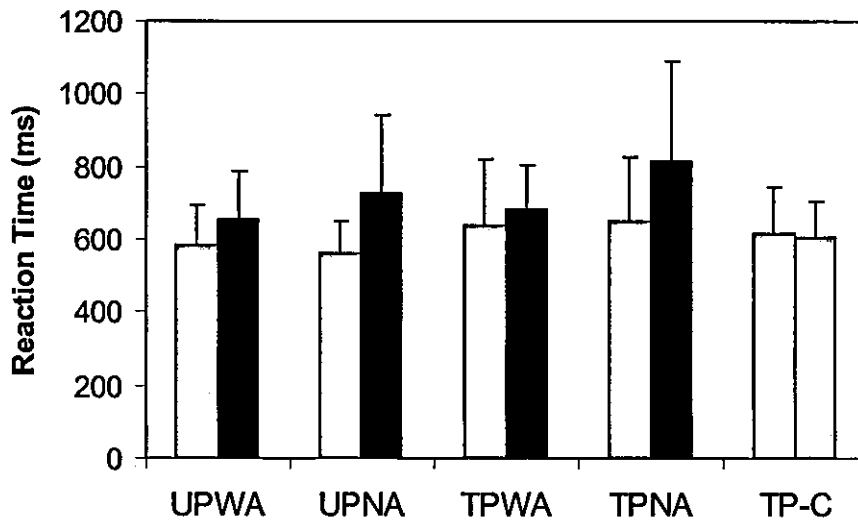
Figure 8.4 Mean reaction times and standard error bars for the four posture conditions: upright with armrests (UPWA); upright no armrests (UPNA); twist with armrests (TPWA); twist no armrests (TPNA) and the twisted posture control condition without vibration (TP-C). Dark bars represent data obtained during the 'no-vibration' treatment and light grey data during the vibration treatment.

Two-way repeated measures ANOVA showed exposure (F = $58.98_{(1, 365)}$) and posture (F = $10.66_{(3, 363)}$) had a significant main effect on the reaction time scores of the participants (p < 0.001). An interaction also exists between the exposure and different postures (p < 0.001), the cause of this interaction can be observed in Figure 8.5. From closer inspection using a Tukey *Post-Hoc* test it becomes clear that differences between reaction times varied depending on which posture was adopted. The reaction times were significantly longer during vibration exposure for both postures with no armrests (p < 0.01). The relationship for the armrest conditions is less clear: the twisted posture with armrests produced longer, but not significantly different, reaction times during vibration exposure, but there was a significant increase in the reaction time for the upright posture with armrests during vibration exposure (p < 0.05).

During the no vibration treatment the reaction times for the twisted postures were consistently longer compared to sitting in an upright posture (p < 0.01). This relationship changed during vibration exposure, as the disturbance due to vibration was greater when there were no armrests (i.e. a steeper gradient in Figure 8.5). The worst performance overall was experienced during the twisted posture condition with no armrests. Compared with the upright posture with arm support the reaction times for the twisted posture without arm support were 9% slower on average during the no-vibration treatment. The reaction times deteriorated further during vibration exposure for the same posture condition, they were 20% slower on average compared with the

upright posture with armrests. The worst performance overall was experienced during the twisted posture condition with no armrests.
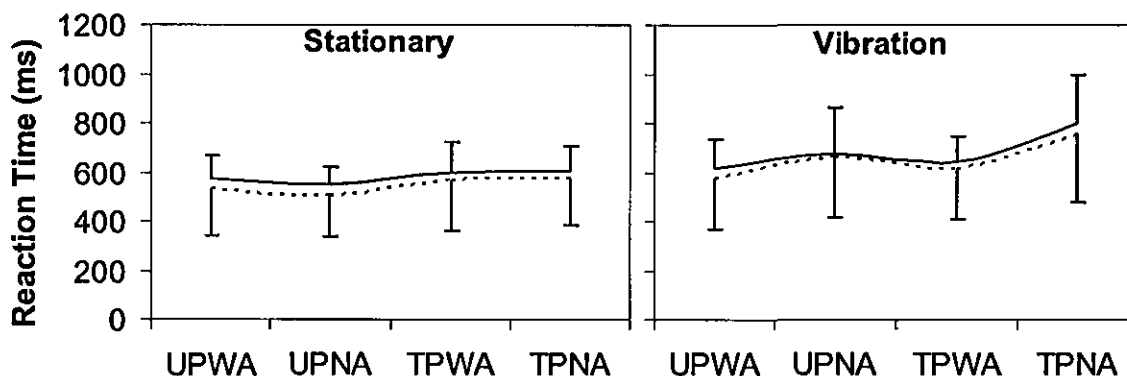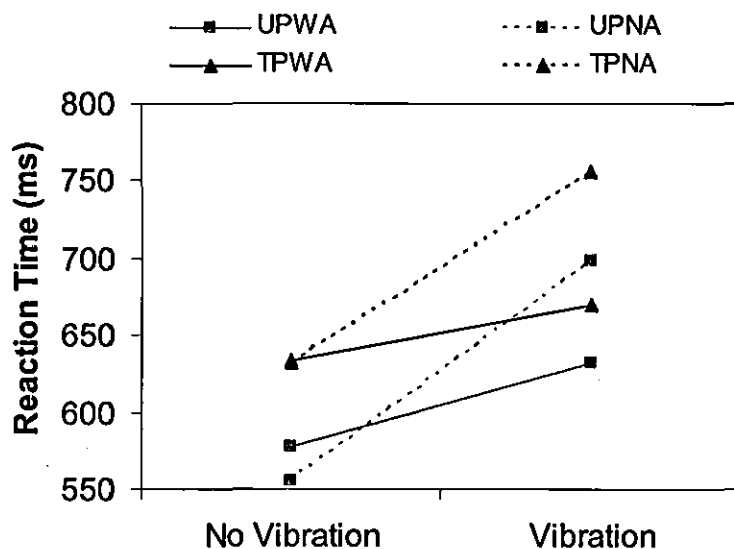

Figure 8.5 Mean reaction times as a function of exposure for the four posture conditions: upright with armrests (UPWA), upright no armrests (UPNA), twist with armrests (TPWA), twist no armrests (TPNA). (presented as estimated marginal means).

Reaction times were very similar for the twisted posture with and without armrests during the no-vibration treatment. This relationship changed during vibration exposure, the twisted posture without armrests produced reaction times 13% slower on average compared with the twisted posture supported with armrests.

8.4.2 Correct responses in the reaction time task for posture and exposure conditions

The number of correct responses made by the participants were analysed as a percentage to enable direct comparisons between the different conditions investigated. This means the lower the percentage value the greater the number of errors, and therefore the poorer the performance. A two-way repeated measures ANOVA showed exposure had a significant main effect on the number of errors made during the reaction time task ($F= 15.32 _{(1, 20)}$, $p < 0.01$); posture did not have a significant influence on the number of errors made ($F= 1.29 _{(3, 18)}$, $p = 0.309$). However, the interaction between vibration exposure and posture does significantly influence the error rates ($p < 0.05$).

221

Figure 8.6 highlights the significant interaction between posture and exposure (p < 0.05). The slight increases in error rates for the upright and twisted postures with armrests were not influenced significantly by vibration exposure. Without armrest support, there was degradation in performance. The post-hoc test confirmed this; the number of errors made was significantly increased during vibration exposure for the upright posture with no armrests (p < 0.05), and for the twisted posture with no armrests (p < 0.01). During vibration exposure adopting a twisted posture with no armrest support resulted in 12% more errors compared with an upright posture with armrests, and 9% more errors compared with a twisted posture with armrests.
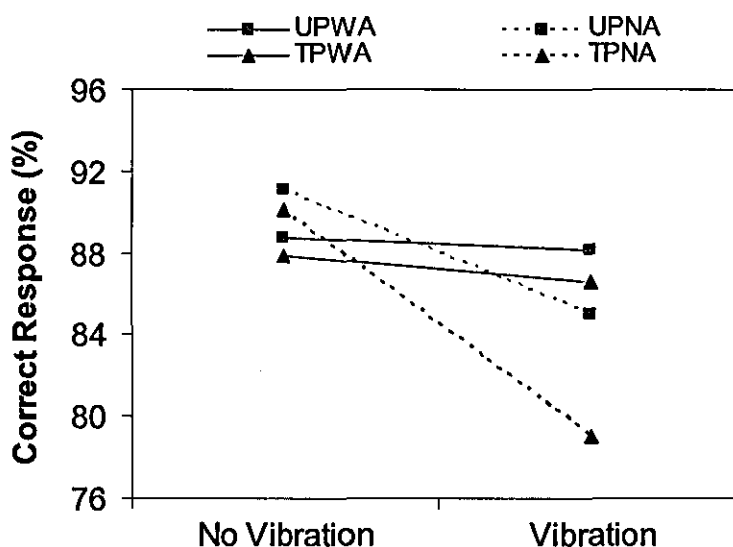
Figure 8.6 Mean percentage of correct responses as a function of exposure for the four posture conditions (presented as estimated marginal means).

8.4.3 Subjective workload

NASA TLX scales were used to determine subjective ratings of workload requirements during each condition. An overall workload score for each posture condition was calculated from the scoring of the individual workload measures. Figure 8.7 provides the overall workload scores for the different postures and exposure conditions. A high score means there is a high effort of demand. Observations and statistical significance provide sound evidence that vibration exposure increased workload demand for all posture conditions (p < 0.001). The control condition for the twisted posture shows that twisting without vibration for three minutes did not have a significant effect on workload demands. However, the interaction between vibration exposure and the twisted posture increased the workload demands compared with the upright posture during vibration exposure (p < 0.05). Including armrest supports proved to be beneficial for the overall

workload demands experienced by the subjects during vibration exposure; this was evident for both postures ($p < 0.05$).
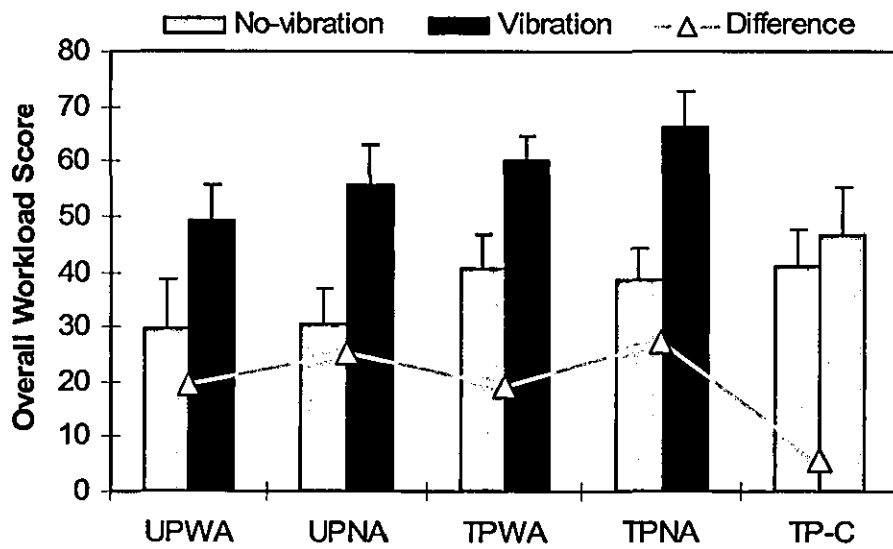
Figure 8.7 Overall workload from the mean scores of the individual workload measures for the four posture conditions, with and without vibration exposure and the twisted posture control condition with no vibration exposure.

The six subscales for the NASA TLX provide greater information about the nature of the workload experienced by the participants. Figure 8.8 provides a breakdown of the individual workload sub-scales.
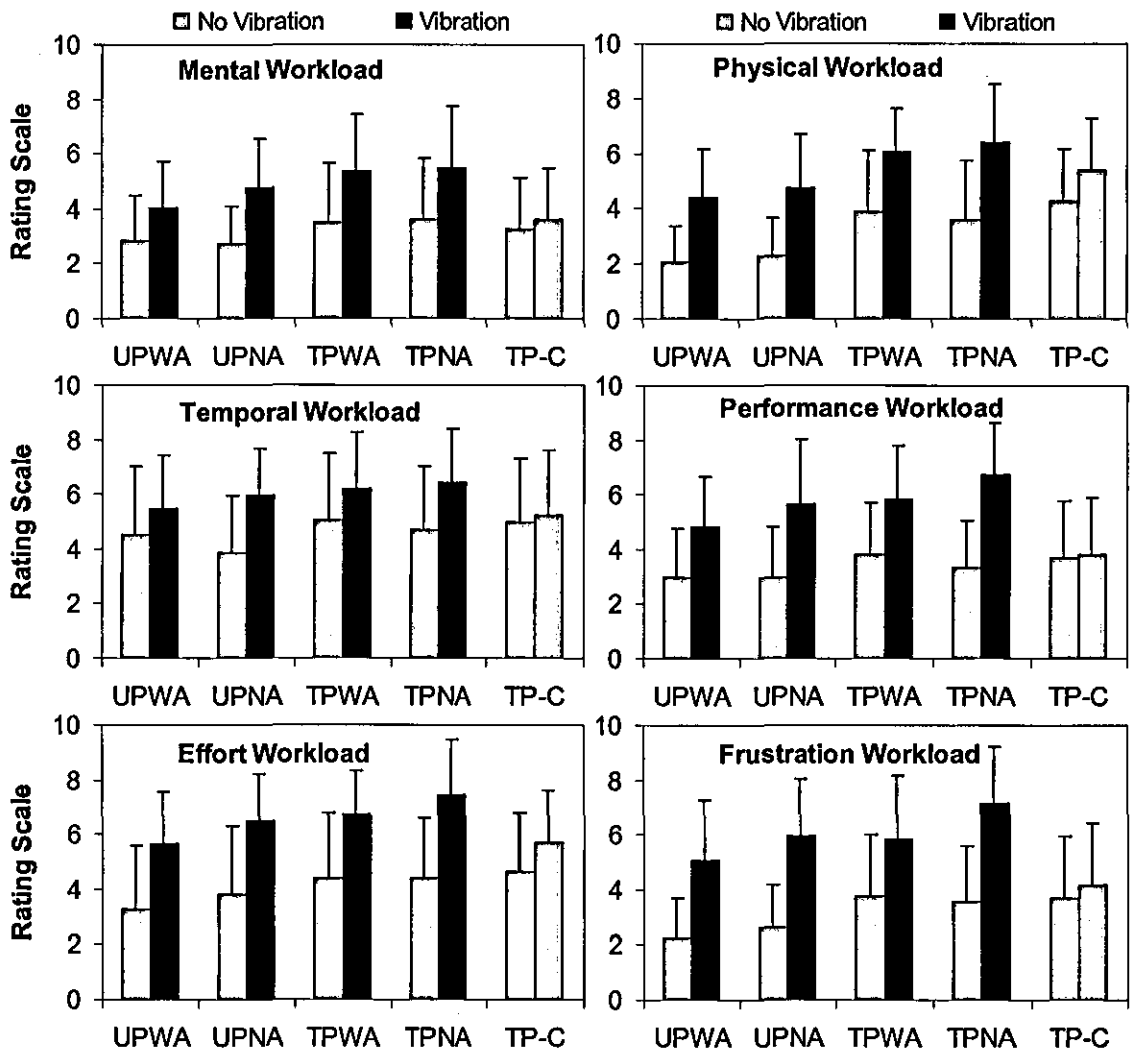
Figure 8.8 Mean workload rating scores with standard error bars for the four posture conditions with and without vibration exposure and one posture condition with no vibration exposure (twisted posture control).

Two-way repeated measures ANOVA showed vibration exposure placed a greater demand on the participants while trying to complete the reaction time task ($p < 0.001$, $df = 1$, 20). The finding was consistent across all the six different sub-scales (Figure 8.8). There was also a significant main effect between the different postures, the level of significance varied between the different sub-scales. Mental, Temporal and Effort were significant at $p < 0.05$, Performance and Frustration were significant at $p < 0.01$ and Physical was highly significant ($p < 0.001$). Significant interactions were found between WBV exposure and posture for Mental ($p < 0.01$), Performance ($p < 0.05$) and Frustration ($p < 0.05$) but for none of the remaining sub-scales (Figure 8.9).

Post-hoc analysis identified that all postures required greater physical demand during vibration exposure ($p < 0.01$), and that greater physical demand was also required for the twisted posture during no vibration exposure compared with the upright posture.

Subjects rated their own performance to be worse for the twisted posture with armrest condition during vibration exposure, whereas performance data showed no differences between the reaction times or error rates. The opposite was found for the upright posture with armrests: subjects did not rate their performance to be worse during vibration exposure; however, reaction time scores indicate a reduction in performance during vibration exposure. The subscale with the greatest increase in perceived demand from no vibration to vibration exposure was 'frustration'. Participants' frustration levels almost doubled during vibration exposure, while seated in the twisted posture without armrests.

Figure 8.8 highlights the change in workload demand from the no-vibration condition to the vibration treatment. From observation of the data it becomes clear that the upright posture had a greater percentage increase in frustration, effort and physical workload from the baseline no-vibration condition to the vibration treatment. Although this may appear contradictory to the main findings it does actually provide a greater insight into the effect of adopting the twisted posture. The reason for a greater increase in workload demand from the baseline to the vibration treatment is simply that during the baseline condition participants found the twisted posture created a higher workload demand even without vibration exposure. The control condition supports this, with 3-minutes stationary sitting in a twisted posture the perceived amount of effort and physical demand increased by 22% and 26% respectively.
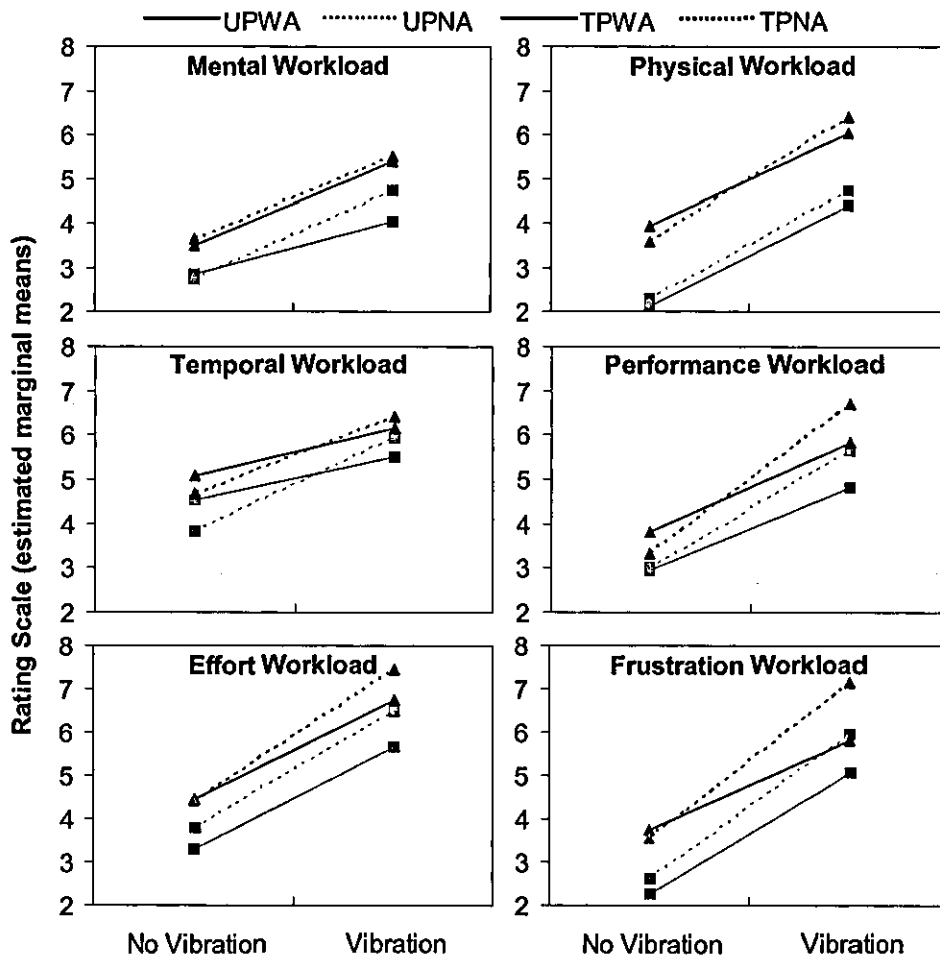
Figure 8.9 Mean workload rating scores as a function of exposure for the four posture conditions; upright posture with armrests (UPWA), upright posture no armrests (UPNA), twist posture with armrests (TPWA), twist posture no armrests (TPNA).

8.5 Discussion

The aim of this study was to investigate the influence of typical driving postures on the reaction time and perceived workload whilst exposed to seated, whole-body vibration. The combined effects of whole-body vibration and twisted posture were found to significantly reduce participants' ability to perform the task and subsequently increased their workload demand. This was particularly evident when the participants did not have armrest support. The findings validate the third hypothesis; *'adopting a twisted posture during vibration exposure will result in a slower reaction response and highest workload demand'*.The durations of exposure were only three minutes in this study, despite many operators adopting twisted postures and being exposed to whole-body vibration for sustained periods of time. It is possible that performance would degrade further for longer exposures, if there is a temporal component to the degradation. If this was the case then workload would increase and the operator could become

fatigued and therefore more likely to make errors. This could culminate into a substantial safety risk and likelihood of an accident occurring would increase. This would need to be explored in future research.

The highest number of errors occurred when participants adopted a twisted posture without armrests, this partially supports the fourth hypothesis; '*greatest number of errors will be made during vibration exposure while seated in a twisted posture*'. However, this was not evident for the twisted posture condition with armrest support, the errors made were not significantly different from the upright posture with armrests. This could be due to the increased stress experienced while adopting the twisted posture, which can lead to maintenance of performance levels up to a maximum point. This phenomenon is discussed further on in this section.

Section 8.4.3 discusses the percentage increase in workload demand from the no-vibration treatment to vibration exposure. Upright posture had a greater increase in some of the workload demands from the baseline condition to vibration exposure. The reason for this is participants found the twisted posture created a higher workload demand even without vibration exposure. The control condition supports this, with 3-minutes stationary sitting in a twisted posture the perceived amount of effort and physical demand increased by 22% and 26% respectively. This finding suggests that exposure risk assessments should also include consideration of times when the vehicle is stationary and the operator is adopting a twisted posture, as workload could be compromised. An example of this could be a time when the operator is checking behind for safety checks before he starts to operate the machine.

In the previous chapter there was a gender effect for the transmissibility of vibration through the body; this relationship was not observed in this chapter, males and females did not exhibit differences in their reaction times or workload demands. Previously both age and sex differences have been found in reaction time performance (Der and Deary, 2006). Evidence has suggested that males have faster reaction times than females on simple and choice reaction time tasks (Blatter *et al.*, 2006; Bell *et al.*, 1982). Contradictory findings have suggested the opposite with females producing a faster reaction time (Landauer et al., 1980; Landauer, 1981). One suggestion for these differences observed is that males and females adopt a different processing strategy (Adam *et al.*, 1999). Females have been found to have a faster processing ability and males to have superior motor skills thus resulting in no difference between genders when the task involves equal measures of decision time and movement time (Vercruyssen and Simonton in Lueder and Noro, 1994). The age of the females in this

study was on average older than the males; therefore one might expect differences due to an interaction between age and gender. Der and Dreary (2006) found simple reaction times began to slow around 50 years old but choice reaction times slowed throughout the adult age range investigated. The ageing of the choice reaction time was a function of the mean speed and the error rate. There was no evidence of this ageing and gender influence in the current study even with a range of ages from 21 – 35 years old for the females and 19 – 29 years old for the males.

BS6841 (1987) states 'Humans have a great ability to compensate for the effects of adverse environments'. In the case of this experiment the subjects managed to keep the error rate low even under vibration exposure, but this has been compensated by the increased workload felt by the subjects and the slower reaction times experienced during vibration exposure. This finding is in support of the first hypothesis; '*vibration exposure will increase the time to respond to the visual stimulus,*' and the second hypothesis; '*workload will increase with exposure to vibration.*' It appears that the strain increases when the participants do not have armrest support and the participants can no longer sustain their performance such that effort level reaches its maximum which results in a greater amount of errors produced during the task.

There was no significant change in reaction time performance under vibration exposure for the twisted posture condition with armrests, yet a significant reduction in performance occurred whilst seated in the upright posture with armrests. One possible explanation for this is the inverted 'U' hypothesis, where, in the middle of the range increased pressure results in greater effort, and maintenance of performance up until a certain point, after which stress becomes too great and so performance begins to suffer (Yerkes and Dodson, 1908). Vibration might alter the motivation or arousal of the exposed subjects or their perception of either the importance of the task or the performance criteria which should be achieved (Griffin, 1990). In the case where the subjects were seated in a twisted posture with armrests they may have perceived the task to be more challenging (increased arousal) and therefore increased their motivation to perform the task. This is confirmed with the subjective measures of workload, the amount of effort required to perform the task in a twisted posture was greater compared with the upright posture with armrests. Hancock and Warm (1989) adapted the inverted 'U' hypothesis to produce the extended-U relationship between stress and performance, highlighted in Figure 8.10. If the inverted 'U' hypothesis can explain the findings then it is likely that the upright posture with armrests will fall

towards the left side of the extended-U and the twisted posture with armrests will fall towards the right side just past the comfort zone.

Physiological Zone of Maximal Adaptibility
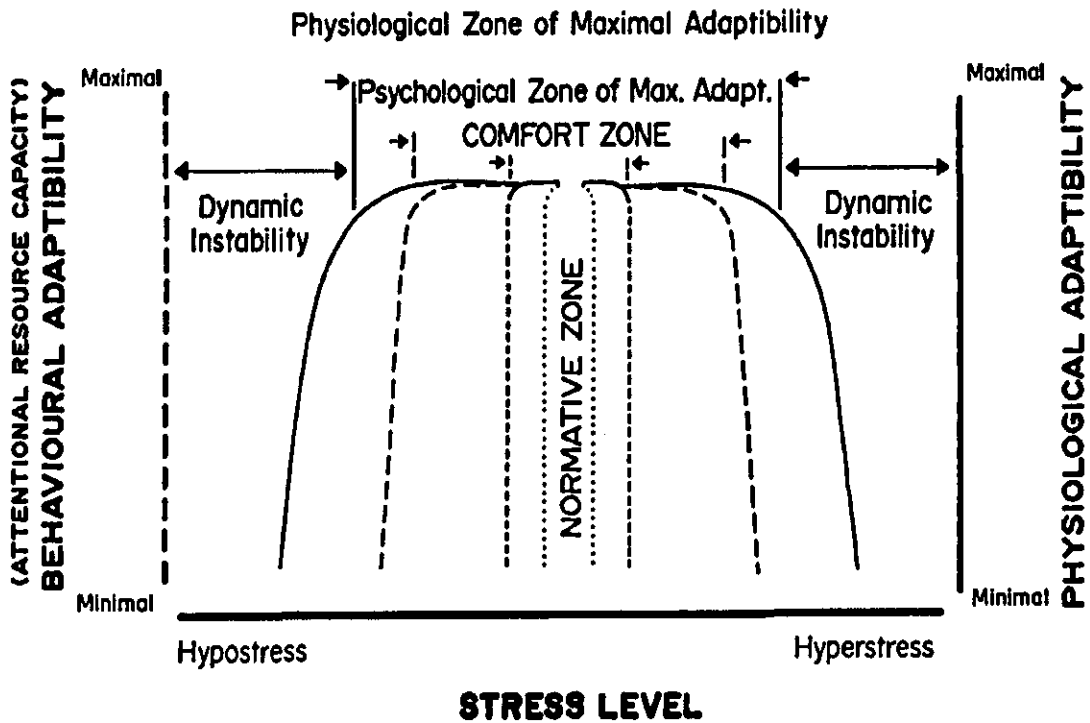
Figure 8.10 Maximal adaptability model of the extended-U relationship between stress level and performance response capacity (Hancock and Warm, 1989)

Griffin (1990) states that many studies using complex reaction time tasks have generally failed to find an effect of vibration which can be confidently attributed to cognitive deficiency, as opposed to mechanical interference or changes in arousal. It is possible that vibration exposure distracted the subjects from focusing on the reaction time task. The subjective scales identify that high levels of frustration were experienced during vibration exposure compared with no vibration for the unsupported arm conditions. This was especially evident for the twisted posture. This frustration level is reflected in the reaction times and errors made during the task.

Certain measures of workload were of greater importance to the participants under the simulated environmental conditions. Effort required during the twisted posture with no armrest condition had the highest weighting of all the conditions and all the subjective measures. This was followed closely by the frustration levels experienced by participants. Physical workload demand was greater for both the twisted postures compared with the upright postures. This is not surprising considering that twisted postures in a vibration environment have been shown to cause increased energy

consumption compared to either twisted posture or vibration as a single exposure variable (Magnusson and Pope, 1998).

Ratings of perceived performance for the task were not totally reflective of the true performance. Reaction times for the twisted posture with no armrests were similar to those for the twisted posture with armrests during no vibration, whereas a small difference was observed between reaction times measured in the upright posture with and without armrests (Figure 8.5). During vibration exposure both conditions without armrests were slower compared to with armrests. Judgements of performance using the NASA TLX method showed that subjects perceived their performance to have degraded more for the conditions with vibration and armrests than occurred in reality. Figure 8.11 identifies participants correlated their judgement of performance with the amount of errors they perceived to make, as opposed to the speed of their reaction to the stimulus.

UPWA (Vibration■) (No vibration□)   UPNA (Vibration◪) (No vibration □)

TPWA (Vibration●) (No vibration○)   TPNA (Vibration◉) (No vibration ○)
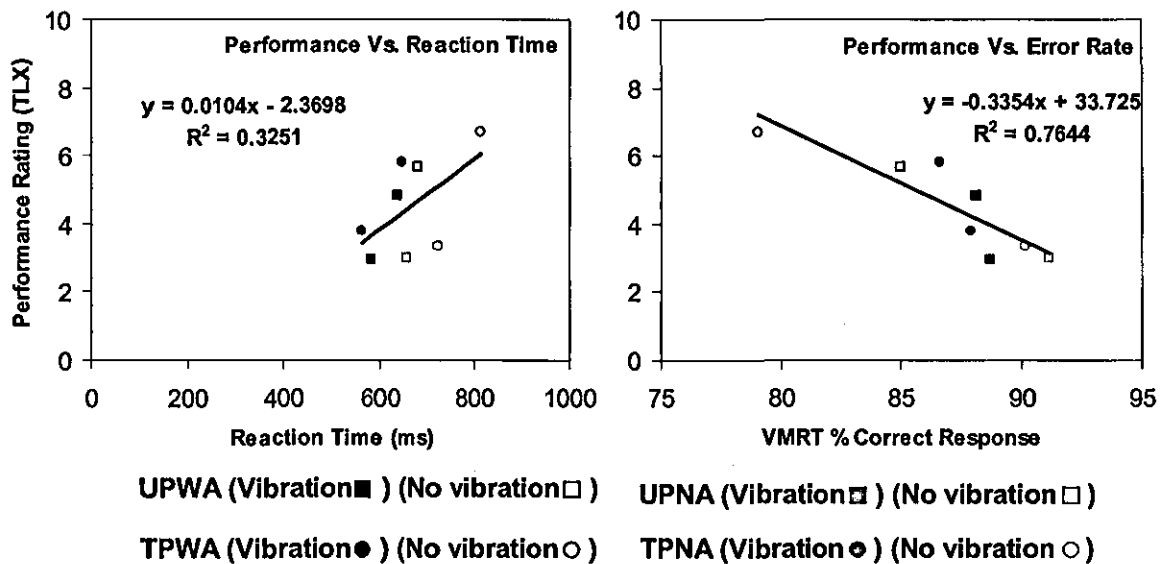
Figure 8.11 Mean perceived performance ratings from the NASA TLX plotted versus reaction time performance and percentage error rates.

The inclusion of armrests was beneficial to the participants' performance in the task and they helped to reduce the workload demands, particularly for effort and frustration. This is in agreement with previous work investigating the effect of armrests on forces transmitted to joysticks, where a reduction in transmission of force was observed with armrests (Paddan and Griffin, 1996). This finding supports Hypothesis[5], 'armrest supports will improve performance during vibration exposure and reduce the workload demands.'

The interaction of the postural conditions and vibration also highlights the importance of ecological validity for human performance trials. For the 'no-vibration' conditions armrests were shown to have no influence on the performance but during vibration their benefit is clear. This is likely to be due to the stabilising effect of the armrest (Paddan, 1996; Torle, 1965) on the pitching motion of the arm and vertical motion of the hand (Paddan, 1994).

Vibration correlated error is more evident when performing simple manual tasks in which small or precise movements of the hand are desired such as activating a button (Griffin, 1990) as is the case here. Therefore application to other controlled movements such as use of a joystick is limited. Despite this inapplicability to other operations the study clearly indicates the beneficial use of supporting the arms during low-frequency vibration environments while seated in a forward and a twisted posture. Armrests have the potential to reduce the workload placed on the operator when carrying out secondary tasks.

One clear finding from the study is both vibration and twisted posture interact to increase the workload demand of the operator even during a simple task. If twisted postures feature regularly in an operator's working day, then one should expect higher workloads for the operator. This could compromise the alertness of the operator and jeopardise safety, therefore twisted postures should be avoided.

8.5.1 Limitations of the Study

There were a number of limitations that need to be acknowledged for this study. This was a laboratory based study which increased internal validity but could influence the external validity of the findings. Only two axes of vibration were included, this leaves scope for future research to include additional axes of vibration, for example, y-axis, roll, pitch and yaw. Future studies could also investigate the use of joystick-type controls and the differences between mounted to the seat and mounted to the floor. This study used subjects between the ages of 20 – 40 years old; one would expect a reduction in reaction time in older participants, this could also be explored in future research.

8.6 Conclusions

The interaction of whole-body vibration exposure and twisted posture had a negative influence on the ability to perform a visual motor choice reaction time task. The combined environmental stressors significantly degraded performance: not only did

participants' reaction times become compromised, their workload demands also increased. During vibration exposure the absence of arm support greatly reduced the participants' ability to complete the task. This study has identified; (1) adopting a twisted posture can increase workload demands of simple tasks, and (2) the importance of considering armrest use when evaluating hazards associated with vibrating machinery, as the support may improve performance and reduce the workload demand experienced by operators.

Chapter 9 - General Discussion

The overall aim of the thesis was to determine the variability between humans, machines and task environments in order to provide knowledge to inform improvements in methods of risk management for whole-body vibration exposure. In order to understand how the risk to workers' health can be controlled the quantification of exposure to whole-body vibration in earthmoving machines, and data concerning typical work environments needed to be systematically recorded. There have been some previous studies addressing this issue but so far they have failed to take multiple measurements of similar machines.

9.1 Whole-body vibration emission and operator exposure in earthmoving machines

In 2003, when this thesis was planned, there was little data available on typical exposures to whole-body vibration exposure. The Health and Safety Executive stated that *'Little data on typical exposures exist but, rather than require employers to undertake complex measurements, we are in discussions with industry groups (currently mining, quarrying and construction) to commission research to develop generic risk assessments of typical exposure on typical activities using typical vehicles, which employers can then adapt to their own circumstances'* (Shepherd, 2003). The research commissioned by HSE was subsequently published in 2005 under "Whole-body vibration on construction, mining and quarrying machines – Evaluation of emission and estimated exposure levels" (Scarlett and Stayner, 2005). The report does provide a thorough account of the research, however, it fails to show the variation between different types of the same machine as only one measurement was made per machine type. A second report sponsored by HSE also published in 2005 described measurements of vibration in more than one machine of the same type, including 8 excavators and 2 skid-steer loaders (Toward *et al.*, 2005), however, the measurements were specific to demolition so they are not comparable to the types of tasks measured for the machines in this thesis.

The whole-body vibration guidance recommends a holistic approach to back pain incorporating factors such as manual handling and posture. This translates into the holistic health monitoring for those who are exposed above the action value, which will identify cases of back pain by self-reporting on symptoms and lead to action on any possible causative factors. They have taken the holistic approach to dealing with

whole-body vibration because suitable methods still do not exist for detecting the onset of back pain and even if they did the back pain could not be linked to whole-body vibration exposure by itself.

HSC suggest that if a person is exposed to two or more factors together then their risk of getting back pain will increase, some combinations of factors included;

- WBV exposure for long periods without being able to change position

- Driving over rough terrain while looking over your shoulder to check on the operation of the attached equipment

- Being exposed to high levels of WBV and then doing work involving manual handling of heavy loads

The operators of the machines measured for this thesis were found to mainly be in operating environments where the top two factors applied. Their primary job was to operate the machine and to ensure any obstacles were avoided; they did not perform any additional tasks involving manual handling. However they were exposed to a variety of different sitting postures, particularly the tracked dozer and loader operators who were found to adopt twisted postures (discussed further in Section 9.3).

The research base has established a link between low back pain and exposure magnitudes, as can be observed in the summary table (Table 9.1). This is reflected in the current European legislation of the Physical Agents (Vibration) Directive. The guidance was adopted for the WBV exposure assessments carried out from the field study data presented in Chapter 4.

Table 9.1 Exposure magnitudes associated with low back pain

Study	Exposure Level (r.m.s.)
Bongers and Boshuizen, 1990	1.8 m/s²
Boshuizen et al., 1992	0.85 m/s²
Brendstup and Biering – Sorenson, 1987	0.8 m/s²
Jonsson et al., 1983	0.9 m/s²
Jonsson et al., 1983	1.5 m/s²
Riihimaki et al., 1989	1.0 m/s²
Bovenzi and Betta, 1994	0.86 – 1.07 m/s²

Source: Coles (2003)

The worst individual machine measured during this work was the challenger tractor; in addition to being propelled by crawlers the machine was also carrying a "hex" compactor style attachment. Discussion with the manufacturers highlighted the issue

of non-compliance with the use of the attachment. However, even without the attachment the machine is still likely to expose the operator to high magnitudes of vibration. Especially considering the machines fitted with crawlers and performing tracking tasks were found to produce the greatest WBV emissions (bulldozers and tracked loaders). The challenger is not typically used in construction it is more likely to be observed in agricultural environments. This machine sets a prime example for how inappropriate selection of machine and attachment for a specific task can expose the operator to unnecessary high vibration magnitudes.

Out of the remaining machines over 70% were found to exceed the exposure action value of the Directive. The bulldozers, tracked loaders, articulated trucks and nearly all the wheel loaders were found to exceed the EAV in half a day. A number of the bulldozers and tracked loaders also had the potential to exceed the ELV in a working day, with vibration magnitudes comparable to the ones presented in Table 9.1.

A number of the different machine types have also been included in the European Good Practice Guide on Whole-Body Vibration (2006). The findings from the field study in this thesis have been superimposed on the graph illustrating the collective data presented in the guide (Figure 9.1). It appears that the current studies findings do not totally correlate with those from the European Good Practice Guide. The data in the guide has been collated from a large number of different institutes and this in itself would increase the variation in the data set. Many different environments may have been measured and the machines could have been performing a variety of tasks. The vibration emission values presented in the guide can give some indication as to typical levels experienced in each machine yet it can also provide confusion due to the large variation in vibration magnitudes for any particular machine. The bulldozers do correlate fairly well with those from the current research, with certain cases of even higher magnitudes in the guide's data. This is also the same as the excavators; the likely reason for the differences between excavators is possibly because the ones in the current study were primarily performing excavation tasks so the machines were stationary throughout the measurement. It is important to acknowledge this mainly because there is definite scope for excavators to produce vibration magnitudes comparable to the other tracked machines and this will need to be taken into account when targeting machines for health risk assessments.
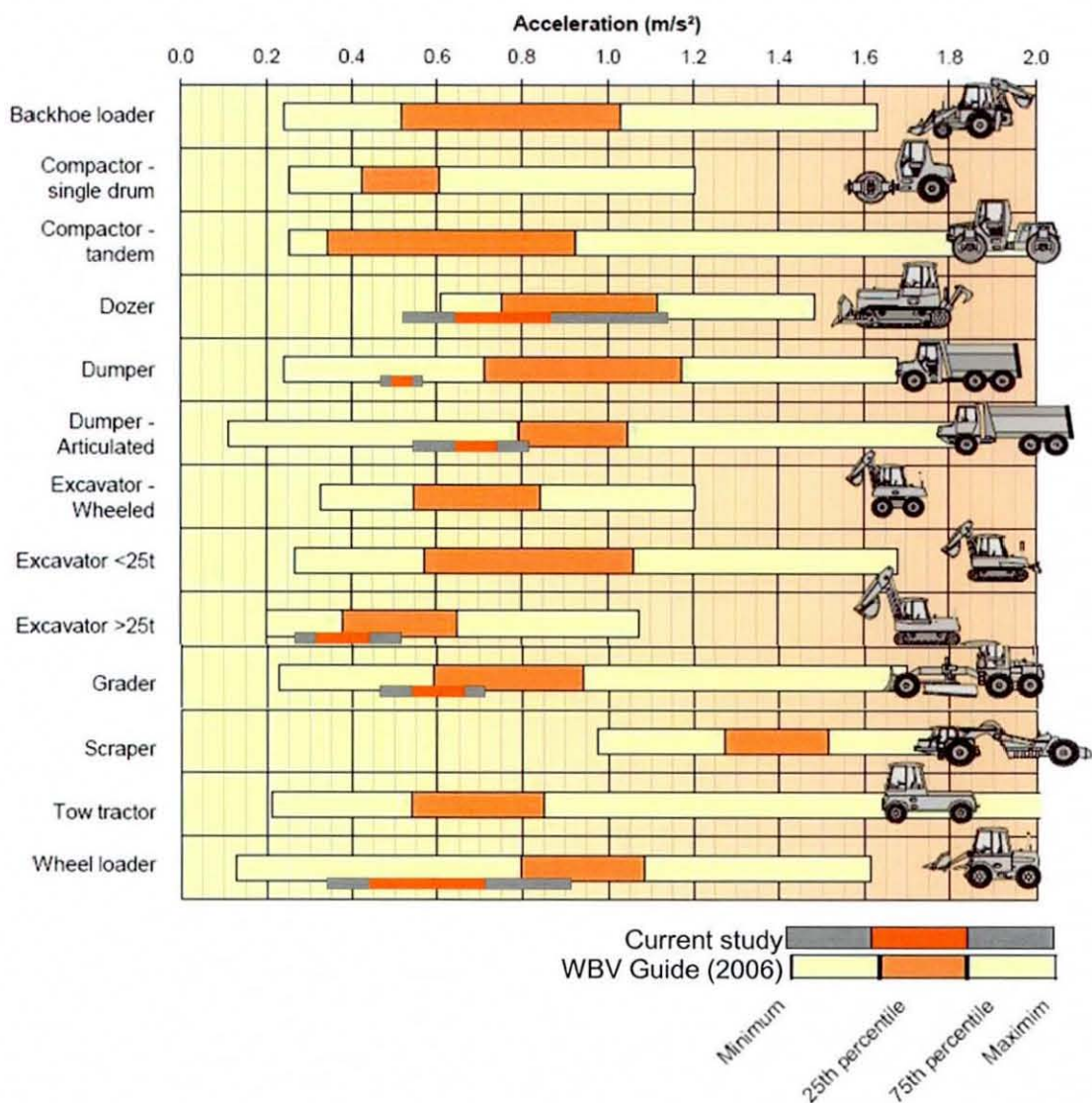
Figure 9.1 Comparison of results from the field study with the European Good Practice Guide on WBV (2006)

The findings of all the earthmoving machine exposure profiles are discussed in more detail in Section 9.5.

9.2   Influence of variation in whole-body vibration on the assessment of risk

There are a number of different kinds of variability that can have an impact on the assessment of risk from whole-body vibration exposure. The field studies presented in Chapter 4 and Chapter 5 have identified many of the sources of variation found between emission and exposure values they will be discussed in the following section and they have been collated into Figure 9.2 presented in Section 9.5.

The study of day-to-day variability found vibration magnitudes measured from one day were not representative of the vibration profile experienced throughout the working week the findings were supported by recent research (Marjanen, 2006). Only 1/3rd of the machines investigated in the current study had coefficient of variations below 10% in all axes for the day-to-day variability. Four out of the 11 machines had greater than 20% variation in two axes, two of which had greater than 30% variability. The study also found that not only did the vibration magnitudes vary but in some cases the dominant axis of vibration also changed, factors like this could make it difficult to provide mitigation for such a machine if the dominant axis is found to switch. Unfortunately measurements could not be made on every single day for the machines so the full extent of the variability throughout a working week or even a working month cannot be realised from these findings. This is an area that requires further research.

Comparison of the variability experienced across different sites found trucks to be very repeatable, most likely because of the similar standards of maintained routes across the sites and similar tasks performed. The wheel loaders on the other hand were found to vary across sites and within the same sites. The majority of wheel loaders were carrying out loading tasks, however, the variety of the loading tasks, load carried and distance travelled varied substantially between measurements.

Only one site could be specifically identified as having higher vibration magnitudes than any other sites operating the same type and model of machine. Unfortunately the site only had two tracked loaders in operation by the same person. Therefore comparison with other machine samples was not possible to confirm if the high vibration magnitudes were related to the actual site and task or to the operator and machine.

The study of inter-cycle variation found vibration magnitudes from one work cycle were not representative of the work cycles for the full operation, in the majority of machines. The dump trucks and articulated trucks fell within the lowest variation category (below 12.5%) and at the other end of the scale in the high category were the excavators (above 25% variation). Kittusamay (2000) also found the vibration to vary significantly for excavators, from sample-to-sample. The coefficient of variation for 8 samples of an excavator digging and loading a truck exceeded 40%.

The variation between work cycles was found to be highest when the terrain type was irregular, for example, a motor grader measured over two days and carrying out the same tasks on both days was found to have substantially more variability in the lateral

axis on the second day. This was caused by the substantial rainfall on the second day's measurement where the track became particularly waterlogged and churned up resulting in increased rolling of the machine, measured as y-axis vibration as the seat is above the centre of rotation. Additional cases of high variation between work cycles were attributed to increased travel during periods of the measurement.

The bulldozers discussed in Chapter 5 highlighted how sampling error can occur during an assessment. During the measurement of the work cycles a number of the dozers had periods of elevated vibration dispersed between work cycles of lower vibration magnitudes. If these periods were not measured then the operators exposure could have been underestimated and if a limited measurement duration happened to measure just the elevated periods then the exposure risk could have been overestimated. Neither of these examples would be desirable as inappropriate risk management strategies would be employed as a result.

One of the sources of variation that is hard to control is the operator behaviour. This became evident during the assessment of multiple measurements of the same wheel loader. The operator performed the same tasks in the same areas over the different measurement periods yet the vibration magnitude in the first measurement was significantly higher than the other measurements. The operator expressed his dislike for the machine and on that particular day a representative from the machine manufacturers was also present. The operator could have intentionally altered vibration profile by adopting a more aggressive driving style. During the pilot study the driver was asked to adopt two styles of operation for a skid steer loader, 'normal' and 'aggressive'. As expected the vibration magnitudes increased during the aggressive driving style by more than 50% compared to normal driving. This provided some evidence for the influence operators could have on their own vibration assessment and highlights the careful approach needed during the measurement process.

Factors that can influence the overall exposure of an operator were also established. One example of an influencing component for the overall exposure was discussed in Chapter 4. The rock crusher machine situated at one of the sites became jammed during the vibration assessment, this required the operator to climb onto a ledge and remove the debris manually. The floor vibration was measured on this machine and it was found to produce very high vertical vibration. Although this is not a mobile machine and only exposes the operators to vibration intermittently it still needs to be highlighted because of the added severity to their overall risk exposure. Griffin (1990) reviewed the history of studies conducted on vibration platforms, some them for construction

workers. It was concluded that such platforms can present a host of vascular and health disorders. One way to manage the operators' exposure is to ensure the crusher machine has a good maintenance record, as this is likely to reduce the frequency of jams in the machine. If there is more than one operator working around the crusher machine then there should be job rotation put in place to reduce individual exposures.

Additional organisational issues were realised during conversations with the operators that could alter the overall vibration exposure. Many of the operators remained in their machines all day, even during break times so their postures were not altered during these rest periods. The operators also expressed their willingness to work overtime regularly to increase their earning potential. The work durations specified in Chapter 4 do not include times when the operators work overtime. Health risk assessments should take account of the periods when operators work overtime and consideration should be given to the frequency of overtime. This could significantly alter the control measures and health surveillance required for an operator. Some of the operators in this study (e.g in the bulldozers) could exceed the ELV if they were carrying out regular overtime.

The overall message from the quantification of variability is the importance of measuring over longer durations and over many work cycles than has previously been done. The amount of variation also highlights the importance of conducting a task analysis prior to performing vibration measurements, such that adequate samples can be obtained for each element of the work cycle.

9.3   Implications of twisted postures for operators of earthmoving machines

The field study involved observations of the operators performing different tasks to determine what the typical postures were during exposure to vibration. The most concerning posture adopted by any of the machinery operators was the twisted posture observed in the bulldozers. Operators were found to adopt twisted postures, greater than 20° from neutral in the trunk and neck. Due to the size of the machine and nature of the tasks performed the operators were usually required to manoeuvre over large areas of ground. The result of this meant that operators were adopting twisted postures for extended periods of time in order to maintain good visibility in the direction of travel. Tracked loader operators were also found to adopt twisted postures of a similar degree of rotation, but with less frequent occurrences and for shorter periods of time.

An upright posture is not necessarily the 'ideal' posture to adopt yet it is present in many driving situations. No single posture can constitute the 'ideal' as any posture maintained for a long period of time can result in discomfort and fatigue. What is clear is that twisted postures adopted during vibration exposure have been found to cause increased energy consumption compared to only twisted postures or vibration alone (Magnusson et al., 1987).

Hartman et al., (2005) indicated that back pain causing sick leave in Dutch agriculture could be significantly associated with increased exposure to physical risk factors including twisting and whole-body vibration. However it should be acknowledged that the calculations of exposure were purely estimates created with the aid of experts, furthermore exposure to vibration was scored only by a yes or no answer with no estimation of the magnitude of vibration exposure. A more substantial study commissioned in 2001 by the US Congress from the National Research Council and Institute of Medicine (Punnett and Wegman, 2004), backs up the findings of Hartman et al. (2005). The report focused on 170 epidemiological studies linking physical ergonomic exposures at work with musculoskeletal disorders. An attributable fraction (AF) score was used for each exposure. The AF is an estimate of the proportion of disease that would be reduced in the exposed population if the exposure were eliminated and represents the relative importance of exposure reduction in those settings where the exposure is prevalent. For physical stressors affecting the back, the AF was as high as 66% for manual material handling and 80% for whole-body vibration among exposed groups, frequent bending and twisting reached 57% in some cases. The authors established that the risk is substantially increased when a job includes exposure to a combination of two or more risk factors; this is in line with the previous comments from the HSC (Section 9.1).

Wiehagen et al. (2001) analysed serious injuries to dozer operators in the U.S. Mining Industry for the U.S. Department of Health and Human Services. Lost time injuries by operator impact identified that backs accounted for the most frequent body part to be injured, either through a sudden jolt or jarring or from musculoskeletal injuries.

Blade/ground work had the highest percentage of serious injuries 57% compared with only 6% of injuries occurring when the operator tracked forward. In comparison the number of serious injuries was approximately four times greater when the operators were tracking backwards (30%). Vertical jarring in the vehicle accounted for 354 injuries, about 40% of the injury set. In over one-half (185) of the injuries, the dozer operator was tracking backwards. Backing up was also reported to be involved with

about 40% of the cases involving a collision. Some of the narratives presented in the report highlight the problems with backing up:

'Operator was backing a bulldozer over rough terrain and was severely jolted, causing muscle spasms in the lower back'

'Victim was backing up dozer when it dropped off into hole, causing jar'

'Too much strain on the back from turning in seat to back up....Too many hours on dozer'

'The employee was operating a bulldozer performing backfilling operation. During normal operator procedures, employee was turning and twisting while operating dozer. Employee started to experience back pains and swelling of muscles in the lower back'

This clearly identifies a significant health and safety issue with this kind of manoeuvre. Factors that could contribute to serious incidents could be poor visibility when reversing and perhaps the inability of the operator to focus on the task due to the constraint posture. Many of the incidents reported the cause of the back injury to be due to longer exposures and not just a singular event, including causes relating to operators twisting or turning in the seat and prolonged dozer usage. There is a need to understand the relationship between vibration exposure and the twisted posture observed in the current study as this posture clearly causes problems for the operators adopting it.

9.4   Simulated field environment for the understanding of human response to vibration in different driving postures

Even though risks have been identified it is still not possible to predict the probability of any disorder from the severity of an exposure to whole-body vibration. There is still no certainty of a specific disorder being linked to whole-body vibration, or what disorders are aggravated by exposure to whole-body vibration and the relative importance of vibration and other risk factors in the development of back disorders is still unknown (Griffin, 2006). The interactions between vibration and twisted postures on the biomechanical transmissibility responses have not been explored previously. The following section discusses the findings on such interactions from the laboratory studies.

241

The studies conducted in the laboratory recreated the vibration and operator postures characterised in the field study (Chapter 4 and 5) in order to simulate a more realistic environment for the assessment of human response to vibration (Chapter 6 and 7) and the effects on workload and performance (Chapter 8). The vibration magnitudes and postures used for the studies were based on the tracked mobile machines found to expose operators to the highest vibrations in the vertical and fore-and-aft directions. Although the findings have applications for a number of different machine types the main focus of the studies was to characterise the human response to the exposures (vibration and posture) found in the bulldozers. It was decided to focus on this particular type of machine for a number of reasons;

(1) All the machines exceeded the EAV in a short period of time

(2) Depending on the application many of the machines also had the potential to exceed the limit value

(3) Nearly all the machines exceeded 17 $m/s^{1.75}$, indicating the presence of high acceleration shock events in the vibration signal, and these events were found in both the vertical and fore-and-aft direction.

(4) The operators of these machines were found to adopt twisted postures in a static seating position for long periods during reversing manoeuvres

(5) Due to the nature of the task performed by these machines and the often remote environments they work in the operators tend to remain in their cab during a lunch hour, adding to the total time spent seated in a static posture

(6) These machines can be found in abundance throughout industry both in Great Britain and throughout the world, therefore the potential health risk reduction strategies could have a wider scope for exposure reduction

(7) Many safety accident cases have been reported involving the use of dozers (Wiehagen et al., 2001)

Tracked loaders were found to have a very similar exposure profile to the bulldozers, these machines were not, however the main focus for the laboratory studies for the following reasons;

(1) There are not as many of these machines in industry, this became evident during the start of the field trials when problems occurred with trying to locate these machines.

(2) There are possible alternatives in terms of machines that can carry out many of the tasks that were performed by the tracked loaders. Wheel loaders in general produce lower vibration and are more readily found in industry performing the same types of tasks, albeit in not so many variations of terrain.

(3) Although operators were found to adopt twisted posture, they were less frequent compared to the operators of the bulldozers and they were not maintained for as long a periods.

9.4.1 Transmissibility changes with twisted postures

The studies presented in Chapter 6 and 7 aimed to establish if adopting twisted postures could change the biomechanical response to whole-body vertical vibration. The study presented in Chapter 7 was specifically designed to both validate the findings from the previous study and to increase the external validity of the findings in a more realistic way. The study aimed to recreate the typical postures, upright and twisted, with and without armrest support on a typical suspension seat used in industry, while being exposed to multi-axis vibration.

The principal resonance in the apparent mass of subjects exposed to vertical vibration while seated in an upright posture was found in the frequency range 4 – 6.3 Hz. This finding supports the previous research on measurements of apparent mass (e.g. Fairley and Griffin, 1989; Mansfield and Griffin, 2000; Mansfield and Griffin, 2002; Rakheja et al., 2002; Wang et al., 2004). No clear differences could be found between postures as subjects seated in a twisted posture also had their principal resonance within the same frequency range. There were significant differences between the two postures, however the trends in apparent mass were small, and less than the differences observed between subjects. Therefore seat designers would not need to alter their design based on the twisted posture, however they would be required to address the variation between people. Apparent mass was found to have a higher degree of repeatability compared to seat-to-head transmissibility. The preferred method from Chapter 6 was the seat-to-head transmissibility as it was found to have a greater application for understanding the mechanisms of vibration transfer to the movement of the head and cervical spine.

Seat-to-head transmissibility data for the upright posture was firstly validated against the previous research (Paddan and Griffin, 1993; 1996; 1998) and secondly validated with the upright and twisted postures from the multi-axis study presented in Chapter 7. There was good correlation across the studies. The small discrepancies between the findings from Chapter 6 and the previous research were found in the axes that produced the greatest movement (vertical and pitch axes); most likely due to variability between subjects (Paddan and Griffin, 1994) as a result of postural and body size differences (Paddan and Griffin, 1988a; Messenger and Griffin, 1989).

Transmissibility in the vertical axis was greater than 1 at the principal frequency resonance for both the upright and the twisted postures measured in Study 2 and Study 3a. In both studies the most significant finding for the differences in seat-to-head transmissibilities between the upright and the twisted posture was the increased motion in the lateral and roll motion at the head (over 80% increase). Both measures changed from being close to zero, with no clear frequency dependence in the upright posture to a system with a clear peak at about 6 to 8 Hz in the twisted posture. The twisted posture was significantly higher than the upright posture at all frequencies above 1.6 Hz for both the single axis and multi-axis vibration studies.

Griffin (1990) suggested that '*if the head oscillates in pitch about a point in the region of the upper cervical vertebrae (the atlanto-axial joints) there will be a different vertical motion at the front of the head than at the rear: the measured magnitude may be considered to be a combination of the translational motion at the centre of rotation and the translational motion produced by the rotation, where the two component motions may not be in phase.*' In the neutral position the centre of mass of the head occurs anterior to the atlanto-occipital joint and therefore vertical vibration generates rotation motion in the fore-aft plane, which is the direction where the neck has the greatest range of motion. Even after rotation of the head as in this study, the centre of mass of the head remains anterior to the base of the neck, due to the associated shoulder rotation, and therefore vertical vibration again induces loading in the (seat) fore-aft plane. In the twisted condition, this corresponds with roll of the head and explains the difference in response between the postures. Furthermore, lateral rotation of the neck (roll) is limited by a smaller range of motion at the joint and therefore mechanical limits would be reached sooner than if the motion was pure pitch (McGill et al., 1999).

The cervical spine can withstand the highest axial compressive loads and sustain the highest load (and strain) magnitudes when it is in the straight neutral position (White and Panjabi, 1990). Sitting in an upright posture with the head in the neutral position

causes a low load on the cervical spine; the load movement is balanced by muscle forces and tension of the passive structures. The more the head departs from neutral, the more the load increases (Thuresson, 2005). Therefore in the neutral position the head and neck will be more adapted to loading, especially in the pitching motion of the head, as observed previously during ambulation (Woodman and Griffin, 1996).

Findings for the twisted posture highlight the importance of considering neck pain and not just lower back pain otherwise the potential risks to the health of the operators may be missed. Driving and operating machines has been associated with an increased risk of severe neck trouble (Viikari-Juntura *et al.*, 1994) and increased symptoms from the neck, shoulders and thoracic region but with no increased risk of low back pain (Rehn *et al.*, 2002; Rehn, 2004). The load on the neck is correlated to the trunk and head position (Magnusson and Pope, 1998) and it can be considered as posing a significant health risk in itself without the consideration of pain in the lower back. It would be detrimental to ignore this hazardous working posture in relevant standards and during a vibration risk assessment. The stability of a joint is also important from a safety perspective this aspect is discussed in more detail in Section 9.6.

9.4.2 Transmissibility variations between males and females

In the upright posture women had significantly less vertical head motion at 2.5 Hz similar to the findings of Griffin *et al.* (1982a) and between 1.5 and 3.5 Hz, with significantly more transmissibility at frequencies between 5.5 and 8.0 Hz, similar to the findings of Griffin and Whitham (1978). Males were also found to have more pitching motion at 2.5 – 3.0 Hz and between 5.0 – 6.5 Hz while seated in an upright posture with armrest support. Findings were quite different for males and females seated in a twisted posture. No clear differences existed between males and females for the fore-and-aft direction and in the vertical direction females had a significantly higher peak resonance between 5.5 and 6.5 Hz for the twisted posture without armrests. There was no clear relationship between males and females for any of the rotational motion at the head. The males in the current study were taller in stature (on average) compared with the females (180 ± 7 cm compared with 168 ± 9 cm). It is possible the increase in peak response for males in the upright posture could be attributed to the greater amount of contact with the backrest, as the relationship is not evident while seated in a twisted posture with less backrest contact. However despite the differences observed between males and females, the size of the differences would not be sufficiently great to warrant different gender criteria for health risk assessments.

9.4.3 Transmissibility changes with armrests

Pitching motion at the head was significantly increased with armrests for the upright posture in the frequency range 8.0 – 16 Hz; however in the twisted posture armrests significantly reduced the pitching motion at 2.5 – 3.0 Hz and 5.0 – 10 Hz. Considering the implications of adopting a twisted posture it appears suitable to recommend that armrests are beneficial and do not adversely increase the vibration transmission for the typical conditions simulated in Study 3a, and therefore could be beneficial in reducing postural fatigue of the arms and shoulders as has previously been shown for general seating (Harrison et al., 1999; 2000).

Armrests and armrest mounted controls need to be considered separately when recommendations are made. Armrest controls more rigidly couple the shoulders, via the upper arms, to a vibration source and bypass the damping provided by the entire arm, potentially increasing the risk of motion-related musculoskeletal problems in the neck and upper trunk (Wilder *et al.* 2006). Consequently, the differences in vibration transmission between standard armrests (like the ones used in the current study) and more sophisticated armrests mounted with controls needs to be fully understood and is a potential area for future research.

9.4.4 Performance and workload changes during vibration exposure and effects of twisted postures

The seat-to-head transmissibilities have highlighted which movements are likely to be problematic for operators of earthmoving machines, particularly for the tracked machines. The movements at the head and neck suggest the operator would not be able to maintain good visual performance in such a posture as the increased movement at the head combined with the awkward sitting position could adversely affect the safe operation of the machine. Wiehagen *et al.* (2001) report discussed previously supports this assumption. In order to obtain a better understanding of the influence of these exposures on the performance and workload of operator's further measures were assessed in the laboratory, including reaction time and NASA task load index measure of workload (presented in Chapter 8).

'Individual operators possess a malleable but ultimately finite attentional capacity. Mental workload represents the proportion of resources demanded by a task or set of tasks. An excessive demand on resources imposed by the task(s) attended to typically results in a degradation of performance.' (Stanton *et al.*, 2005). Chapter 8 showed an

increase in workload and subsequent degradation in performance for participants seated in a twisted posture and exposed to whole-body vibration. This was counteracted by allowing the participants to use armrest supports.

In Chapter 7 there was a gender effect for the transmissibility of vibration through the body; this relationship was not observed in Chapter 8, males and females did not exhibit differences in their reaction times or workload demands. Reaction times were very similar for the twisted posture with and without armrests during the no-vibration treatment. The relationship changed during vibration exposure, the twisted posture without armrests produced reaction times 13% slower on average compared with the twisted posture supported with armrests. The inclusion of armrests was also beneficial to the participants' workload demands, particularly seen in a reduction of effort and frustration required. The finding supports the recommendation made in Chapter 7 where armrests were found to reduce some of the vibration transmission while providing additional support to the operator in the non-neutral twisted posture.

During the baseline 'no-vibration' condition participants found the twisted posture created a higher workload demand even without vibration exposure. The control condition also supported this finding. The perceived amount of effort and physical demand increased by 22% and 26% respectively, during three minutes exposure to the twisted posture without vibration exposure. This finding suggests that exposure risk assessments should also include consideration of times when the vehicle is stationary and the operator is adopting a twisted posture, as workload could be compromised. An example of this could be a time when the operator is checking behind for safety checks before he starts to operate the machine.

The participants managed to keep the error rate low even under vibration exposure, but at a cost in terms of increased perceived workload and slower reaction times. It appeared the strain on performance increased further when the participants did not have armrest support. At that point the participants could no longer sustain their performance resulting in greater number of errors as their required effort reached its maximum. One 'Compensatory Control Model' proposed by Hockey (1997) suggests that simple methods may not be sufficient to capture stressor effects, as the individual may choose to 'protect' the level of observable performance through the application of increased effort or a change in strategy. Therefore performance can be maintained under high levels of both environmental stress and task demands, at a cost to the individual on other levels. Uncovering the 'latent' effects may help to identify when an individual may be in a high-risk 'strain' state (Conway et al., 2007). If only measures of

reaction time performance were taken during Study 3a then these latent effects would have been missed.

The durations of exposures only lasted for three minutes in Study 3. In reality the operators of the bulldozers were found to adopt twisted postures for sustained periods of time during exposure to high magnitude vibration. It is possible that performance could degrade further for longer exposures if there is a temporal component to the degradation. Subjects may have been able to maintain performance for the short periods of time by concentrating more than usual on keeping performance at some 'acceptable' (to the subject) level, (Straker *et al.*,1997; Straker and Mekhora, 2000) suggest that extra focus may not be possible in longer tasks or where attention is limited by some other factor. If this was the case then workload would be compromised and the operator could become fatigued and therefore more likely to make errors. This could culminate into a substantial safety risk and increase the potential for accidents. This would need to be explored in future research.

One clear finding from the study is both vibration and twisted posture interact to increase the workload demand of the operator even during a simple task. If twisted postures feature regularly in an operator's working day, then one should expect higher workloads for the operator. This could compromise the alertness of the operator and jeopardise safety, therefore twisted postures should be considered in assessments of the operator and they should be avoided where possible.

9.5 Whole-body vibration exposure risk profiles for earthmoving machines

HSE estimates that between 9,000 to 21,000 cases of back pain in the UK may be caused by whole-body vibration, with a further 13,500 to 21,500 cases made worse by WBV at work, giving an estimated total between 22,500 to 52,500 cases. With an estimated cost to wider society including the individual, 10-year benefit of between £521 million – £1,314 million. However under the present values when the cost benefit analysis was performed it was estimated that over a 10-year period costs for risk management may be between 2-10 times higher than the benefits of reducing vibration exposure (Coles, 2003). It is therefore extremely important that any costs made to manage the risk are done so in the most effective manner. Griffin (2004) highlights this concern *'Where reducing risk solely involves reducing vibration magnitude or exposure duration, ill-founded evaluation methods will not increase risk. Where prevention involves a redistribution of vibration over frequencies or directions, or balancing a*

change in magnitude with a change in duration, an inappropriate evaluation method can increase risk' (Griffin, 2004).

Brereton and Nelson (2005) have outlined the criteria for assessing whether an exposure is to be considered moderate or high. They specify that;

- Moderate exposure can be regarded as exposures likely to exceed the EAV on some days or exposure below the EAV but containing occasional high magnitude shocks where VDV is usually less than 17 m/s$^{1.75}$

- High exposure can be regarded as exposures likely to exceed the EAV and a VDV of 17 m/s$^{1.75}$ and likely to exceed or approach the limit value if not adequately managed.

These factors were taken into consideration for categorization of the machines measured in this thesis. The findings have been drawn together from both the field and lab studies. The studies measuring the human response to vibration while seated in a twisted posture (Chapter 6 and 7) have indicated that twisted postures could place the neck in a very vulnerable position. Considering the tracked machines have also been found to expose the operators to high acceleration shocks, the likelihood of injury could increase considerably. Therefore to ensure the risks are adequately managed the bulldozers and tracked loaders have been placed in the high exposure category for a health risk assessment.

Figure 9.2 outlines a model of the vibration exposures and variability between work cycles from the earthmoving machines measured for this thesis. It highlights the machines of most concern and therefore the ones that should be targeted for measurement where there is likely to be cases exceeding the limit value of the Directive. It also identifies the machines that are most likely to be assessed incorrectly based on measurement of a limited number of work cycles. Therefore anyone using the table can identify the machine of interest and if it required further measurement to determine the true vibration exposure then the right hand side of the figure can be referred to for an idea of the variability to account for. For example, bulldozers fall within the high exposure for the fore-and-aft or vertical vibration combined with twisted postures and therefore are high priority for risk management. They also have a high amount of variability between work cycles for the horizontal axes of vibration; therefore many repeat cycles should be measured in order to get an accurate estimate of exposure. Articulated trucks may also be targeted in certain cases, due to the high

249

exposures in the lateral axis. However, unlike the bulldozers they have very repeatable work cycles due to the typical nature of their task and the smoother terrain. The skid steer loader has been placed in the middle of the moderate exposure category because although the vibration magnitude in the vertical direction was just below the limit value the exposure duration is limited to a short period each day.

WBV Exposure Risk Management

| Operators at risk from exposure environment | Operators at risk from incorrect assessment |

Challenger Tractor: z (1) + "hex" attachment

Bulldozers: x (5), or z (3)
Tracked Loaders: x (6), or z (2)

High

— — Limit value

Articulated Trucks: y (5), or x (1)
Wheel Loaders: x (11), or y (6)
Motor Graders: y (4)

Roller: y (1)
Skid Steer Loader: z (1)
Dump Trucks: z (3)
Compactor: y (1)

Moderate

Excavators: x (6)
Rollers: z (2)
Material Handler: x (1)

Possible

Action value 12.5%

Bulldozers: x, or y
Excavators: x, y, or z

Rollers: x, y, or z

High

25% — — —

Wheel Loaders: x, y, or z
Tracked Loaders: x, y, or z

Motor Graders: x, y, or z
Skid Steer Loader: y, or z
Compactor: x, or y
Material Handler: x, y, or z

Moderate

Dump Trucks: x, y, or z
Articulated Trucks: x, y, or z
Challenger Tractor: x, y, or z

Possible

Vibration Magnitude
Worst axis (no. of machines)

Coefficient of variation (%)

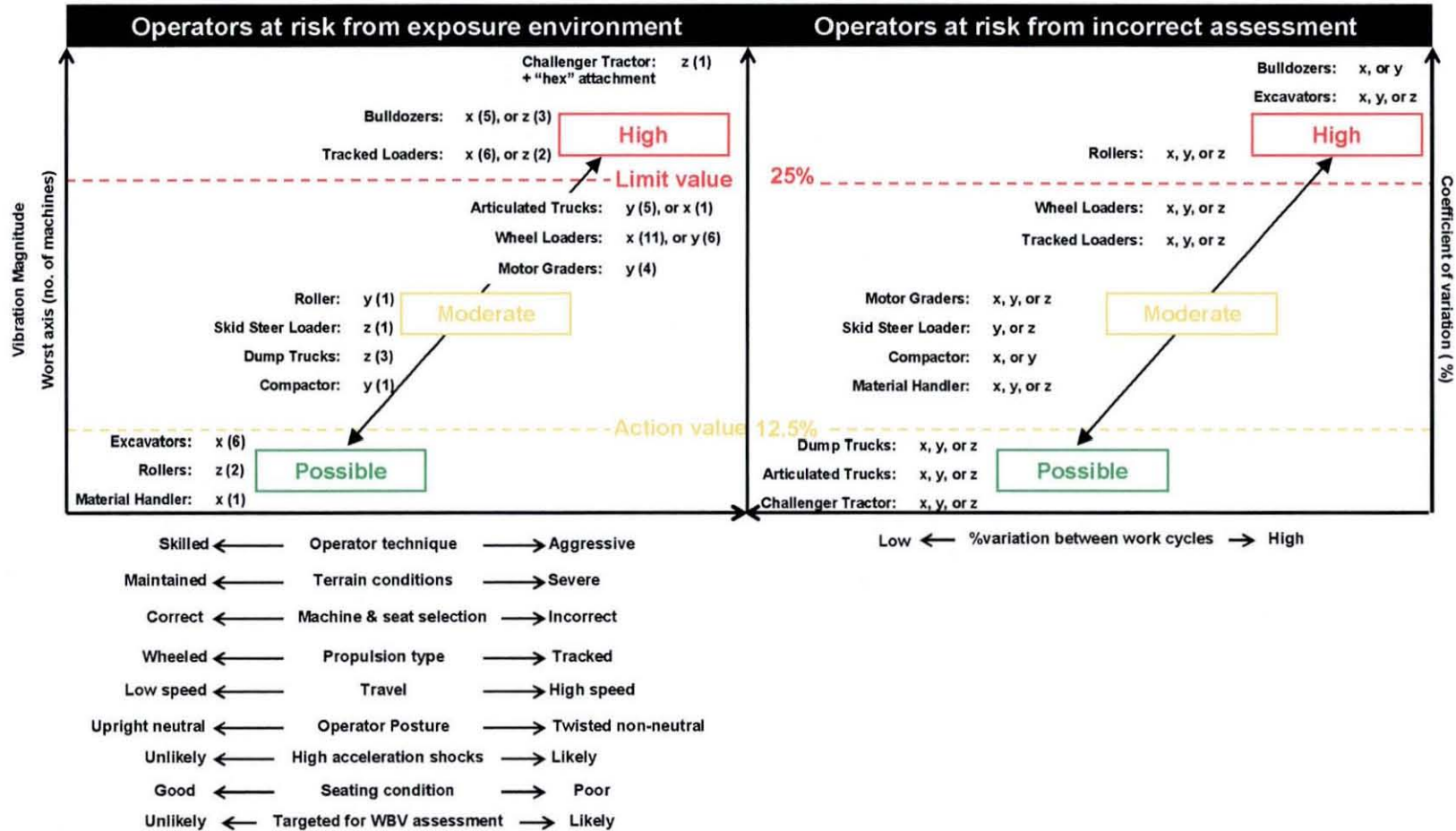| Skilled ← Operator technique → Aggressive | Low ← %variation between work cycles → High |
Maintained ← Terrain conditions → Severe	
Correct ← Machine & seat selection → Incorrect	
Wheeled ← Propulsion type → Tracked	
Low speed ← Travel → High speed	
Upright neutral ← Operator Posture → Twisted non-neutral	
Unlikely ← High acceleration shocks → Likely	
Good ← Seating condition → Poor	
Unlikely ← Targeted for WBV assessment → Likely	

Figure 9.2 Characterization of earthmoving machinery operator health risk exposures from; construction, mining and quarrying environments and the likelihood of obtaining an unreliable estimate of the operators' vibration exposure using measurements of individual work cycles.

251

9.6 Whole-body vibration risk management and hazard reduction

The first method of reducing exposure to vibration is to try and reduce vibration at source. This can often be a difficult and costly task. However, in certain circumstances it could save the company money at the start followed by unknown cost savings over a longer term for potential increased productivity, less wear-and-tear on machines, reduced sick leave, no compensation claims and prevention of re-training due to loss of operators. The current research provides a prime example of this with the company that were using the Challenger tractor with a "hex" attachment. The sole task of this machine on the particular work site visited was to flatten the ground in preparation for building construction to commence. The vibration magnitudes were extremely high in this machine and there was only one operator that could use it for a total of 8 hours a day. They would exceed the limit value in 2 ½ hours, so under the Control of Vibration at Work Regulations they would be required not continue with the operation of the machine and attachment. The most cost effective solution would be to replace the machine with a roller, as this type of machine performs the same tasks as the Challenger and two of the rollers did not exceed the action value within an 8-hour period. The third roller would have exceeded the action value in 5 hours, the likely cause of the increased vibration magnitude in that particular machine was probably a combination of the varied speed (max 6.7 mph), mixed terrain and variety of gradients. Compared with the roller machine with the lowest vibration magnitude, the operator of this machine was required to smooth out a small area that had little change in gradient, with a constant speed around 2 mph (max 3.3 mph); as can be observed in the vibration and speed data presented in Appendix A8 Considering the task for the Challenger involved very repetitive cycles with almost identical variation to the last roller discussed, it would be most appropriate to purchase or hire a similar roller to replace the challenger. A compactor machine might also be considered but this should be avoided as the compactor measured in the field study produced lateral vibration of 0.72 m/s² r.m.s. The roller replacement appears to be the most viable solution to provide protection for their employee while also adhering to the regulations. It is often the case that large construction companies will have a number of the machines on loan this would make it even easier to implement the changes in a cost effective manner.

During the operation of a vehicle the seating dynamics can influence the exposure of the operator to whole-body vibration. In certain environments improving the dynamic response of the seat has been found to lessen the severity of whole-body vibration

252

exposures in a variety of working environments (Paddan and Griffin, 2001; TESTOPS, 2000). However, the suspension of the seat or the vehicle itself may not necessarily attenuate the exposure. In order to produce the maximum damping effect the seat's resonant frequency needs to be less than the frequencies produced by the vehicle. This is often not achieved and subsequently can result in amplification, rather than an attenuation of the vibration (Paddan and Griffin, 2001). At lower frequencies the seat will amplify the vibration especially around the resonance frequency of the suspension seat. This is especially of concern for the machines in the field study they were found to mainly expose vibrations at lower frequencies. However, there is some potential scope for improving the seating in a number of the machines. Although SEAT values could not be calculated because the floor data was not measured the frequency spectrum was determined in a large selection of the machine types, therefore frequencies holding the most energy could be established. Any suggestions for improvements of seating can only be based on assumptions that the current seating is not performing to its maximum attenuation characteristics.

The bulldozers, tracked loaders and wheel loaders were all found to have very low frequency fore-and-aft components, below 1 Hz. In many cases this is a behavioural issue due to the task and not the machine itself (e.g. for a 'V-shaped' motion loading task with short duration). ISO2631-1 (1997) allows for vibration at frequencies below 1 Hz to be neglected if the frequency range below 1 Hz is not relevant or important. Notini et al. (2006) argues that the origin of the vibration will not directly affect the biomechanical responses to it yet the effect of omitting the low frequency vibration below 1 Hz was generally found to be greater than 20% in the case of ISO2631-1 metrics for the x- and y-axes. Regardless of the debate on ISO2631-1 filter frequency there is scope to reduce this component through training to ensure the operators do not drive the machines in such way that promotes these components. There are limited engineering control measures for this problem, as fore-and-aft suspension mechanisms for a seat could not prevent this. It is, however, important that the cab mounting systems for these machines are designed and maintained so that the fore-and-aft shocks generated when the bucket or blade of the machine hits the ground or a loading pile are not then amplified into the rocking motion of the cab (Scarlett and Stayner, 2005). This problem appeared to be particularly relevant for the operator of a particular tracked loader measured for this thesis. The operator himself identified concerns of the machine hitting the ground when they tracked up a steep gradient or when they changed direction in the machine, again this could be improved with

appropriate training to ensure the machine is operated as intended in order to prevent the low frequency component (highlighted previously in Chapter 4, Figure 4.10).

There is also scope to reduce the vertical vibration component in a number of the machines including a selection of the bulldozers, articulated truck and motor graders. Unfortunately without seat effective transmissibilities it is not possible to specify whether the current seating is already attenuating most of the component., if the travel become too long other considerations of the mechanisms that allow the driver to maintain control of the driving task would become an important factor. The lower the attenuation frequency the longer the required seat suspension travel will be, e.g. 3cm above 3 Hz and up to ~15cm at 1.5 Hz so providing a heavily damped seat might not be appropriate in some of the restricted cab sizes (Donati, 2002).

Terrain and driving style / speed were found to affect the vibration exposure of operators in dozer machines. One of the most practical methods of reducing the vibration exposure in the dozer machines is to educate the operators on correct driving speeds and appropriate usage of the machine. For example, the operator of Dozer 7 could reduce the vibration exposure by reducing the speed especially while operating with demanding terrain conditions. Alternatively an excavator machine could be used to perform the clearing task at this section of the site, this machine is capable of completing the task while stationary and therefore a greater reduction in vibration exposure will be achieved. Operator driving style was also observed to influence the measurement of vibration in range of construction, mining and quarrying machines (Scarlett and Stayner, 2005). It was found that vibration magnitudes vary according to how hard/enthusiastically the bucket of a loader was driven into a stock pile. It was also established that three of the four machines with the lowest vibration measured in their study were owner operated. For this reason the operator's behaviour appeared to be influenced by the cost of maintenance and repairs of their machine. This phenomenon was not present for the machines that were hired or owned by "the company" nor was it a factor in for the dozers measured for this thesis.

Wikström (1993) found subjective discomfort and EMG activity of the trapezius muscles increased with twisting of the neck or back compared with a neutral posture whilst driving. The author concluded that allowable work times should be reduced for those working with twisted postures when compared to those working in symmetrical postures. From the findings in this thesis one would choose to disagree with the previous author. Although reducing allowable exposure times while operating in a twisted posture will provide some benefit. It will not reduce the hazardous posture

itself. The interactions between the twisted posture and the vibration response indicate that individuals are at an increased risk regardless of the exposure duration. If a sudden jolt were to hit the machine and the operator was adopting this posture then their chances of sudden impact injury like the ones reported by Wiehagen *et al.* (2001) could be substantially greater due the neck not being able to sustain such force in the rotated lateral direction. The twisted posture is likely to contribute to increased risks of a back injury due to the uneven distribution of the vibration and shock forces on the spine.

Firstly it is important to understand why they are adopting such a posture and to try and identify a way of eliminating it. If it is due to the cab design and issues with visibility then the cab will need to be redesigned. The operators may not trust using a mirror or camera mounted in the cab depending on how long they have been using posture as a visibility aid therefore it is important to implement a reduction strategy that the operators will actually adopt. Training them on the hazards of posture and vibration with examples could be an appropriate approach before any redesigns took place.

Operators are regularly required to reverse during their working day, minimizing the time spent in reverse both in terms of distance and time could be another way to tackle the problem. By twisting and looking behind, their purpose is to avoid the larger hazards (e.g. uneven terrain causing jolts in the machine). If they do not look behind (in order to maintain a good body posture), then they become more susceptible to the risk of larger shocks (jolts and jars) due to unseen undulations or obstacles (Wiehagen *et al.*, 2001). The authors also suggest that bulldozer operators may tend to maximize their amount of material moved by minimizing their necessary, but unproductive time in reverse. Higher tracking speeds (generally about 5 miles per hour maximum for bulldozers) in reverse may introduce risk by exacerbating the effects of uneven terrain and provide a low margin of error in perception, judgement, and corrective action such as slowing down. The authors add that '*if operators recognized the hazard, the response might be direct and more reliable-slow down and manoeuvre the dozer through or around the obstacle*' and '*If one accepts that jolts are unexpected, then one solution is for the dozer operators to recognize terrain conditions that are likely to produce high levels of shock.*' Again this could be managed through adequate training especially for the younger operators who will have less experience with dealing with different types of terrain and are more likely to be the ones less able to adapt to the hazards because of underdeveloped musculature.

Overall the most practical method of reducing the vibration exposure experienced in the machines measured in this thesis is through training, to ensure the machine operators adjust their driving technique depending on the task and environment and to make sure they do not adopt an aggressive driving style. It is the most cost effective method of reducing exposures as it does not require replacement of equipment or new equipment to be purchased. Re-educating the operators regarding appropriate driving techniques could help to minimise their exposures for both vibration and postures, this is particularly relevant for the bulldozers during tracking operations.

Chapter 10 – Conclusions

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

- The machines with the greatest vibration emission were generally those that spent most of their time tracking. The Challenger tractor 85D produced the most severe vibration magnitudes out of all the earthmoving machines. Operators of this machine would exceed the EU Physical Agents Exposure Limit Value in about 2.5 hours. The most likely cause of the high exposure was the unauthorised use of a "hex" attachment used to flatten the ground. Selection of appropriate machine for the task could significantly reduce the exposure of the operator, for example, rollers can perform the same task and during the study they were found to produce low magnitudes of vibration for a comparable task.

- Out of the remaining machinery operators over 70% were found to exceed the exposure action value of the Directive. The operators of the bulldozers, tracked loaders, articulated trucks and nearly all the wheel loaders were found to exceed the EAV in half a day. A number of the bulldozer and tracked loader operators also had the potential to exceed the ELV in a working day, considering the long working hours typically observed in industry for some of these machines.

- The influence of variability between work cycles was found to be a particular problem for the bulldozer and excavator machines, variation between work cycles exceeded the 25% variance limit criteria. If these machines were targeted for a WBV health risk assessment then the measurement durations will need to take account of this variation in the extrapolation to an 8-hour exposure.

- Day-to-day variability was lower than 10% in only 1/3rd of the machines measured. Nearly half had greater than 20% variation in two axes and two of which were greater than 30% variability. The study also found that not only did the vibration magnitudes vary but in some cases the dominant axis of vibration also changed, factors like this could make it difficult to provide mitigation for such a machine if the dominant axis is found to switch.

- Task type, terrain and driving style / speed were found to affect the vibration exposure of operators driving earthmoving machines. The machines appear to produce similar trends of vibration magnitudes when operating in a range of different environments, from granite quarries and open cast coal mines to airport construction sites.

- The most concerning posture adopted by any of the machinery operators was the twisted posture observed in the bulldozers. Operators were found to adopt twisted postures, greater than 20° from neutral in the trunk and neck. Due to the size of the machine and nature of the tasks performed the operators were usually required to manoeuvre over large areas of ground and they were adopting twisted postures for extended periods of time in order to maintain good visibility in the direction of travel.

- Findings demonstrated that operators are likely to be putting their necks in a vulnerable position in the twisted posture due to the large increase in rotational movement at the head during exposure to vibration. Decrements in reaction time performance and increases in workload were also found while individuals were sat in a twisted posture and exposed to vibration.

- The vibration dose values indicated that shock-type vibration may be present in the working environments of a number of the machines, especially in the bulldozers and tracked loaders. If these movements are unpredictable then the operator would be in a vulnerable position when they are adopting a twisted posture.

- In both laboratory studies the most significant finding for the differences in seat-to-head transmissibilities between the upright and the twisted posture was the increased motion in the lateral and roll motion at the head (over 80% increase). Findings for the twisted posture highlight the importance of considering neck pain and not just lower back pain otherwise the potential risks to the health of the operators may be missed.

- Both vibration and twisted posture interact to increase the workload demand of the operator even during a simple task. If twisted postures feature regularly in an operator's working day, then one should expect higher workloads for the operator. This could compromise the alertness of the operator and jeopardise safety, therefore twisted postures should be

considered in assessments of the operator and they should be avoided where possible.

- Armrests were found to reduce some of the vibration transmission while providing additional support to the operator in the non-neutral twisted posture. The inclusion of armrests was also beneficial to the participants' workload demands, particularly seen in a reduction of effort and frustration required.

Chapter 11 - Future Work

The following bullet points highlight the key areas that could be investigated as part of the future work. This is by no means a definitive list however it identifies some of the key considerations:

- Unfortunately measurements could not be made on every single day for the machines so the full extent of the variability throughout a working week or even a working month cannot be realised from this findings. This is an area that requires further research.

- Only one site could be specifically identified as having higher vibration magnitudes than any other sites operating the same type and model of machine. Unfortunately the site only had two tracked loaders in operation by the same person. Therefore comparison with other machine samples was not possible to confirm if the high vibration magnitudes were related to the actual site and task or to the operator and machine. Additionally the following areas could be addressed to increase the understanding of vibration and posture exposure:

  o Determining the variation in exposure duration for the calculation of A(8).

  o Establish a method of assessing combined risks such as twisted postures and vibration, as observed for some drivers. Such data would assist in prioritisation of risk reduction strategies.

  o Investigation of vibration emission whilst operating with non-approved or unusual machine attachments, as observed for the challenger / hex combination.

  o Using a higher sample size of each machine and collecting data on a larger number of tasks could improve the validity and application of the findings.

- Ideally the measurements of seat-to-head transmissibility would have been divided into response to single axis (vertical and fore-and-aft and lateral)

and then combinations of the axes to get a deeper understanding of the mechanisms inherent to the bodies response and to determine how much is influenced by the different axes of input. Measurements of the dynamic responses of the human body to individual translational axes, rotational axes and combinations of these are required to increase the understanding of the mechanisms inherent in the body. Required to understand possible injury mechanisms of the body, particularly the spine both lower and upper due to vibration, shock and twisted postures as well as investigation of bend over postures in a multi-axis environment

- Measurements of subjective discomfort combined with measurements of the dynamic response of the body may provide greater insight into the true effects on the body from combined vibration and awkward posture exposures.

- Possible detrimental effects of horizontal shock-type vibration in the neck region and their prevention must be studied further since there are several questions to be resolved. Due to the nature of the hazards this would most likely have to involve epidemiological studies.

- Muscle activity can play a significant role in the development of musculoskeletal disorders and considering the high rotational component experienced in the neck while seated in a twisted posture studies involving quantification of muscle activity should be explored.

- Performance and workload study provided a clear indication of how vibration and twisted postures over a short period of time can negatively impact performance and increase the perceived workload of participants. The problem is the reaction time task was very simple to perform in order that anyone could be trained in it quickly. In the future it would be more externally valid to recreate an operating environment in the laboratory but using a simulator programme that allows the participants to carry out simulated tasks that would typically be performed in industry. This could include both arm mounted controls such as joysticks and also addressing the different types of controls that can be mounted directly to the floor.

- The durations of exposures only lasted for three minutes in the laboratory studies. In reality the operators of the bulldozers were found to adopt

twisted postures for sustained periods of time during exposure to high magnitude vibration. It is possible that performance could degrade further for longer exposures if there is a temporal component to the degradation. Longer duration experiments could be performed to determine if there is a temporal component to the operator's performance and workload under different exposures to vibration and twisted postures.

- NASA TLX workload scales were used to assess the individual's perceived workload. The subjective assessment did provide a good correlation with the different types of postures adopted. However, there must always be some doubt about the validity of the participant's answers. It is sometimes difficult to get the true profile when the participants reply with what they think you would want to hear. Additional ways of assessing the workload of the participants should be explored in the future.

- The differences in vibration transmission between standard armrests (like the ones used in the current study) and more sophisticated armrests mounted with controls needs to be fully understood and is a potential area to explore further.

References

Adam JJ, Paas FGWC, Buekers MJ, Wuyts IJ, Spijkers WAC and Wallmeyer P., 1999. Gender differences in choice reaction time: Evidence for differential strategies. *Ergonomics*, 42(2), 327-335.

Ahlin, K., Granlund, J. and Lundstrom, R., 2002. Whole-body vibration when riding on rough roads, *37th United Kingdom Group Meeting on Human Response to Vibration*, 18-20 September 2002, 412.

Atkinson, S., Robb, M and Mansfield, N. J., 2002. Long term vibration dose for truck drivers - preliminary results and methodological challenges, *37th United Kingdom Conference on Human Responses to Vibration*, 18-20 September, 194 - 202.

Barnes, G.R. and Rance, B.H., 1975. Head movement induced by angular oscillation of the body in the pitch and roll axes. *Aviation, Space and Environmental Medicine*, 46 (8), 987-993.

Bell PA, Loomis RJ and Cervonne JC., 1982. Effects of heat, social facilitation, sex differences, and task difficulty on reaction time. *Human Factors*, 24(1), 19-24.

Blatter K, Graw P, Munch M, Knoblauch V, Wirz-Justice A and Cajochen C., 2006. Gender and age differences in psychomotor vigilance performance under differential sleep pressure conditions. *Behavioural Brain Research*, 168(2), 312-317.

Boshuizen, H.C., Hulshof, C.T., and Bongers, P.M., 1990. Long-term sick leave and disability pensioning due to back disorders of tractor drivers exposed to whole-body vibration. *International Archives of Occupational and Environmental Health*, 62 (2), 117-122.

Boulanger, Mistrot, Poirot and Roure., March 1978. Evaluation of the amount of exposure to vibrations transmitted to the whole-body. Case of vibrations due to a loader mounted on Caterpillar tracks, a fork-lift truck and a hydraulic excavator. *Institut National de Recherche et de Securite, Report No.245/RE** October 1976, Ministry of Defence (Farnborough, Hants).

Bovenzi, M., and Betta, A., 1994. Low -back disorders in agricultural tractor drivers exposed to whole-body vibration and postural stress. *Applied Ergonomics,* 25 (4), 231-241.

Bovenzi, M., and Hulshof, C.T.J., 1998. An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain. *Journal of Sound and Vibration,* 215 (4), 595-612.

Bovenzi, M., and Hulshof, C.T.J., 1999. An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain (1986-1997). *International Archives of Occupational and Environmental Health,* 72 (6), 351-365.

Bovenzi, M., Pinto, I., and Stacchini, N., 2002. Low back pain in port machinery operators. *Journal of Sound and Vibration,* 253, 3-20.

Brereton, P. and Nelson, C., 2003. HSE's consultative document on future regulations and guidance – whole-body vibration. *38th United Kingdom Conference on Human Response to Vibration,* held at Institute if Naval Medicine, Alverstoke, Gosport, England, 17-19 September 2003.

British Standards Institution., 1989. Guide to safety aspects of experiments in which people are exposed to mechanical vibration and shock. BS7085.

British Standards Institution.. 1987. Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock. 1987. BS6841.

Buchholz, B., Moir, S., and Virji, M.A., 1997. An ergonomic assessment of an operating engineer: a pilot study of excavator use. *Applied Occupational Environmental Hygiene,* 12, 23-27.

Cann, A. P., Salmoni, A.W., Vi, P. and Eger, T. R., 2003. An exploratory study of whole-body vibration exposure and dose while operating heavy equipment in the construction industry. *Applied Occupational and Environmental Hygiene,* 18(12), 999-1005.

Cardinale, M., 2004. High-frequency vibration training able to increase muscle power in postmenopausal women. *Archives of Physical Medicine and Rehabilitation*, 85(4), 687-688.

Chaffin, D., and Andersson, G., 1991. *Occupational Biomechanics*. Chichester: Wiley.

Chen, J.C., Chan, W.P., Katz, J.N., Chang, W.P., and Christiani, D.C., 2004. Occupational and personal factors associated with acquired lumbar spondylolisthesis of urban taxi drivers. *Occupational and Environmental Medicine*, 61, 992-998.

Coles, B., 2002. Regulatory impact assessment of the Physical Agents (Vibration) Directive. Health and Safety Executive.

Conway, G.E., Szalma, J.L., and Hancock, P.A., 2007. A quantitative meta-analytic examination of whole-body vibration effects on human performance. *Ergonomics*, 50(2), 228-245.

Corbridge, C., 1987. Vibration in vehicles: its effect on comfort. *PhD Thesis*, University of Southampton.

CR12349., 1996. Mechanical vibration – Guide to the health effects of vibration on the human body. *CEN Report*

Darlington, P., and Tyler, R, G., 2004. Measurement uncertainty in human exposure to vibration. *39th Meeting of the UK Group on Human Response to Vibration*. 15th – 17th September, RMS Vibration Test Laboratory, Ludlow.

Der G and Deary IJ., 2006. Age and sex differences in reaction time in adulthood: Results from the United Kingdom Health and Lifestyle Survey. *Psychology and Aging*, 21(1), 62-73.

Donati, P., 1998. A procedure for developing a vibration test method for specific categories of industrial trucks. *Journal of Sound and Vibration*, 215(4), 947-957.

Donati, P., 2002. Survey of technical preventative measures to reduce whole-body vibration effects when designing mobile machinery. *Journal of Sound and Vibration*, 253(1), 169-183.

Eger T, Stevenson J, Boileau PE and Smets M., 2006. Whole-body vibration exposure and driver posture evaluation during the operation of LHD vehicles in underground mining, 1st American Conference on Human Vibration, 5 - 7 June 2006, NIOSH.

European Commission (1998) Council Directive 98/37/EC on the approximation of the laws of the Member States relating to machinery. Official Journal of the European Communities L207.

European Committee for Standardization., 2002. Safety of industrial trucks: test methods for measuring vibration. BS EN13059. Brussels.

European Committee for Standardization., 2003. Mechanical vibration: testing of mobile machinery in order to determine the vibration emission value. EN1032. Brussels.

European Committee for Standardization., 2003. Mechanical vibration - Measurement and evaluation of occupational exposure to whole-body vibration with reference to health - Practical guidance. PrEN14253.

European Council., 2002. Directive 2002/44/EC of the European Parliament and Of The Council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (Vibration). Official Journal of the European Communities, (EN) 177, 13-19.

Fairlamb, P., and Haward, B., 2005. An evaluation of the impact and effect of the Physical Agents (Vibration) Directive on surface coal mining operations in the UK. *40th United Kingdom Conference on Human Response to Vibration*, HSE, Liverpool, 13-15 September 2005.

Fairley, T.E., and Griffin, M.J. 1989. The apparent mass of the seated human body: vertical vibration. *Journal of Biomechanics* 22 (2) 81-94.

Frey-Law, L., Rahmatalla, S., Wilder, D., Grosland, N., Xia, T., Hunstad, T., Contratto, M. and Kopp, G., 2006. Arm and shoulder muscle activity are greater with steering wheel vs. seat mounted controls, R. DONG, ed. In: *First American Conference on Human Vibration,* 5-7 June, 2006, NIOSH pp132.

Funakoshi,M., Taoda, K., Tsujimura, H. and Nishiyama, K., 2004. Measurement of whole-body vibration in taxi drivers. *J.Occup.Health.*, 46(2), pp. 119-124.

Gould, K.S., 2002. An assessment of whole-body vibration exposure in excavators and an evaluation of the validity of self-reported posture ratings. Master of Science in Ergonomics edn. Loughborough: Loughborough University.

Griffin, M.J. 1990. *Handbook of Human Vibration*. First Edition, (Academic Press, London).

Griffin, M.J., 1998a. Comparison of standardized methods for predicting hazards of whole-body vibration and repeated shocks. *Journal of Sound and Vibration*, 215(4), 883-914.

Griffin, M.J., 1998b. Fundamentals of human responses to vibration. In: F.J. FAHY AND WALKER, ed, Fundamentals of noise and vibration. London: E & FN Spon, pp. 179-205.

Griffin, M.J., 2004. Minimum health and safety requirements for workers exposed to hand-transmitted vibration and whole-body vibration in the European Union; a review. *Occupational and environmental medicine*, 61(5), 387-397.

Griffin, M.J., 2006. Health effects of vibration – The known and the unknown. 1st *American Conference on Human Vibration*, NIOSH, Morgantown, USA.

Griffin, M.J., and Whitham, E.M. 1978. Individual variability and its effect on subjective and biodynamic response to whole-body vibration. *Journal of Sound and Vibration*, 54. 107-116.

Griffin, M.J., Whitham, E.M., and Parsons, K.C. 1982a. Vibration and comfort I. Translational seat vibration. *Ergonomics*, 25 (7), 603-630.

Griffin, M.J., Whitham, E.M., and Parsons, K.C. 1982b. Vibration and comfort IV. Application of experimental results. *Ergonomics*, 25 (8), 721-739.

Hancock P and Warm J., 1989. A dynamic model of stress and sustained attention. *Human Factors*, 31, 519 – 537.

Harrison DD, Harrison SO, Croft AC, Harrison DE and Troyanovich SJ., 1999. Sitting biomechanics Part I: Review of the Literature. Journal of Manipulative and Physiological Therapeutics, 22(9), 594-609.

Harrison DD, Harrison SO, Croft AC, Harrison DE and Troyanovich SJ., 2000. Sitting biomechanics, Part II: Optimal car driver's seat and optimal driver's spinal model. *Journal of Manipulative and Physiological Therapeutics*, 23(1), 37-47.

Hart SG and Staveland LE., 1988. Development of a NASA-TLX (Task Load Index): Results of empirical and theoretical research. In: Hancock, PA and Meshkati, N. eds, *Human Mental Workload.* Amsterdam, Holland: Elsevier Science, 139-183.

Hartman, E., Oude Vrielink, H.H.E., Metz, J.H.M., and Huirne, R.B.M., 2005. Exposure to physical risk factors in Dutch agriculture: Effect on sick leave due to musculoskeletal disorders. *International Journal of Industrial Ergonomics,* 35(11), 1031-1045.

Hassan, R. and McManus, K., 2003. Assessment of interaction between road roughness and heavy vehicles. Transportation Research Record, Conference Title: Eighth International Conference on Low-Volume Roads (1819), 236-243.

Hinz, B., Seidel, H., Menzel, G. and Bluthner, R. 2002. Effects related to random whole-body vibration and posture on a suspended seat with and without backrest. *Journal of Sound and Vibration,* 253(1), pp. 265-282.

HMSO., 2005. Control of Vibration at Work Regulations 2005, Statutory Instrument 2005 No.1093, ISBN 0110727673.

Hockey, G.R.J., 1997. Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework. *Biological Psychology,* 45, 73-93.

Holmes, J., and Paddan, G.S., 2004. Effect of different types of tyres on vibration in a forklift truck. *39th UK Conference on Human Response to Vibration*, RMS Vibration Test Laboratory, Ludlow, Shropshire, 15 – 17th September.

Howarth, H. 2003. A laboratory study of the effects of posture on head movement during low frequency fore-and-aft oscillation. *38th United Kingdom Conference on*

Human Response to Vibration, Institute of Naval Medicine, Gosport. 17th – 19th September.

Hoy, J., Mubarak, N., Nelson, S., Sweerts de Landas, M., Magnusson M., Okunribido. O., Pope, M. 2005. Whole body vibration and posture as risk factors for low back pain among forklift truck drivers, *Journal of Sound and Vibration*, 284, 933-946.

HSE, 2003. The Physical Agents (Vibration) Directive: Exposure action and limit values for whole-body vibration: An important choice. http://www.hse.gov.uk/vibration/

Hulshof, C.T.J., Van Der Laan, G., Braam, I.T.J., and Verbeek, J.H.A.M., 2002. The fate of Mrs Robinson: Criteria for recognition of whole-body vibration injury as an occupational disease. *Journal of Sound and Vibration*, 253(1), pp. 185-194.

International Organization for Standardization 2631., 1974. Guide for the evaluation of human exposure to whole-body vibration. ISO2631.

International Organization for Standardization 2631., 1978. Guide for the evaluation of human exposure to whole-body vibration. ISO2631.

International Organization for Standardization 2631-1., 1985. Evaulation of human exposure to whole-body vibration - Part 1 general requirements. ISO2631-1.

International Organization for Standardization 2631-1., 1997. Mechanical vibration and shock - Evaulation of human exposure to whole-body vibration - Part 1 general requirements. ISO2631-1.

International Organization for Standardization 5982., 2001. Mechanical vibration and shock – range of idealized values to characterize seated-body biodynamic response under vertical vibration. ISO5982.

International Organization for Standardization 8041., 1990. Human response to vibration. Measuring instrumentation. ISO8041.

International Organization for Standardization 5347-5, 1993. Calibration of vibration and shock pick-ups. ISO5347-5.

International Organization for Standardization 8041, 2003. Human response to vibration - Measuring instrumentation. ISO8041

International Organization for Standardization 8041, 2005. Human response to vibration - Measuring instrumentation. ISO8041.

International Organization for Standardization TR25398. 2006. Earth-moving machinery – Guidelines for assessment of exposure to whole-body vibration of ride-on machines – Use of harmonized data measured by international institutes, organizations and manufacturers. ISO/TR 25398.

International Organization for Standardization 13090-1., 1998. Mechanical vibration and shock – Guidance on safety aspects of tests and experiments with people. Part 1: Exposure to whole-body mechanical vibration and repeated shock. ISO13090-1.

International Organization for Standardization 6165., 2002. Earth-moving machinery. Basic types. Vocabulary. ISO6165.

International Organization for Standardization 10326-1.,1992. Mechanical vibration – Laboratory method for evaluating vehicle seat vibration. ISO10326-1.

Ishitake T., Miyazaki, Y., Noguchi, R., Ando, H. and Matoba, T., 2002. Evaluation of frequency weighting (ISO 2631-1) for acute effects of whole-body vibration on gastric motility. Journal of Sound and Vibration, 253(1), 31-36.

Jiao,K., Li, Z., Chen, M., Wang, C. and Qi, S., 2004. Effect of different vibration frequencies on heart rate variability and driving fatigue in healthy drivers. *International archives of occupational and environmental health,* 77(3), 205-212.

Justinova, L., 2005. Risk factors associated with low back pain among taxi drivers. *40th United Kingdom Conference on Human Responses to Vibration,* held at Liverpool, England, 13-15 September.

Kitazaki, S., and Griffin, M.J. 1998. Resonance behaviour of the seated human body and effects of posture, *Journal of Biomechanics,* 31, 143-149.

270

Kittusamy, N.K., 2000. Characterization of ergonomic exposures among operators of heavy earthmoving construction equipment. PhD Thesis. University of Massachusetts Lowell.

Kittusamy, N.K., and Buchholz, B. 2001. Ergonomics evaluation of excavating operations: A pilot study, *Applied Occupational and Environmental Hygiene*, 16(7), 723-726

Kittusamy, N.K., and Buchholz, B. 2004. Whole-body vibration and postural stress among operators of construction equipment: a literature review, *Journal of Safety Research*, 35(3), 255-261

Landauer AA, Armstrong S and Digwood J. 1980. Sex difference in choice reaction time, *British Journal of Psychology*, 71, 551-5.

Landauer AA., 1981. Sex differences in decision and movement time. Perceptual and *Motor Skills*. 52, 90.

Lewis CH and Griffin MJ., 1978. A review of the effects of vibration on visual acuity and continuous manual control. II: Continuous manual control. *Journal of Sound and Vibration.* 56(3), 415-457.

Lewis, C.H. AND Griffin, M. J., 1998. A comparison of evaluations and assessments obtained using alternative standards for predicting the hazards of whole-body vibration and repeated shocks. *Journal of Sound and Vibration*, 215(4), 915-926.

Ljungberg J, Neely, G and Lundström R., 2004. Cognitive performance and subjective experience during combined exposures to whole-body vibration and noise. *International archives of occupational and environmental health*, 77(3), 217-221.

Maeda, S., and Morioka, M., 1998. Measurement of whole-body vibration exposure from garbage trucks. *Journal of Sound and Vibration*, 215(4), 959-964

Magnusson ML and Pope MH., 1998. A review of the biomechanics and epidemiology of working postures (it isn't always vibration which is to blame!). *Journal of Sound and Vibration*, 215(4), 965-976.

Mansfield, N. J. And Atkinson, A., 2003. Comparison of full working shift measures of whole-body vibration with short 'representative' samples for a rigid dump truck, loading shovel and a bus. *11th Japan Group Meeting on Human Response to Vibration*, 2003, 1-15.

Mansfield, N.,J. and Griffin, M.J., 2000. Difference thresholds for automobile seat vibration. *Applied Ergonomics*, 31, 255-261.

Mansfield, N.J. 2005. *Human Response to Vibration,* First Edition, (CRC Press, Boca Raton).

Mansfield, N.J. 2005. Impedance methods (apparent mass, driving point mechanical impedance and absorbed power) for assessment of the biomechanical response of the seated person to whole-body vibration. *Industrial Health* , 43 (3), 378-389.

Mansfield, N.J., 2003. The European Physical Agents (Vibration) Directive: Can the demolition and quarrying industries comply? *11th Japan Group Meeting on Human Response to Vibration*, July 23-25, 2003.

Mansfield, N.J., and Griffin, M.J. 2000. Non-linearities in apparent mass and transmissibility during exposure to whole-body vibration. *Journal of Biomechanics* 33 (8), 933-941.

Mansfield, N.J., and Griffin, M.J. 2002. Effects of posture and vibration magnitude on apparent mass and pelvis rotation during exposure to whole-body vertical vibration. *Journal of Sound and Vibration*, 253, 93-107.

Mansfield, N.J., and Maeda, S. 2005. Effect of backrest and torso twist on the apparent mass of the seated body exposed to vertical vibration. *Industrial Health*, 43 (3), 413-420.

Mansfield, N.J., and Maeda, S., 2005. Comparison of the apparent mass of the seated human measured using random and sinusoidal vibration. *Industrial Health*, 43, 233-240.

Mansfield, N.J., and Marshall, J.M., 2001. Symptoms of musculoskeletal disorders in stage rally drivers and co-drivers. *British journal of sports medicine,* 35, 314-320.

Mansfield, N.J., Atkinson, S. and Payne, G., 2003. Effect of increasing measurement duration on 'Accuracy' of whole-body vibration field measurements. *38th United Kingdom Conference on Human Response to Vibration*, 2003, 1-11.

Marjanen, Y. 2006. Long term measurements and analysis of day-to-day variability on whole body vibration exposure levels in work environments, July 2-6 2006

Matsumoto, Y., and Griffin, M.J. 1998. Movement of the upper-body of seated subjects exposed to vertical whole-body vibration at the principal resonance frequency, *Journal of Sound and Vibration,* 215 (4), 743-762.

McLeod, R.W., and Griffin, M.J. 1989. Review of the effects of translational whole-body vibration on continuous manual control performance, *Journal of Sound and Vibration,* 133(1), 55-115

Messenger, A.J., and Griffin, M.J. 1989. Effects of anthropometric and postural variables on the transmission of whole-body vertical vibration from seat-to-head. *Institute of Sound and Vibration Research Technical Report,* 172. University of Southampton.

National Institute for Working Life., 2003, & 2004. Whole-body vibration emission data. Internet database; *http://vibration.arbetslivsinstitutet.se/eng/wbvhome.lasso.* NIWL, Umea.

Notini, L., Mansfield, N.J., and Newell, G.S., 2006. An assessment of the contribution of earth-moving machine WBV components below 1 Hz to ISO 2631-1 and ISO2631-5 metrics. *41st UK Conference on Human Response to Vibration*, Farnham, 20th to 22nd September 2006.

Noyes JM and Bruneau DPJ. 2007. A self-analysis of the NASA-TLX workload measure. *Ergonomics,* 50(4), 514-519.

Okunribido,O.O., Magnusson, M. and Pope, M., 2005. Delivery drivers and low-back pain: A study of the exposures to posture demands, manual materials handling and whole-body vibration. *International Journal of Industrial Ergonomics.*

Paddan GS and Griffin MJ. 1996. Effect of arm support on force at a hand-held joystick during exposure to vertical seat vibration. *Proceedings of InterNoise* 1996, 1731-1735.

Paddan GS. 1994. Effect of arm and body posture on the transmission of fore-and-aft seat vibration to the head. *United Kingdom Informal Group Meeting on Human Response to Vibration, Institute of Naval Medicine*, Alverstoke, Gosport, 19-21 September 1994.

Paddan, G. 2000. Effect of measurement period on the analysis of whole-body vibration. *35th United Kingdom Meeting on Human Response to Vibration*, ISVR, University of Southampton, 13–15 September, England.

Paddan, G. S. and Griffin, M. J., 2002. Evaluation of whole-body vibration in vehicles. *Journal of Sound and Vibration*, 253(1), 195-213.

Paddan, G. S., Haward, B. M., Griffin, M, J. and Palmer, K. T., 1999. Whole-body vibration: *Evaluation of some common sources of exposure in Great Britain. Southampton.* Health and Safety Executive.

Paddan, G., S. and Griffin, M. J., 2001. Use of seating to control exposures to whole-body vibration. Southampton. *Health and Safety Executive.*

Paddan, G.S., 2003. Effect of road surface on vibration in vehicles, *38th United Kingdom Conference on Human Response to Vibration*, 17-19 September 2003, 341.

Paddan, G.S., and Griffin, M.J. 1988a. The transmission of translational seat vibration to the head, I: vertical seat vibration. *Journal of Biomechanics*, 21 (3), 191-198.

Paddan, G.S., and Griffin, M.J. 1988b. The transmission of translational seat vibration to the head, II: horizontal seat vibration. *Journal of Biomechanics*, 21 (3), 199-206.

Paddan, G.S., and Griffin, M.J. 1993. Transmission of vibration through the human body to the head: a summary of experimental data. *ISVR Technical Report 218*, University of Southampton.

Paddan, G.S., and Griffin, M.J. 1994. Individual variability in the transmission of vertical vibration from seat to head. *Institute of Sound and Vibration Research Technical Report, 236.* University of Southampton.

Paddan, G.S., and Griffin, M.J. 1994. Transmission of roll and pitch seat vibration to the head, *Ergonomics,* 37 (9), 1513-1531.

Paddan, G.S., and Griffin, M.J. 1996. Transmission of mechanical vibration through the human body to the head. *ISVR Technical Report 260,* Institute of Sound and Vibration Research, University of Southampton

Paddan, G.S., and Griffin, M.J. 1998. A review of the transmission of translational seat vibration to the head, *Journal of Sound and Vibration,* 215 (4), 863-882.

Palmer, K.T., Coggon, D., Bednall, H.E, Pannett, B., Griffin, M.J., and Haward, B.M. 1999. Whole-body vibration: occupational exposures and their health effects in Great Britain, Health and Safety Executive, *Contract Research Report,* 233, Sudbury, U.K. HSE Books.

Parsons, K.C., and Griffin, M.J. 1982. Vibration and comfort II. Rotational seat vibration. *Ergonomics,* 25 (7), 631-644.

Parsons, K.C., and Griffin, M.J. 1982. Vibration and comfort III. Translational vibration of the feet and back. *Ergonomics,* 25 (8), 705-719.

Pinto I, Stacchini N. 2005. Uncertainty in the evaluation of occupational exposure to whole-body vibration. *3rd International Conference on Whole-Body Vibration injuries,* Nancy, France, 7-9 June 2005.

Rakheja, S., Haru, J., and Boileau, P.E. 2002. Seated occupant apparent mass characteristics under automotive postures and vertical vibration. *Journal of Sound and Vibraiton,* 253, 57-75.

Rehn, B., 2004. Musculoskeletal disorders and whole-body vibration exposure among professional drivers of all-terrain vehicles, Doctoral Thesis, *Umea University Library Press.*

Rehn, B., Bergdahl, I.A., Ahlgren, C., From, C., Jarvholm, B., Lundstrom, R., Nilsson, T. and Sundelin, G., 2002. Musculoskeletal Symptoms Among Drivers of All-Terrain Vehicles. *Journal of Sound and Vibration*, 253(1), 21-29.

Rehn, B., Lundstrom, R., Nilsson, L., Liljelind, I. and Jarvholm, B. 2005. Variation in exposure to whole-body vibration for operators of forwarder vehicles--aspects on measurement strategies and prevention. *International Journal of Industrial Ergonomics*, 35(9), 831-842.

Robinson, D., Martin, S.H., Roddan, G., Gibbs, G.H. and Dutnall, J., 1997. The Application of Vibration Assessment in Mining Vehicles to Return-to-Work Protocols. *Journal of Low Frequency Noise, Vibration and Active Control*, 16(2), 73-79.

Russon C.R., Lauretani, F., Bandinelli, S., Bartali, B., Cavazzini, C., Guralnik, J.M. and Ferrucci, L., 2003. High-frequency vibration training increases muscle power in postmenopausal women. *Archives of Physical Medicine and Rehabilitation*, 84(12), 1854-1857.

Sandover, J., 1997. High acceleration events in industrial exposure to whole-body vibration. *Health and Safety Executive Report, 134.*

Sandover,J., 1998. The fatigue approach to vibration and health: is it a practical and viable way of predicting the effects on people? *Journal of Sound and Vibration*, 215(4), 699-721.

Scarlett, A. J., and Stayner, R. M., 2005a. Whole-body vibration measurements in construction, mining and quarrying. *40th United Kingdom Conference on Human Response to Vibration*, HSE, Liverpool, 13-15 September 2005.

Scarlett, A. J., and Stayner, R.M., 2005b. Whole-body vibration on construction, mining and quarrying machines: Evaluation of emission and estimated exposure levels. *HSE Research Report 400.*

Schwarze, S., Notbohm, G., Dupuis, H., and Hartung, E., 1998. Dose-respose relationships between whole-body vibration and lumbar disk disease - A field study on 388 drivers of different vehicles. *Journal of Sound and Vibration*, 215(4), 613-628.

Sherwin, L.M., Owende, P.M.O., Kanali, C.L., Lyons, J. and Ward, S.M., 2004. Influence of tyre inflation pressure on whole-body vibrations transmitted to the operator in a cut-to-length timber harvester. *Applied Ergonomics*, 35, 253-261.

Smith SD, Smith JA and Newman RJ. Head and helmet biodynamics and tracking performance during exposure to whole-body vibration. *39th United Kingdom Conference on Human Response to Vibration*, 15-17 September 2004, Ludlow.

Sorainen, E., Vahanikkila, A., Taattola, K., and Rytkonen, E., 2006. Vibration of agricultural tractors. *Proceedings of Internoise*, Honolulu, Hawaii, 3-6 December 2006.

Stayner., 2005. Personal Communication, *40th United Kingdom Conference on Human Responses to Vibration*, held at Liverpool, England, 13-15 September.

Stayner, R., 2001. Whole-body vibration and shock: a literature review: extension of a study of over travel of seat suspensions. *Health and Safety Executive, Contract Research Report* 333. Sudbury, U.K.: HSE Books.

Stayner, R.M. and Scarlett, A.J., 2003. Vibration exposure on agricultural machines case of ATVS ("Quad Bikes"), *38th United Kingdom Conference on Human Response to Vibration.* 17-19 September 2003, 349.

Teschke, K., Nicol, A.M., Davies, H., and Ju, S., 1999. Whole-body vibration and back disorders among motor vehicle drivers and heavy equipment operators: A review of the scientific evidence. *Workers' Compensation Board of British Columbia Report*, Vancouver, BC, Canada:

TESTOPS, 2000. Testing Suspension Seats for End-stop Impacts. Project no. SMT4 CT97 2161. EC Standards Measurements and Testing Programme.

Thuresson, M. 2005, On neck load among helicopter pilots – Effects of head-worn equipment, whole-body vibration and neck position, *Thesis*, Neurotec Department, Division of Physiotherapy, Karolinska Institutet, Stockholm, Sweden.

Tian LG, Gang WL, Ping HJ, Li LC and Fang LY. 1996. Investigation of eyestrain and working capacity for female crane operators. International Journal of Industrial Ergonomics, 18(2-3), 221-224.

Torle G. 1965. Tracking performance under random acceleration: effects of control dynamics. *Ergonomics*. 1965, 8(4), 481-486.

Toward, M.J.R., Gunston, T.P., and Griffin, M.G., 2005. Evaluation of whole-body vibration exposure in British Industry. HSE Books, Report 377.

Vercruyssen, M and Simonton, K. Effects of posture on mental performance: we think faster on our feet than our seat. In: LUEDER, R. and NORO, K., eds, 1994. *Hard facts about soft machines - The ergonomics of seating.* London: Taylor & Francis Ltd. 119-133.

VIBRISKS., 2007. Risks of occupational vibration exposure. VIBRISKS Final Technical Report. European Commission, QLK4-2002-02650.

Village, J., Morrison, J.B., and Leong, D.K., 1989. Whole-body vibration in underground load-haul-dump vehicles. *Ergonomics,* 32(10), 1167-1183.

Von Gierke, H. E., McCloskey K. and Albery, W.B., 1991. Military performance in sustained acceleration and vibration environments. Chapter 18 in Handbook of Military Psychology. Ed: Gal R. and Manglesdorff, A. D. John Whiley and Sons, Chichester, UK.

Wang, W., Rakheja, S. and Boileau, P. 2004. Effects of sitting postures on biodynamic response of seated occupants under vertical vibration. *International Journal of Industrial Ergonomics,* 34(4), pp. 289-306.

White, A.A., and Panjabi, M.M. 1990. *Clinical Biomechanics of the Spine,* Second Edition (Lippincott-Raven, Philadelphia).

Wikström, B., 1994. Health effects of long-term occupational exposure to whole-body vibration: a review. *International Journal of Industrial Ergonomics,* 14, 273-292.

Wikström, B., 1993. Effects from twisted postures and whole-body vibration during driving. *International Journal of Industrial Ergonomics,* 12(1-2), pp. 61-75.

Wilder, D., Rahmatalla, S., Contratto, M., Xia, T., Frey-Law, L., Kopp, G. and Grosland, N. 2006. Head-trunk motion increase with arm-rest controls. ed. In: *First American Conference on Human Vibration,* June 5-7, 2006, NIOSH pp66.

Woodman, P.D., and Griffin, M.J. 1996, Six axes of head acceleration during ambulation, *Proceedings of Inter-noise,* Liverpool, UK, 1719-1724

Yerkes RM and Dodson JD. 1908. The relation of strength of stimulus to rapidity of habit formation. Journal of Comparative and Neurological Psychology, 18, 459-482.

Zimmerman, C.L., and Cook, T.M. 1997. Effects of vibration frequency and postural changes on human responses to seated whole-body vibration exposure. *International Archives of Occupational and Environmental Health,* 69, 165-179.

Zimmerman, C.L., Cook, T.M., and Rosecrance, J.C., 1997. Operating Engineers: Work-related musculoskeletal disorders and the trade. *Applied Occupational and Environmental Hygiene,* 12, 670-680.

APPENDIX A1 –Summary results of whole-body vibration 'artefacts' experienced in a wheel loader, mini-excavator, car and office worker's chair
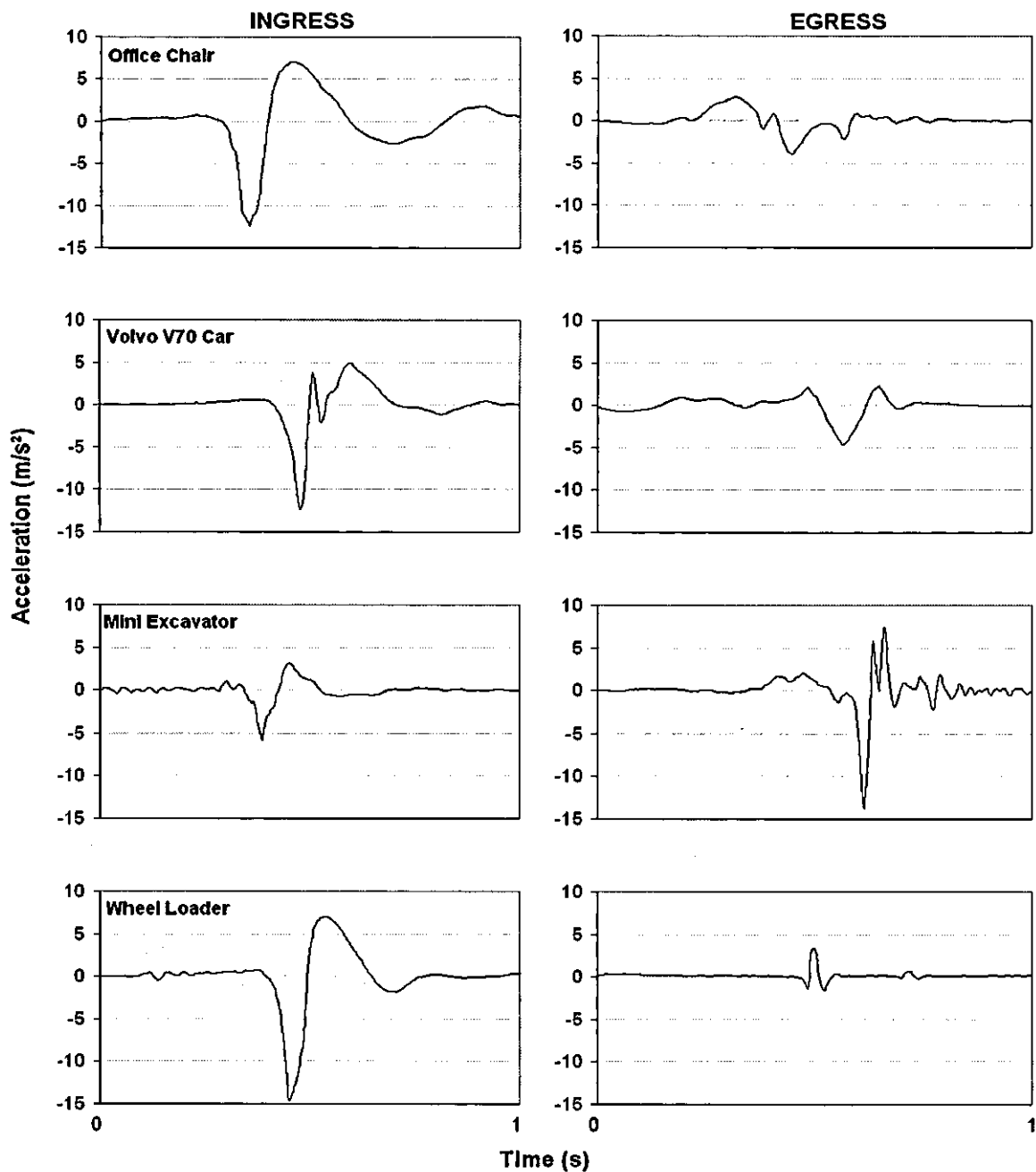
Typical acceleration waveforms for each seating condition during ingress and egres.

Individual VDV's across all subjects and seating conditions for the vertical axis

Condition	Subject	Weight (kg)	Vibration Dose Value m/s$^{1.75}$ (z-axis)											
			Ingress				Egress				Ingress & Egress			
			1	2	3	mean	1	2	3	mean	1	2	3	mean
Office Chair	1	68	3.4	5.3	5.4	4.7	1.3	1.8	2.1	1.7	3.4	5.3	5.4	4.7
	2	89	2.3	4.0	3.5	3.3	4.8	4.3	4.2	4.4	4.8	4.9	4.6	4.8
	3	57	1.9	2.5	1.9	2.1	2.6	1.8	2.3	2.2	2.8	2.7	2.5	2.7
	4	80	1.0	2.8	3.5	2.4	2.5	4.0	3.5	3.3	2.5	4.2	4.1	3.6
	5	89	2.6	1.5	2.3	2.1	5.5	4.8	4.4	4.9	5.6	4.8	4.5	5.0
Volvo V70 Car	1	68	5.5	4.8	5.8	5.4	1.8	2.1	2.0	2.0	5.5	4.8	5.8	5.4
	2	89	9.1	1.6	0.8	3.8	1.8	2.6	2.7	2.4	9.1	2.7	2.7	4.8
	3	57	6.4	8.0	6.1	6.8	0.8	1.2	1.0	1.0	6.4	8.0	6.1	6.8
	4	80	4.4	4.1	4.0	4.2	0.4	0.7	1.0	0.7	4.4	4.1	4.0	4.2
	5	89	4.7	3.1	2.2	3.3	0.5	1.4	0.6	0.8	4.7	3.1	2.2	3.3
Mini Excavator	1	76	2.4	2.4	2.6	2.5	3.9	4.5	4.5	4.3	4.0	4.6	4.6	4.4
	2	76	2.0	1.1	1.5	1.5	4.5	4.3	4.5	4.4	4.5	4.3	4.5	4.4
	3	76	3.7	3.9	3.3	3.6	5.0	4.8	4.1	4.6	5.4	5.3	4.5	5.1
	4	68	1.9	2.2	1.3	1.8	4.7	4.2	3.7	4.2	4.7	4.3	3.7	4.2
	5	74	4.5	3.3	3.0	3.6	4.1	4.0	4.5	4.2	5.1	4.4	4.7	4.7
Wheel Loader	1	100	4.6	4.7	4.5	4.6	6.8	6.5	7.1	6.8	7.2	6.9	7.4	7.2
	2	65	5.9	5.4	4.8	5.4	4.1	3.9	2.7	3.6	6.2	5.8	4.9	5.6
	3	66	5.9	4.9	5.2	5.3	2.5	2.4	2.4	2.4	6.0	5.0	5.2	5.4
	4	92	4.3	5.2	7.9	5.8	3.2	3.0	3.5	3.2	4.6	5.4	8.0	6.0
	5	92	5.1	5.1	4.7	5.0	3.6	3.8	3.0	3.5	5.4	5.4	4.9	5.2

Number of times subjects can get in and out of a seat before reaching the action value and limit value of the Physical Agents (Vibration) Directive

Seating condition	Mean VDV value (m/s$^{1.75}$)	Action value (9.1 m/s$^{1.75}$)	Limit value (21 m/s$^{1.75}$)
Office Chair	4.14	23 times a day	662 times a day
Volvo V70 car	4.90	12 times a day	337 times a day
Mini Excavator	4.57	16 times a day	446 times a day
Wheel Loader	5.87	6 times a day	164 times a day

Number of times subjects with the highest VDV's can get in and out of a seat before reaching the action value and limit value of the Physical Agents (Vibration) Directive

Seating	Maximum VDV value (m/s$^{1.75}$)	Action value (9.1 m/s$^{1.75}$)	Limit value (21 m/s$^{1.75}$)
Office Chair	4.95	11 times a day	324 times a day
Volvo V70 car	6.80	3 times a day	91 times a day
Mini Excavator	5.03	11 times a day	304 times a day
Wheel Loader	7.13	3 times a day	75 times a day

282

APPENDIX A2 – Pilot Study WBV data

Location & Date	Machine Type	Model	Year/Serial No	r.m.s. (m/s²)			Duration (minutes)	Operation
				x*1.4	y*1.4	z*1.0		
Desford	Mini Excavator	3025	2002	0.52	0.36	0.49	13	Excavating (bucket)
04/02/04	Mini Excavator	3025	2002	0.45	0.36	0.57	8	Roading (bucket)
	Mini Excavator	3025	2002	0.35	0.25	0.45	11	Hammering metal plate (HJ)
	Mini Excavator	3025	2002	0.34	0.35	0.57	11	Roading (HJ)
	Small Wheel Loader	924G		0.97	0.71	0.53	10	Stock piling (normal)
	Small Wheel Loader	924G		1.53	1.08	0.89	11	Stock piling (aggressive)
	Small Wheel Loader	924G		1.33	0.74	0.95	7	Roading (unladen)
	Small Wheel Loader	924G		1.32	0.74	0.90	7	Roading (laden)
	Skid Steer Loader	216	5F200277	1.78	0.98	1.22	16	Stock piling
	Skid Steer Loader	216	5F200277	0.73	0.53	1.17	7	Roading
Bruntingthorpe	Compact Wheel Loader	908		1.50	1.43	0.99	11	Stock piling
05/02/04	Compact Wheel Loader	908		1.75	2.32	1.15	10	Axle track/rough terrain (unladen)
	Compact Wheel Loader	908		2.22	1.93	1.22	10	Axle track/rough terrain (laden)
	Compact Wheel Loader	908		0.65	0.41	0.85	8	Roading concrete (unladen)
	Telehandler	580B	2003	0.47	0.22	0.74	7	Roading concrete (laden)
	Telehandler	580B	2003	0.48	0.21	0.83	6	Roading concrete (unladen)
	Telehandler	580B	2003	0.29	0.10	0.26	8	Static/Hydrostatic functions (unladen)
	Telehandler	580B	2003	0.38	0.10	0.26	4	Static/Hydrostatic functions (laden 1410kg)
	Telehandler	580B	2003	1.11	1.03	1.26	10	Axle track/rough terrain (laden 1410kg)
	Telehandler	580B	2003	1.16	1.04	1.29	10	Axle track/rough terrain (unladen)
	Compact Wheel Loader	906		1.86	2.26	1.16	11	Axle track/rough terrain (unladen)
	Compact Wheel Loader	906		2.22	1.93	1.22	10	Axle track/rough terrain (laden)
	Compact Wheel Loader	906		1.50	1.43	0.99	11	Stock piling
	Compact Wheel Loader	906		0.65	0.40	4.85	9	Roading concrete (unladen)

Location	Machine Type	Model	Year/Serial No	Vibration Dose Value (m/s$^{1.75}$)					Duration (minutes)	Operation
				X-axis	x*1.4	Y-axis	y*1.4	z*1.0		
Desford	Mini Excavator	3025	2002	3.88	5.43	2.41	3.37	7.06	13	Excavating (bucket)
04/02/2004	Mini Excavator	3025	2002	3.28	4.59	2.10	2.94	7.29	8	Roading (bucket)
	Mini Excavator	3025	2002	2.77	3.88	1.86	2.60	6.08	11	Hammering metal plate (HJ)
	Mini Excavator	3025	2002	2.00	2.80	1.95	2.73	6.09	11	Roading (HJ)
	Small Wheel Loader	924G		5.07	7.10	3.77	5.28	9.06	10	Stock piling (normal)
	Small Wheel Loader	924G		8.27	11.58	5.68	7.95	9.68	11	Stock piling (aggressive)
	Small Wheel Loader	924G		6.85	9.59	3.60	5.04	6.94	7	Roading (unladen)
	Small Wheel Loader	924G		6.08	8.51	3.53	4.94	7.11	7	Roading (laden)
	Skid Steer Loader	216	5F200277	10.42	14.59	6.15	8.61	11.07	16	Stock piling
	Skid Steer Loader	216	5F200277	4.01	5.61	3.06	4.28	10.11	7	Roading
Bruntingthorpe	Compact Wheel Loader	908		7.69	10.76	7.70	10.78	7.30	11	Stock piling
05/02/2004	Compact Wheel Loader	908		8.62	12.07	12.15	17.00	8.22	10	Axle track/rough terrain (unladen)
	Compact Wheel Loader	908		11.05	15.47	10.20	14.28	9.19	10	Axle track/rough terrain (laden)
	Compact Wheel Loader	908		3.78	5.29	2.42	3.39	5.79	8	Roading concrete (unladen)
	Telehandler	580B	2003	2.24	3.13	1.17	1.64	4.85	7	Roading concrete (laden)
	Telehandler	580B	2003	2.19	3.06	1.21	1.69	5.47	6	Roading concrete (unladen)
	Telehandler	580B	2003	2.12	2.97	0.75	1.05	2.85	8	Static/Hydrostatic functions (unladen)
	Telehandler	580B	2003	1.93	2.70	0.66	0.93	2.19	4	Static/Hydrostatic functions (laden 1410kg)
	Telehandler	580B	2003	5.84	8.18	5.57	7.80	10.98	10	Axle track/rough terrain (laden 1410kg)
	Telehandler	580B	2003	5.92	8.28	5.61	7.85	10.66	10	Axle track/rough terrain (unladen)
	Compact Wheel Loader	906		9.32	13.05	12.07	16.90	8.18	11	Axle track/rough terrain (unladen)
	Compact Wheel Loader	906		11.05	15.47	10.20	14.28	9.19	10	Axle track/rough terrain (laden)
	Compact Wheel Loader	906		7.69	10.76	7.70	10.78	7.30	11	Stock piling
	Compact Wheel Loader	906		3.17	4.44	2.12	2.96	4.85	9	Roading concrete (unladen)

APPENDIX A3 – Machine Operating Conditions

Machine Type (ID)	Model (Site)	Operation
Bulldozer (1)	D31E (6)	Moving superficials
Bulldozer (2)	D3G (6)	Moving superficials
Bulldozer (3)	D5N (1)	Moving granite
Bulldozer (4)	D6M (7)	Moving superficials, ground six F and top soil
Bulldozer (5)	D85EX (6)	Moving superficials
Bulldozer (6)	D7RII (6)	Moving clay and superficials
Bulldozer (7)	D8R (4)	Moving coal
Bulldozer (8)	D9R (4)	Moving coal
Tracked loader** (1)	953C (7)	Levelling six F demolition material / loading lorries
Tracked loader** (2)	953 (7)	Levelling demolition material / steep ground
Tracked loader (3)	953C (8)	Levelling superficial material
Tracked loader (4)	963B (8)	Levelling superficial material / loading lorries
Tracked loader (5)	963B (9)	Levelling top soil and stone / loading lorries
Tracked loader (6)	963B (10)	Levelling superficial material
Wheeled loader (1)	966F (2)	Loading granite into aggregate lorries
Wheeled loader** (2.1)	972G (4)	Loading coal into crusher
Wheeled loader** (2.2)	972G (4)	Loading coal into crusher
Wheeled loader*** (3)	972G (2)	Loading granite into aggregate lorries
Wheeled loader** (4)	970F (4)	Loading coal into train Loading coal into crusher
Wheeled loader (5)	L180D (1)	Loading granite into aggregate lorries
Wheeled loader (6.1)	980G (5)	Loading scrap metal into lorries
Wheeled loader (6.2)	980G (5)	Loading scrap metal into lorries
Wheeled loader (7)	980G (2)	Loading granite into aggregate lorries
Wheeled loader (8)****	988F (2)	Loading granite into aggregate lorries Pushing debris in after blasting (quarry face)

Machine Type (ID)	Model (Site)	Operation
Articulated Trucks (1)	TA30 (2)	Transporting granite
Articulated Trucks** (2)	735 (4)	Transporting coal
Articulated Trucks*** (3)	A40D (6)	Transporting superficials
		Transporting clay
Dump Trucks (1)	777B (2)	Transporting granite
Dump Trucks (2)	777D (2)	Transporting granite
Dump Trucks (3)	777B (4)	Transporting coal
Motor Grader** (1)	16H (4)	Smoothing muddy track
Motor Grader (2)	16H (6)	Smoothing clay and lime
Motor Grader (3)	14G (6)	Smoothing clay and lime
Excavator*** (1)	345BL (6)	Loading clay and superficials
Excavator (2)	70CL (6)	Loading and moving superficials
Excavator (3)	320CL (6)	Loading rocks into crusher
Excavator (4)	RH30 (6)	Loading coal
Roller (1)	BW216 (6)	Smoothing superficial
Roller (2)	BW213 (6)	Smoothing superficial
Roller (3)	BW219 (7)	Smoothing rubble and top soil
Skid Steer	753 (3)	Loading sand bags / travelling concrete
Material Handler	M325C (5)	Lifting scrap metal / travelling concrete and scrap
Compactor	825G(6)	Compacting superficial
Challenger	85D (10)	Compacting top soil and rock

APPENDIX A4 –Earthmoving machine images

WHEEL LOADER 988F	**DUMP TRUCK 777B**
ARTICULATED TRUCK TA30	**WHEEL LOADER 972G**
DUMP TRUCK 777D	**WHEEL LOADER 966F**
WHEEL LOADER 980G	**SKID STEER LOADER 753**
ARTICULATED TRUCK 735	**DUMP TRUCK 777B**

WHEEL LOADER 970F

BULLDOZERS D9R

MOTOR GRADER 16H

WHEEL LOADER 972G

BULLDOZER DR8

EXCAVATOR RH30

MATERIAL HANDLER M325C

WHEEL LOADER 980GI

WHEEL LOADER 980GII

BULLDOZER D7R

EXCAVATOR 345

ARTICULATED TRUCK A40D

MOTOR GRADER 16H

MOTOR GRADER 14G

BULLDOZER D85EX

BULLDOZER D31E

BULLDOZER D3G

ROLLER 216

EXCAVATOR 70CL

COMPACTOR 825G

ROLLER 213

EXCAVATOR 320CL

PEGSON ROCK CRUSHER

TRACK LOADER 953C

BULLDOZER D6M

ROLLER 219

TRACKED LOADER 953

TRACKED LOADER 963B

TRACKED LOADER 953C

TRACKED LOADER 963B

TRACKED LOADER 963B

CHALLENGER 85D

APPENDIX A5 –Power Spectra of the machines measured with Biometrics

Caveat: The measurements are from the seat accelerometer as there was no collection of floor data.
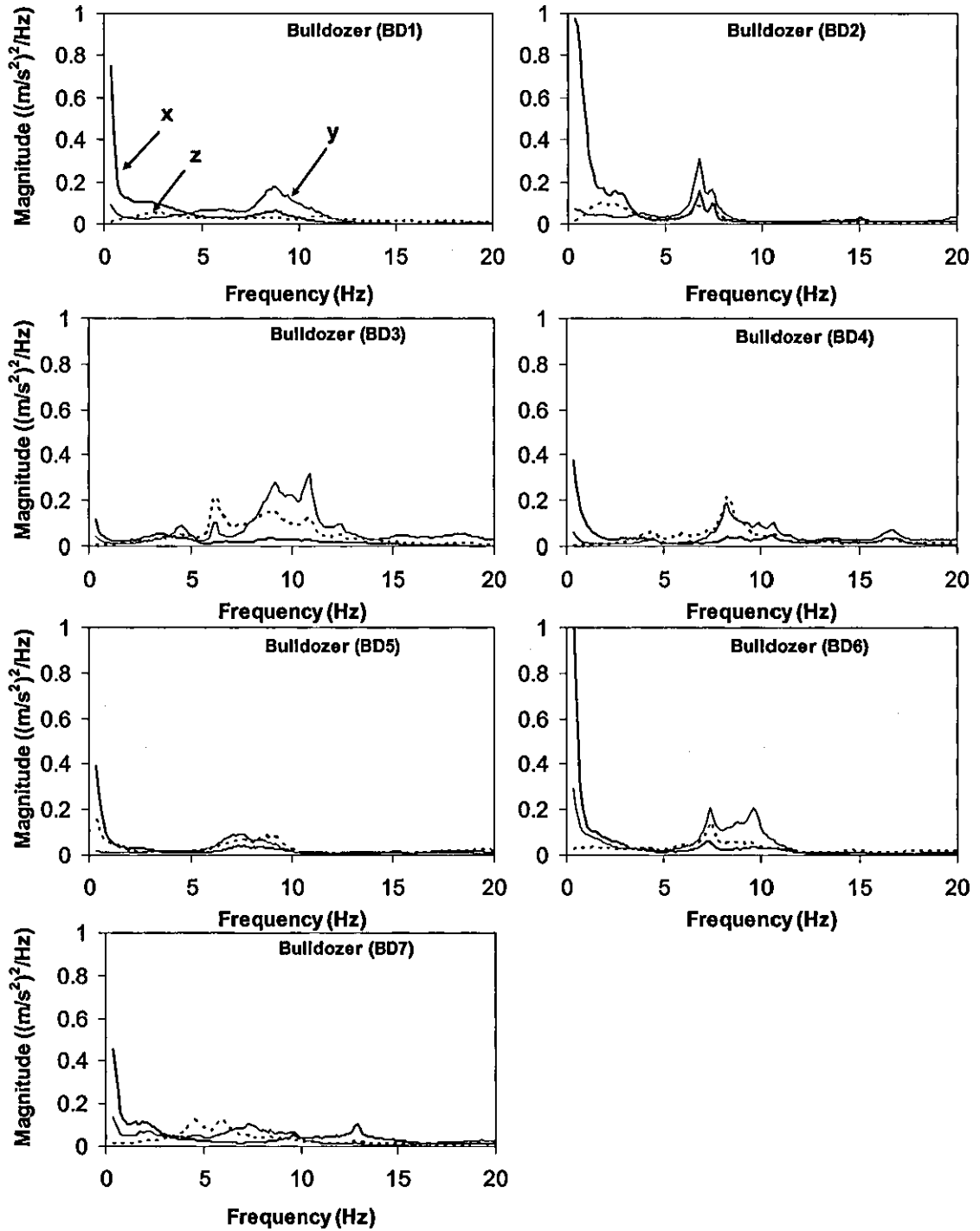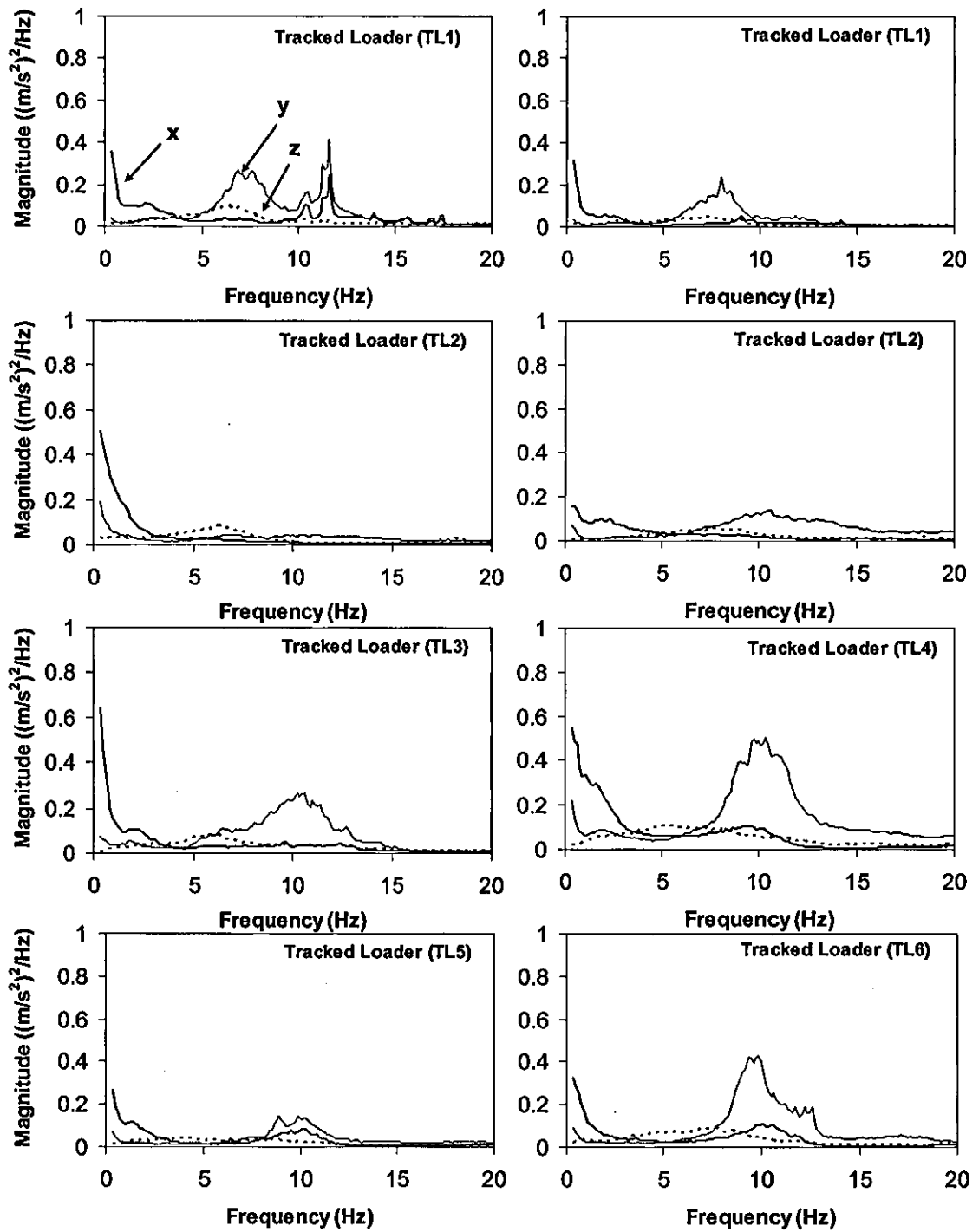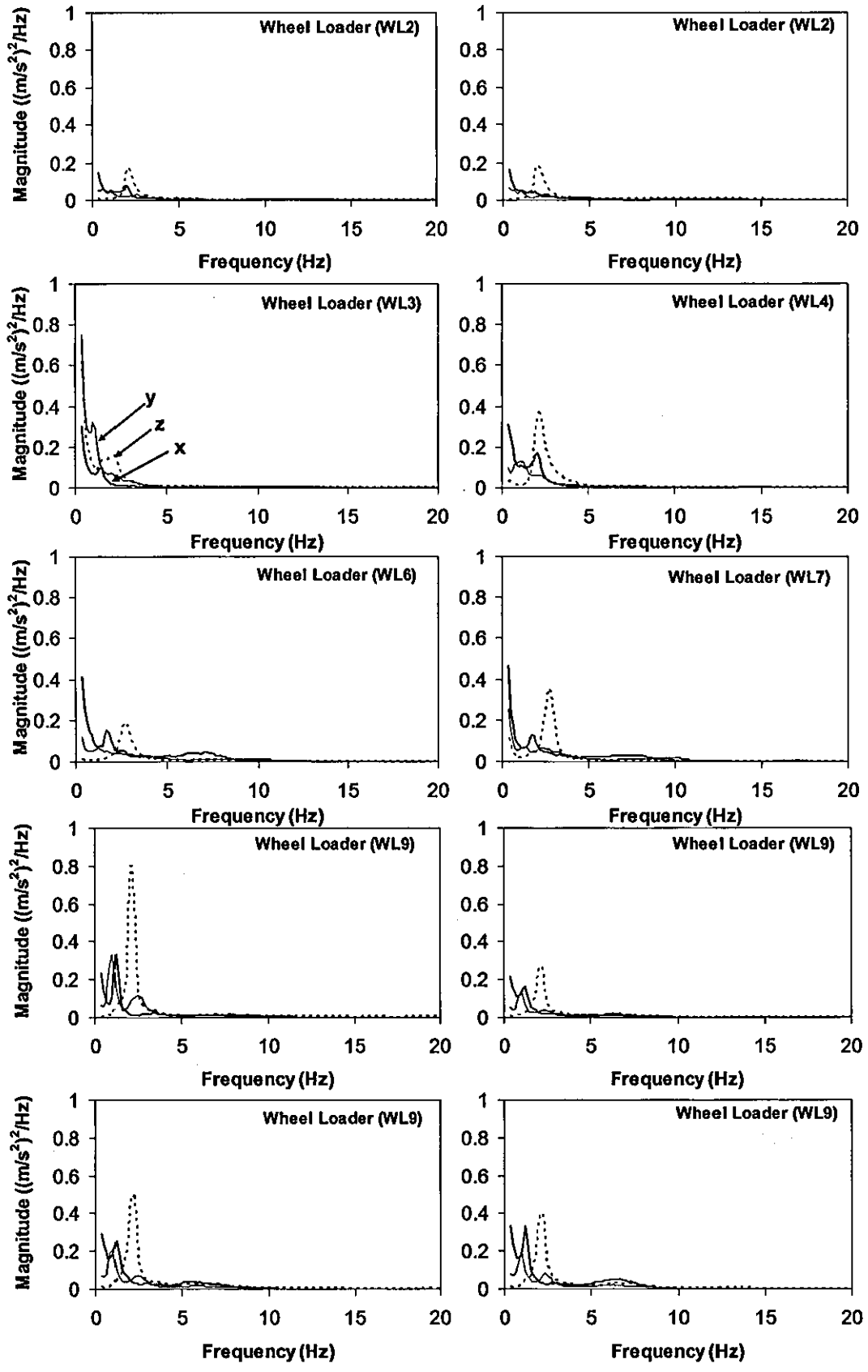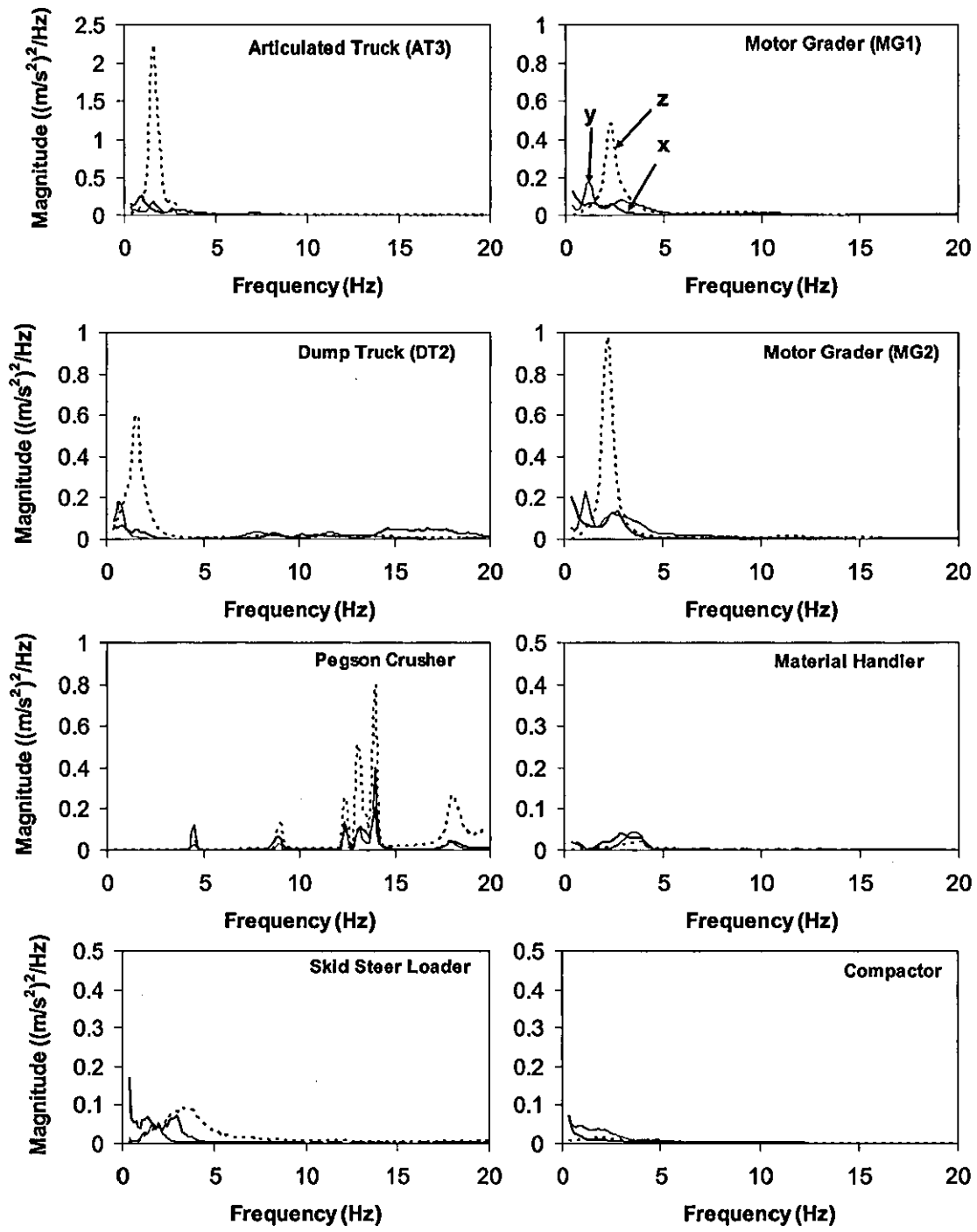
APPENDIX A6 – Vibration Dose Values for the earthmoving machines measured across a range of industries

| Vehicle	VDV *axis multiplier (m/s$^{1.75}$) x * 1.4	y * 1.4	z * 1.0	VDV duration	Worst axis 8-hour VDV	Time to EAV h:min (9.1 m/s$^{1.75}$)	Time to ELV (21 m/s$^{1.75}$)
BulldozerD5N	9.2	8.7	16.0	273	18.4	0:28	13:30
BulldozerD9R	15.0	10.9	13.3	123	21.0	0:16	7:58
BulldozerD8R	13.9	9.7	12.6	115	19.8	0:21	10:06
BulldozerD7R II	15.7	11.2	10.2	176	20.2	0:19	9:26
BulldozerD85EX	10.5	6.4	10.7	153	14.2	1:20	37:50
BulldozerD31E	18.8	8.7	9.2	97	28.0	0:05	2:32
BulldozerD3G	11.6	7.3	14.0	114	20.1	0:20	9:37
BulldozerD6 LGP	8.7	4.5	7.8	64	14.4	1:17	36:32
Tracked Loader953C	10.8	7.4	12.9	132	17.8	0:32	15:27
Tracked Loader953C	10.6	7.1	11.4	66	18.7	0:26	12:37
Tracked Loader953C	7.6	4.7	7.7	26	15.9	0:51	24:28
Tracked Loader953C	9.5	5.3	14.0	90	21.3	0:16	7:34
Tracked Loader963B	12.5	7.8	10.8	57	21.3	0:15	7:32
Tracked Loader953C	10.9	7.6	8.7	21	23.8	0:10	4:50
Tracked Loader963B	7.9	4.8	6.1	36	15.2	1:02	29:30
Tracked Loader963B	9.4	6.4	13.6	75	21.6	0:15	7:12
ExcavatorRH30	12.8	9.2	17.8	83	27.5	0:05	2:42
Excavator345BL	5.4	3.4	4.1	155	7.1	21:12	601:28
Excavator345BL	6.0	3.8	7.8	144	10.6	4:25	125:27
Excavator70CL	6.1	4.1	9.3	42	17.1	0:38	18:21
Excavator345BL	4.6	3.1	7.3	45	13.3	1:45	49:57
Excavator320CL	5.0	3.1	3.4	37	9.4	6:55	196:33
Wheel LoaderL180D	8.8	9.2	6.0	181	11.8	2:52	81:20
Wheel Loader988F	7.7	8.7	7.5	23	18.6	0:27	13:08
Wheel Loader988F	10.6	9.7	14.6	184	18.6	0:27	13:07
Wheel Loader972G	26.3	29.1	14.8	128	40.4	0:01	0:34
Wheel Loader972G	11.1	12.1	9.2	61	20.3	0:19	9:07
Wheel Loader988F	11.7	10.6	12.6	141	17.1	0:38	18:04
Wheel Loader980GII	11.4	12.5	7.9	59	21.0	0:16	7:56
Wheel Loader988F	10.2	9.0	8.3	99	15.2	1:01	29:05
Wheel Loader966F	12.1	12.9	9.2	195	16.2	0:47	22:40
Wheel Loader972G	8.7	20.9	10.3	152	27.8	0:05	2:36
Wheel Loader970F	10.1	8.1	8.1	126	14.1	1:23	39:33
Wheel Loader972G	6.4	5.3	3.8	85	9.9	5:38	160:10
Wheel Loader972G	5.5	3.5	2.5	31	10.8	3:59	113:03
Wheel Loader970F	7.5	5.9	10.2	134	14.1	1:23	39:30
Wheel Loader972G	5.5	4.3	5.9	38	11.1	3:35	101:38
Wheel Loader972G	6.2	3.8	2.5	35	11.9	2:46	78:47
Wheel Loader980G	11.2	9.9	5.4	120	15.8	0:52	24:43
Wheel Loader980G	9.9	10.1	5.6	45	18.2	0:29	14:07
Articulated TruckTA30	10.6	12.3	11.0	147	16.6	0:43	20:29
Articulated Truck735	9.3	11.4	7.0	109	16.5	0:44	20:50
Articulated Truck735	9.2	11.7	6.4	120	16.5	0:44	21:01
Articulated TruckA40D	12.5	13.5	12.3	150	18.0	0:31	14:50
Articulated TruckA40D	11.6	10.1	10.9	161	15.3	1:00	28:37
Articulated TruckA40D	8.3	10.2	9.4	60	17.2	0:37	17:40
Dump Truck777B	9.9	10.1	10.7	245	12.6	2:10	61:43
Dump Truck777D	7.3	7.4	7.9	199	9.8	5:50	165:36
Dump Truck777B	8.0	6.9	15.3	134	21.0	0:16	7:56
Motor Grader16H	8.8	9.6	8.9	114	13.8	1:30	42:40
Motor Grader16H	7.8	9.1	7.4	98	13.5	1:38	46:19
Motor Grader16H	8.5	8.0	7.4	143	11.6	3:03	86:50
Motor Grader14G	7.0	7.1	9.9	146	13.3	1:45	49:52
RollerBW216 DH-3	7.1	10.5	7.1	103	15.4	0:58	27:25
RollerBW213DH-3	4.5	4.9	7.6	74	12.1	2:32	71:53
Roller219 DH-3	3.1	2.8	4.7	48	8.3	11:24	323:42
Skid Steer Loader753	6.9	4.5	14.5	12	36.3	0:01	0:53
Material Handler325	8.3	5.7	7.3	101	12.2	2:28	70:19
Compactor825G	5.1	7.4	3.1	61	12.4	2:18	65:13
Challenger85D	15.1	9.5	18.6	27	38.2	0:01	0:44
Crusher	2.3	2.1	30.4	26	63.0	0:00	0:05

APPENDIX A7 –Example of variation at different points during a measurement of earthmoving machines
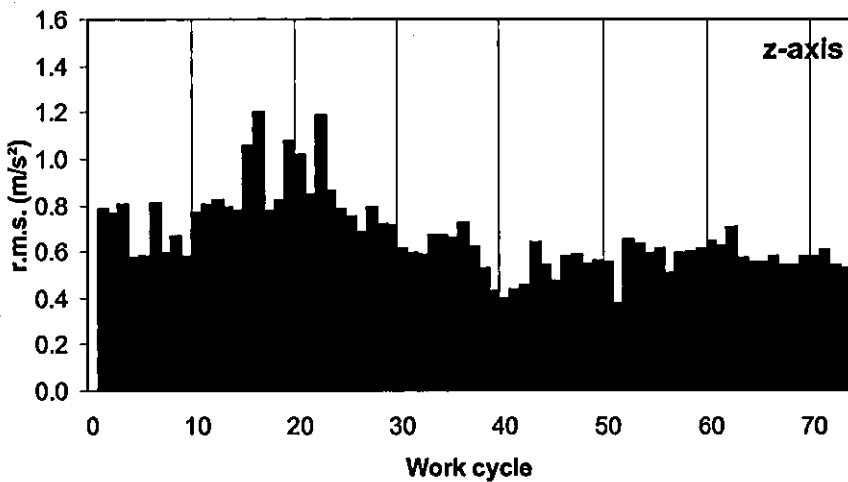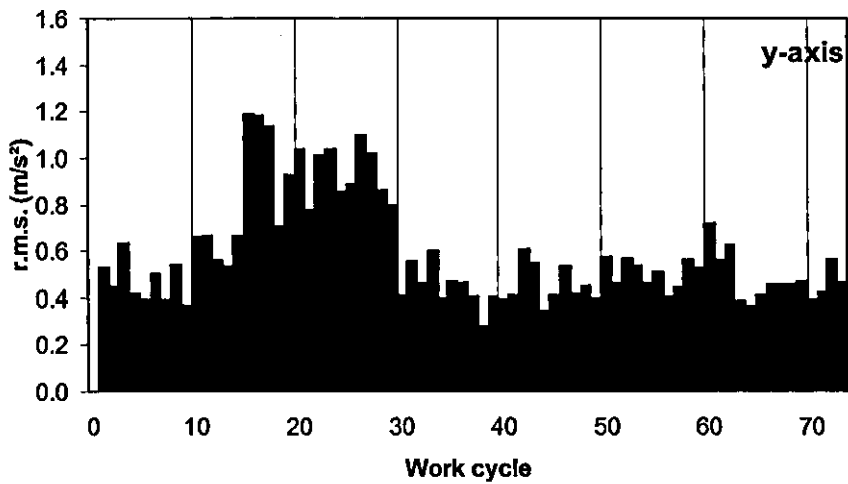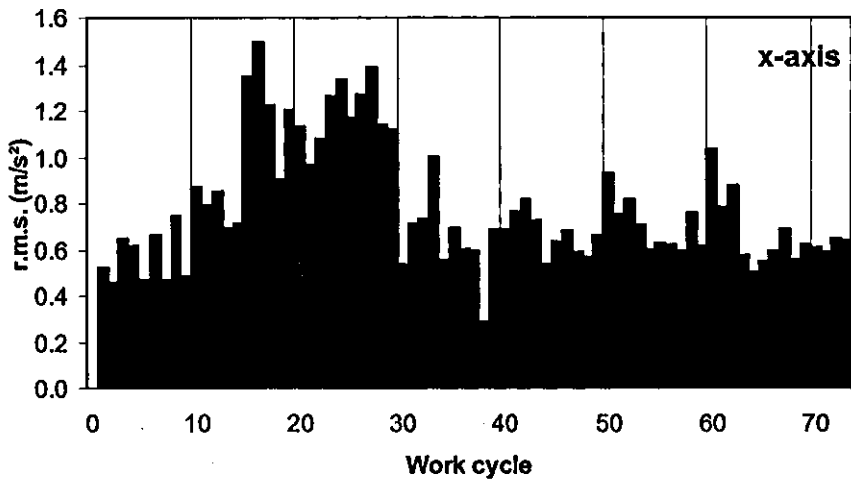
Frequency weighted r.m.s. magnitude of individual work cycles for
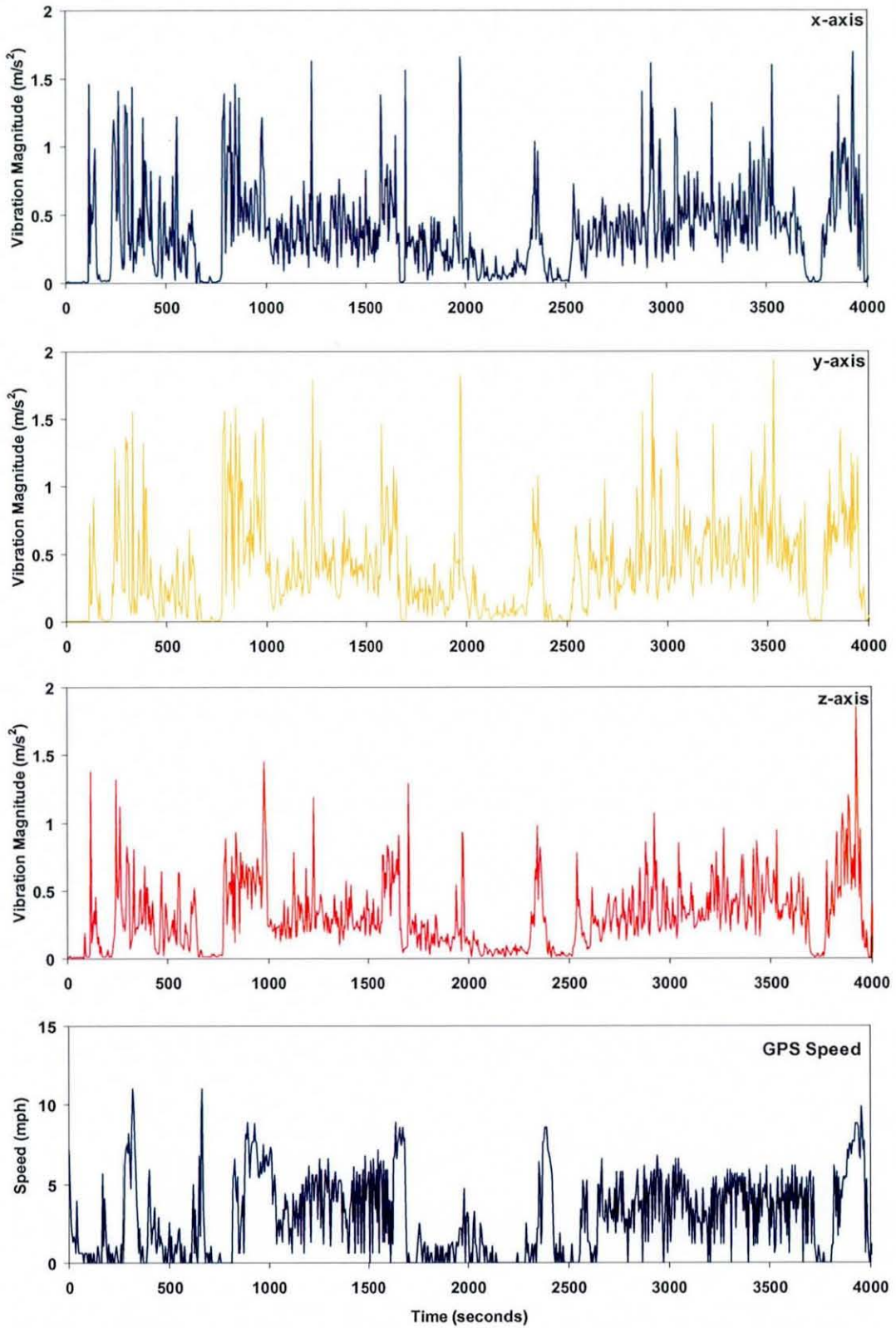
Dozer 7 – Operating at Site 4
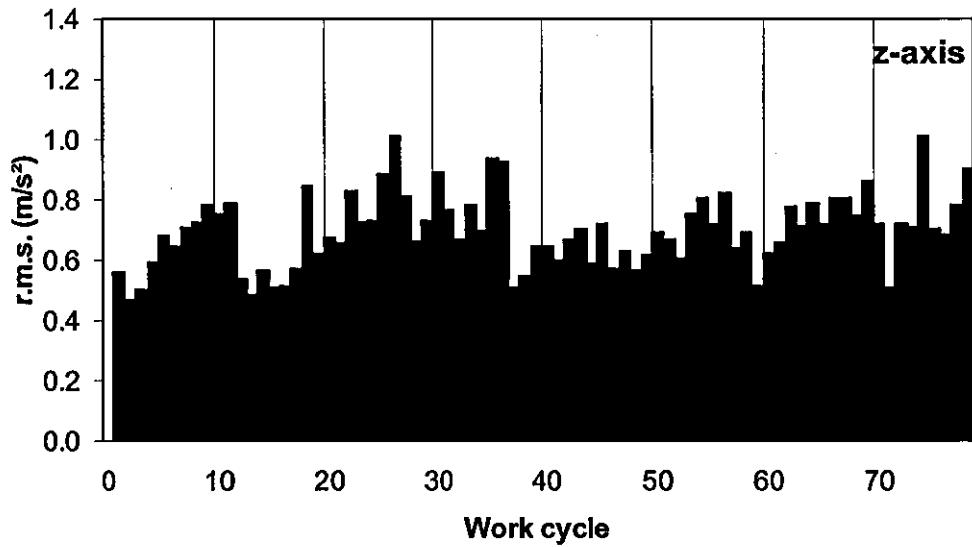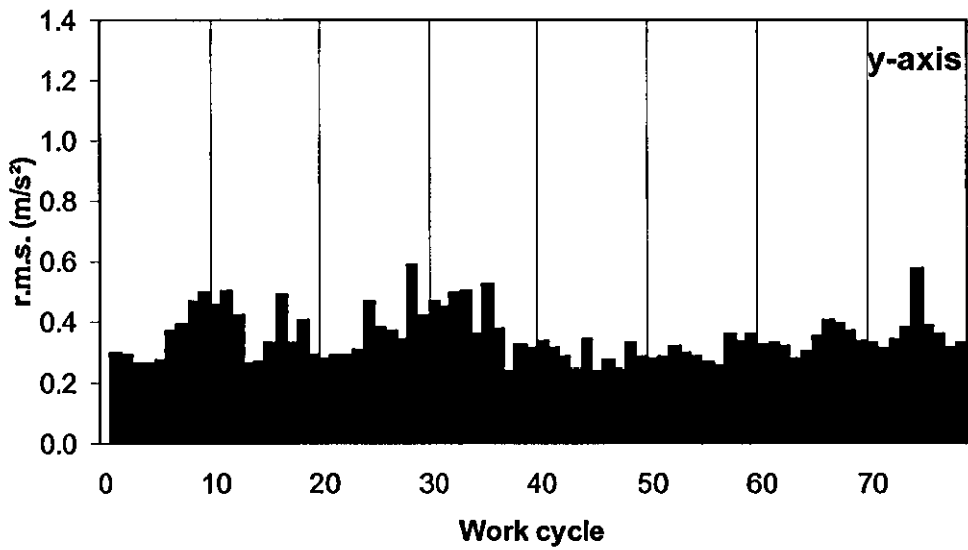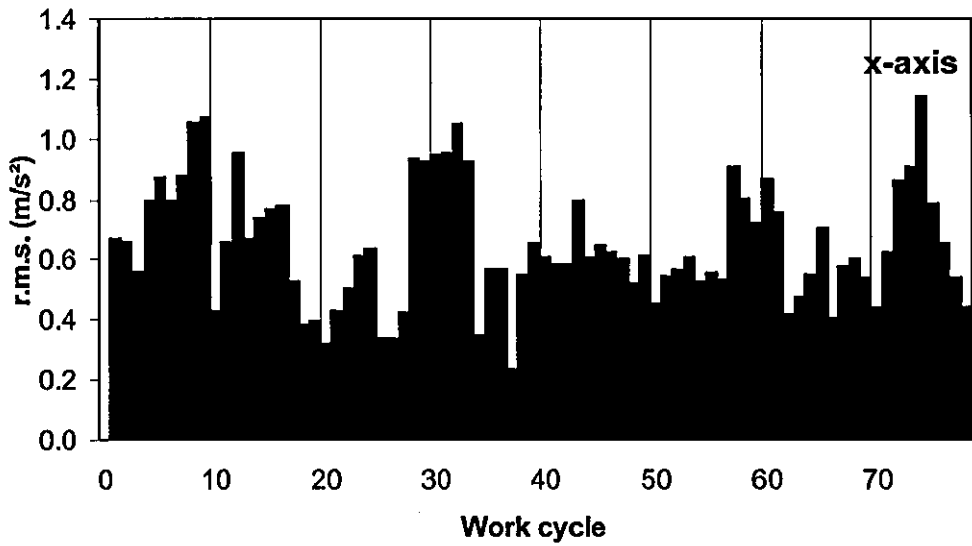
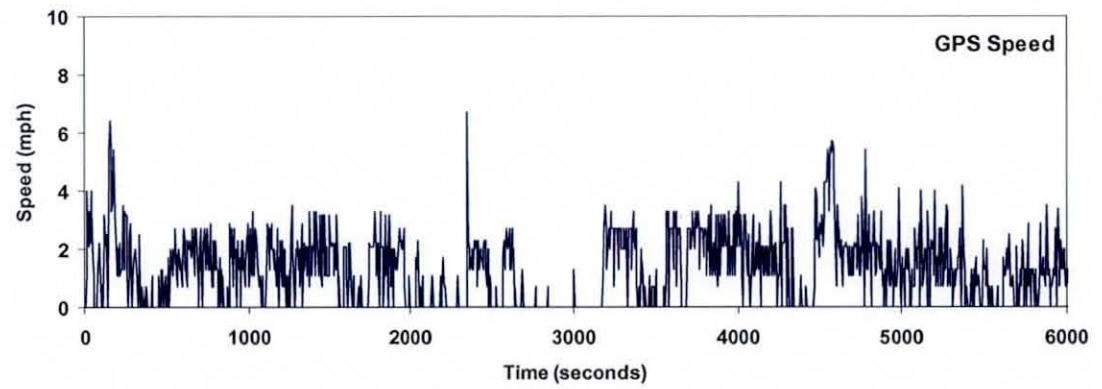Frequency weighted r.m.s. magnitude of individual work cycles for Dozer 4—Operating at Site 7
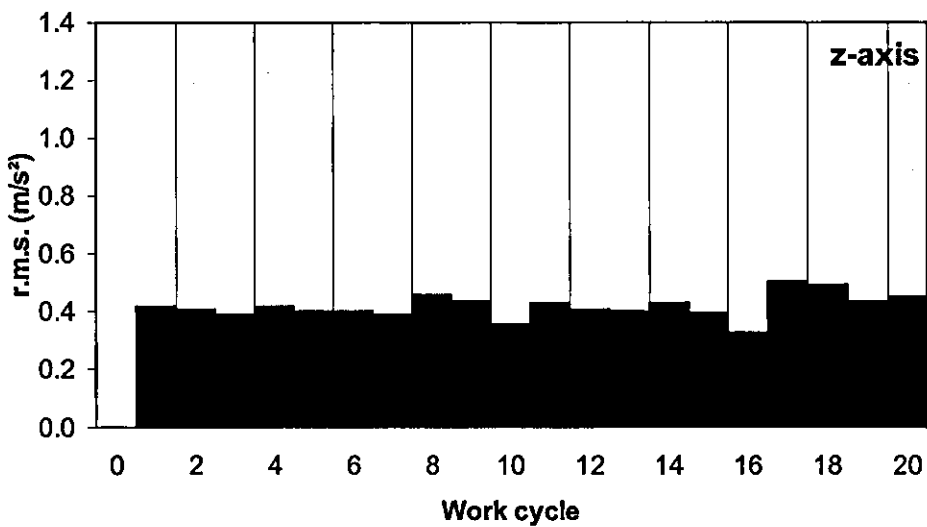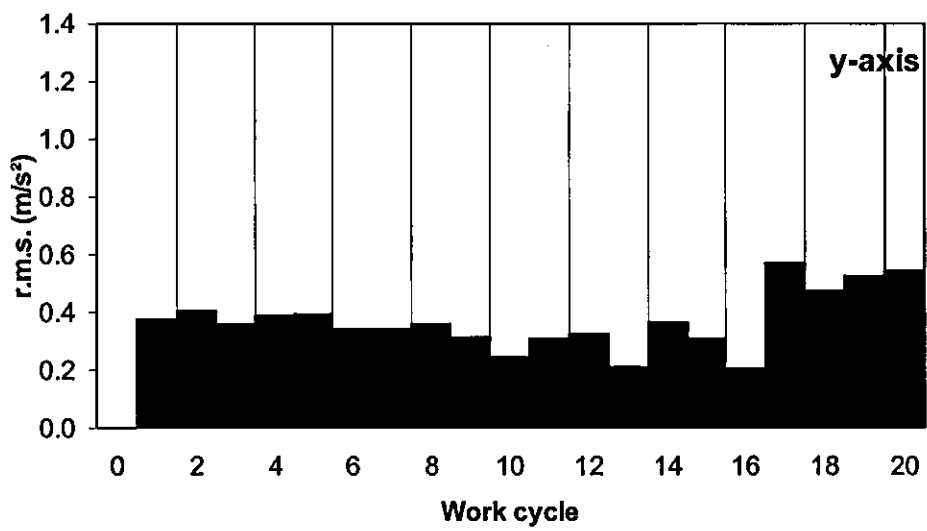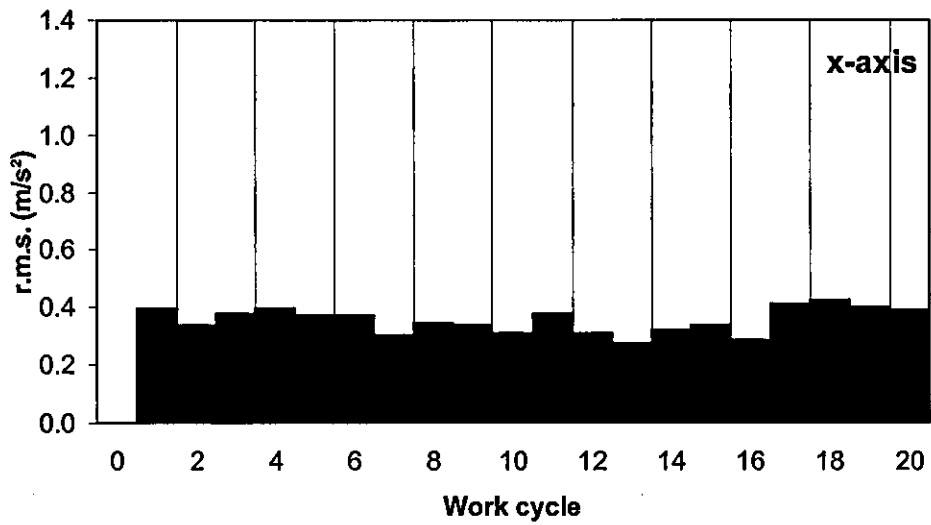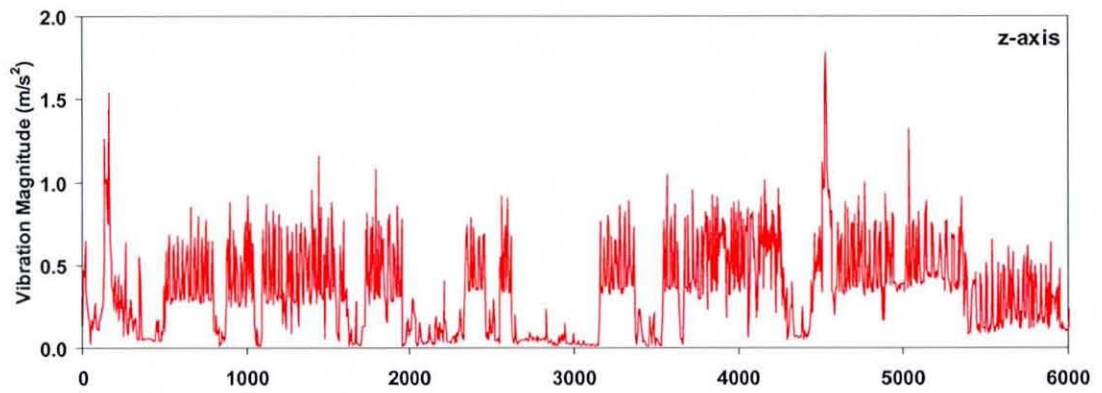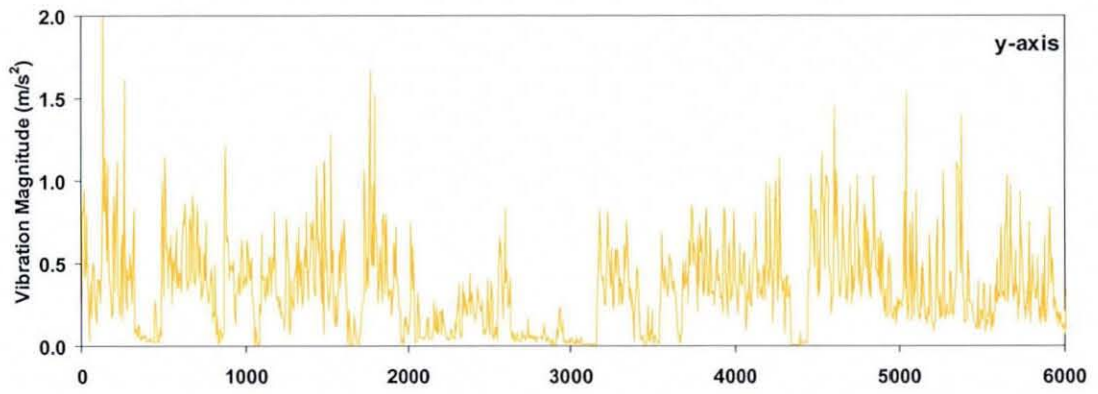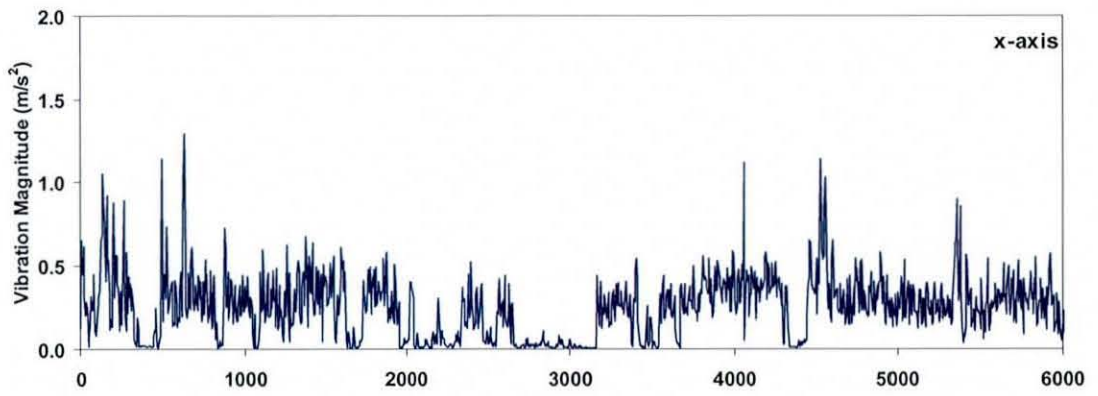
Frequency weighted r.m.s. magnitude of individual work cycles for Roller – Operating at Site 6 on Day 3

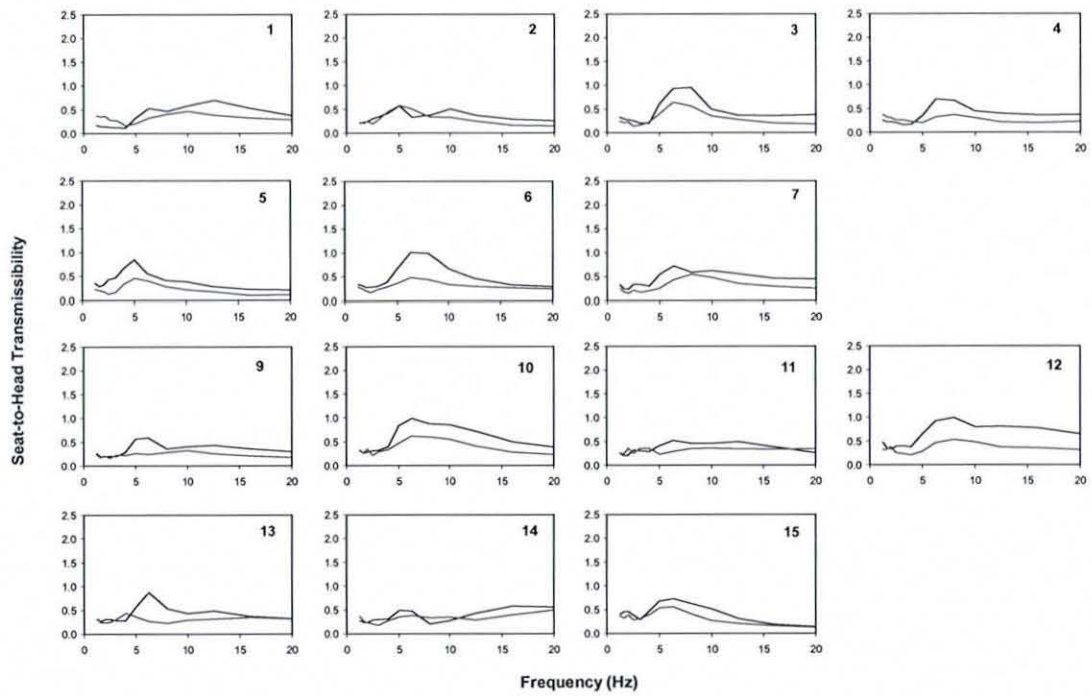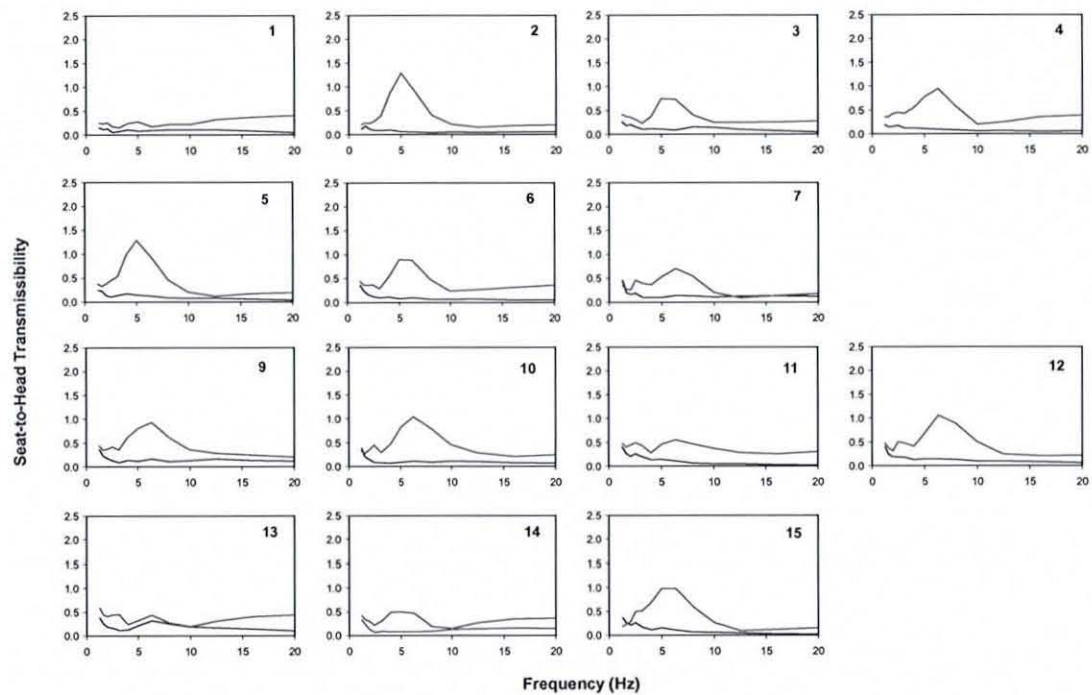# APPENDIX A8 –Influence of speed on vibration magnitude
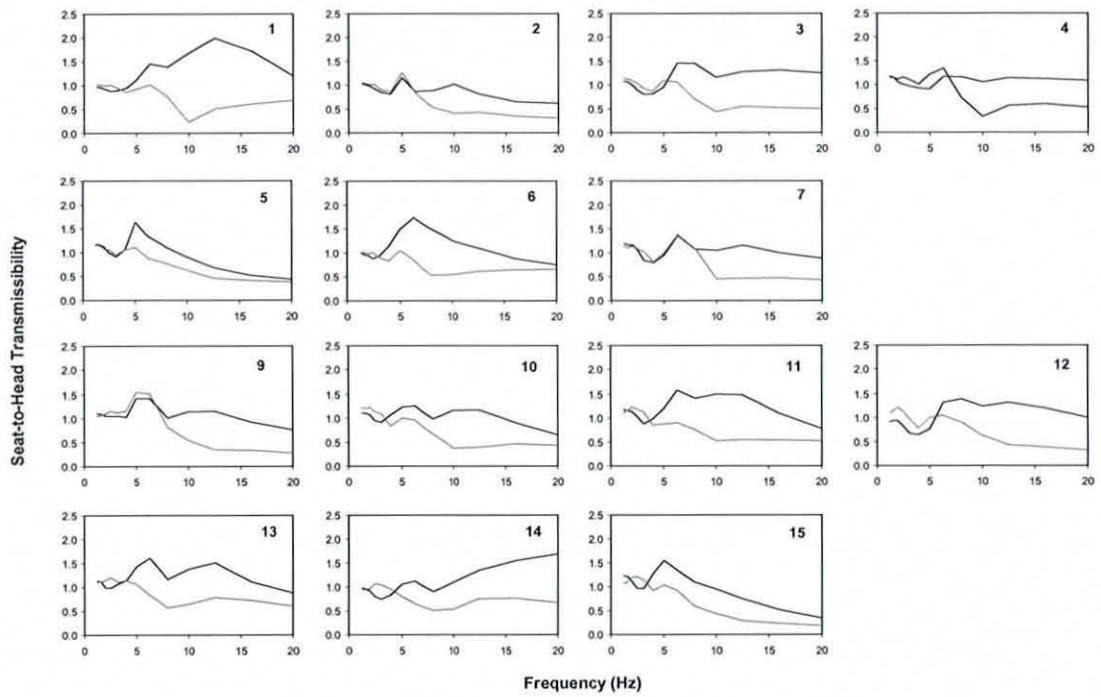

Wheel Loader 8

Roller 216

299
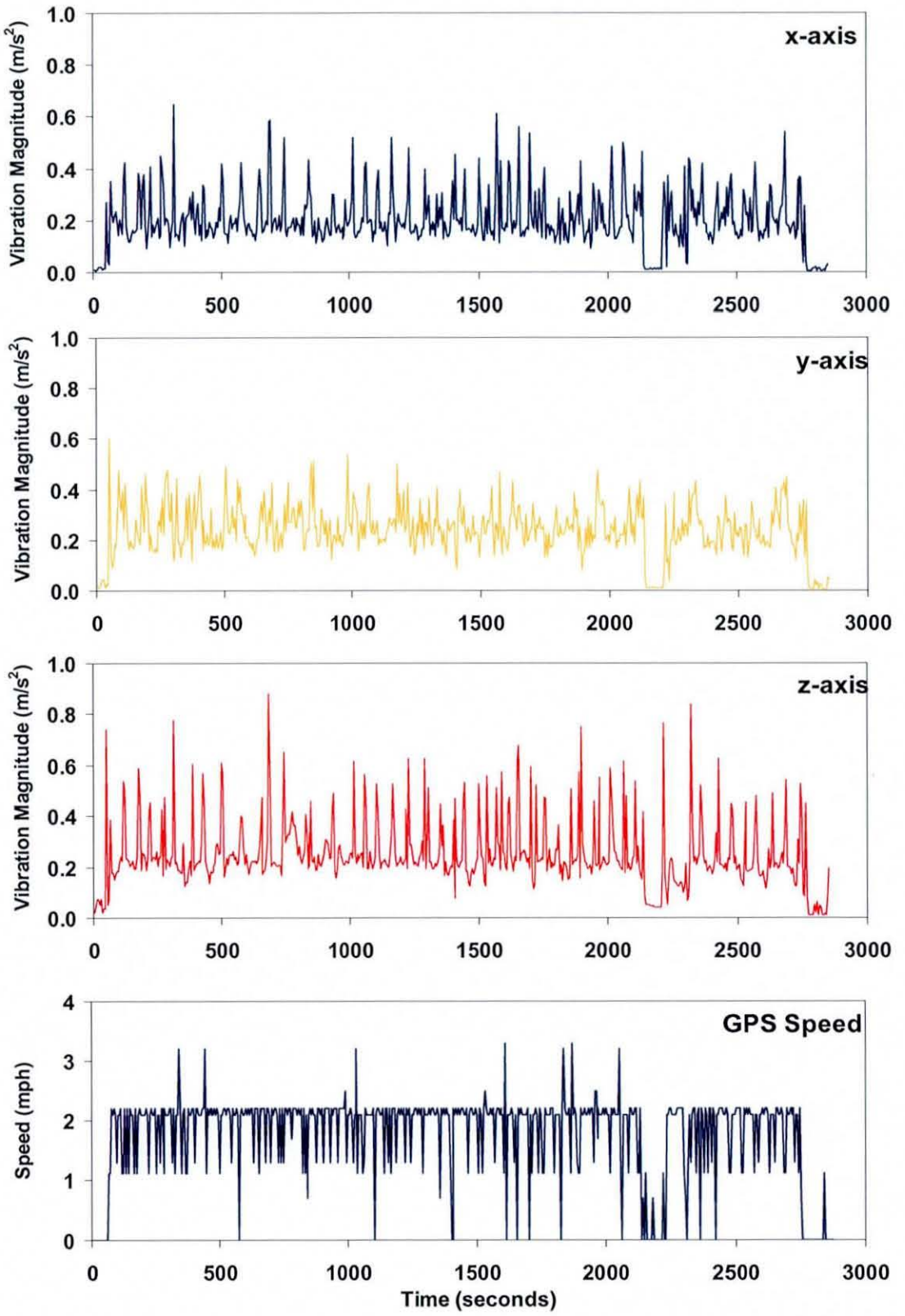
Roller 219
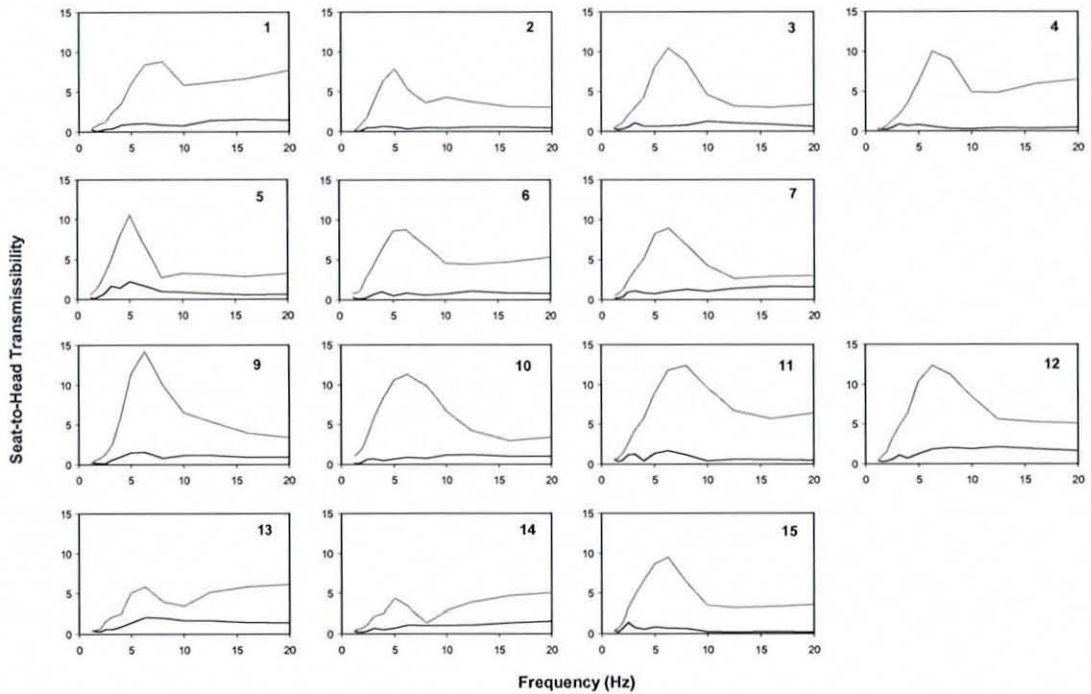
APPENDIX A9 –Individual Seat-to-Head Transmissibility

Individual transmissibility in the x-axis for 14 subjects exposed to random vertical vibration (1-20 Hz, 1.0 m/s² unweighted r.m.s) and seated in an upright (black line) or twisted posture (grey line).

Individual transmissibility in the y-axis for 14 subjects exposed to random vertical vibration (1-20 Hz, 1.0 m/s² unweighted r.m.s) and seated in an upright (black line) or twisted posture (grey line).
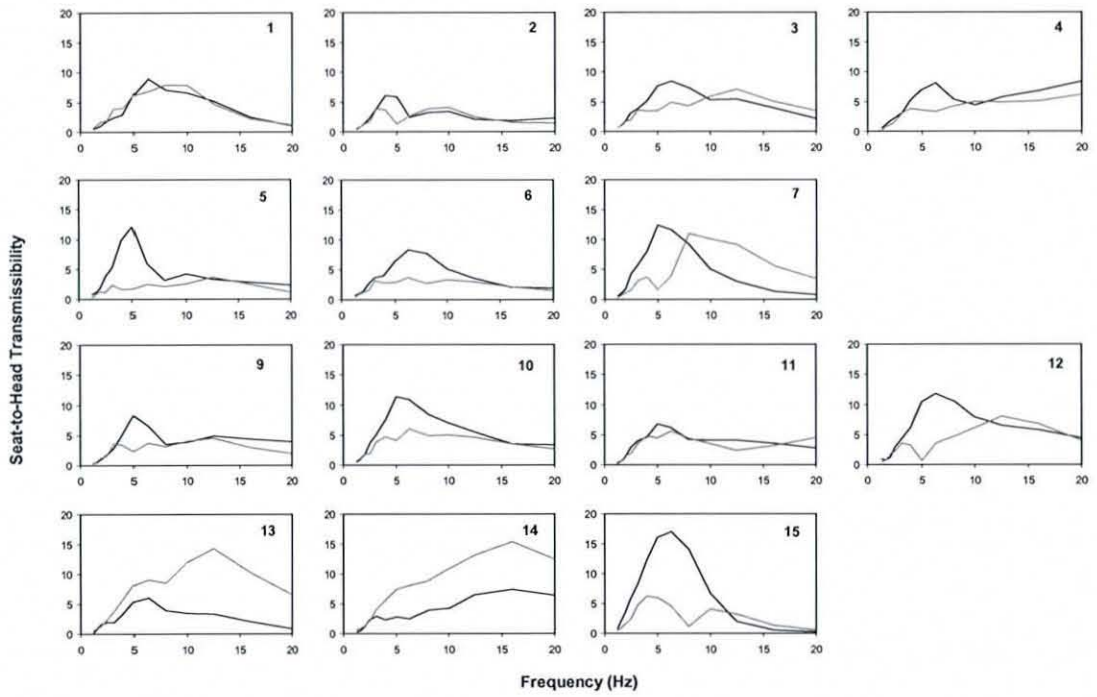
Individual transmissibility in the z-axis for 14 subjects exposed to random vertical vibration (1-20 Hz, 1.0 m/s² unweighted r.m.s) and seated in an upright (black line) or twisted posture (grey line).

Individual transmissibility to roll motion at the head for 14 subjects exposed to random vertical vibration (1-20 Hz, 1.0 m/s² unweighted r.m.s) and seated in an upright (black line) or twisted posture (grey line).

Individual transmissibility to pitch motion at the head for 14 subjects exposed to random vertical vibration (1-20 Hz, 1.0 m/s² unweighted r.m.s) and seated in an upright (black line) or twisted posture (grey line).

APPENDIX A10 – Influence of Gender on Vibration Transmissibility

Values are presented as the grey lines for the twisted posture no armrests (grey lines and crosses twisted posture with armrests) and the black lines for upright posture no armrests (black lines and crosses upright posture with armrests).

y-axis

Transmissibility (m/s²)/(m/s²)

Frequency (Hz)

305