The influence of whole-body vibration and axial rotation on musculoskeletal discomfort of the neck and trunk

By

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Declaration

No portion of this work referred to in this thesis nor the original work contained therein has been submitted to this or any other institution for a degree.

Signed:

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Lauren Morgan

'Farming looks mighty easy when your plough is a pencil and you're a thousand miles from the field' Dwight D. Eisenhower

Loughborough University

Certificate of Originality

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgments or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a degree.

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Abstract

Elements of an individuals' occupational exposure, such as their posture can affect their comfort during work, and also their long term musculoskeletal health. Knowledge as to the extent of the influence of particular aspects of the exposures can help in providing guidance on risk evaluation, and direct future technical design focus. In many situations the exposures interact, and even if the effects of individual exposures are understood, the interactions are often less so. This is certainly the case with off-road driving exposures. Specific investigations have focussed on the effects of vibration exposure, resulting in the development of international standards and guidelines on measurement and evaluation of exposure. Consideration of the posture of the operator can be accomplished through postural assessment tools, although none of the currently available methods are developed specifically for use within a vehicle environment. The issues of both the posture of the operator and the seated vibration exposure are particularly apparent in off-road agricultural driving environments, where the driving task dictates that operator is often required to maintain specific postures whilst also exposed to whole-body vibration. In agriculture, many of the tasks require the operator to maintain axially rotated postures to complete the task effectively. The analysis of the combined effects of the axial rotation of the operator and the whole-body vibration exposure has been limited to a few studies within the literature, and is currently poorly understood.

The overall aim of the thesis was to assess the influence of axial rotation and whole-body vibration on the musculoskeletal discomfort of the neck and trunk, in order that the true extent of the exposure risk may be evaluated. A field study was conducted to determine the common characteristics of some typical exposures, to provide a basis for the laboratory studies. A survey of expert opinion was conducted, examining the knowledge and experience of experts in assessing the relative influence of axial rotation and whole-body vibration on operators' musculoskeletal health. The main investigations of the thesis are focussed in the laboratory, where the objective and subjective effects of axial rotation (static and dynamic) and whole-body vibration were investigated. Objective measures included the investigation of muscular fatigue in response to exposures.

The tasks investigated in the field study indicated that the exposures often exceed the EU Physical Agents Exposure Limit Value, and that the axial rotation is a large component of the postures required. The survey of expert opinion concluded that combined exposure to axial rotation and whole-body vibration would increase the risks of lower back pain, and that acknowledgement of combined exposures should be included when assessing for risk. The results of the laboratory studies indicated that the greatest discomfort was present when subjects were exposed to axial rotation in the neck and shoulders. Out of the 8 muscles investigated, at most 6 of the 8 indicated fatigue during an experimental exposure. The muscle group which was affected most by the exposures was the m. trapezius pars decendens. Findings demonstrated that when subjects were exposed to axial rotation and whole-body vibration they indicated discomfort and their muscles fatigued. However, there was poor correlation between the sites of discomfort and the location of muscular fatigue. The discomfort findings suggest that there is an increased risk of discomfort from experiencing axial rotation together with whole-body vibration. Investigations of muscular fatigue do not substantiate this finding.

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Acronyms & Abbreviations

Acronym	Meaning
A(8)	Equivalent magnitude over 8 hours
Ag/AgCl	Silver/Silver Chloride
ANOVA	Analysis of variance
ARV	Average rectified value
ATP	Adenosine Tri Phosphate
BMI	Body mass index
C7	7th cervical vertebrae
CCTV	Closed circuit television
CI	Confidence interval
CNH	Case New Holland
CUELA	Computerised assisted recording and long term analysis of musculoskeletal load
DOF	Degrees of freedom
DV	Dependant variable
EA	Electrical Activity
EAV	Exposure Action Value
ECG	Electrocardiographic
ELV	Exposure Limit Value
EMG	Electromyography
ES	Erector spinae pars longissimus
FFT	Fast Fourier transform
Ha	Hectares
Hp	Horsepower
HRV	Human Response to Vibration [conference]
HSE	Health & Safety Executive
Hz	Hertz
IEHF	Institute for Ergonomics and Human Factors
IFA	Institute for Occupational Safety and Health of the German Social Accident Insurance
ISO	International Standards Organisation
IV	Independent variable
JASA	Joint analysis of spectrum and amplitude
Kph	Kilometers per hour

LBD	Low back discomfort
LBP	Low back pain
MAV	Mean absolute value
MF	Median Frequency
MF	Multifidus
MPF	Mean Power Frequency
MSD	Musculoskeletal discomfort
MTVV	Maximum transient vibration value
MVC	Maximum voluntary contraction
OCRA	Concise exposure index
OE	Operator expert
OWAS	Ovako working posture analysis system
P0	Control (no rotation)
P1	110° rotation
P1V1	110° rotation, 0.5m/s² vibration
P1V2	110° rotation, 1.0m/s² vibration
P2	170° rotation
P2V1	170° rotation, 0.5m/s² vibration
P2V2	170° rotation, 1.0m/s² vibration
PA(V)D	Physical Agents (Vibration) Directive
PC	Personal computer
PE	Posture/ergonomics expert
PSD	Power spectral density
PTO	Power take-off
PV0	Control (no vibration no rotation)
QEC	Quick Exposure Checklist
r.m.q.	Root mean quad
r.m.s.	Root mean square
r.s.s.	Root sum square
REBA	Rapid Entire Body Assessment
RR	Relative risk
RSI	Repetitive strain injury
RULA	Rapid Upper Limb Assessment
s.d	Standard deviation
SB0, P0	Seat base 0°, no rotation
SB0, Pmov	Seat base 0°, dynamic rotation

SB30, P0	Seat base 30°, no rotation
SB30, Pmov	Seat base 30°, dynamic rotation
SB90, Pmov	Seat base 90°, dynamic rotation
SEAT	Seat effective amplitude transmissibility
SENIAM	Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles
TA L	m. trapezius pars ascendens (left)
TA R	m. trapezius pars ascendens (right)
TD L	m. trapezius pars decendens (left)
TD R	m. trapezius pars decendens (right)
UK	United Kingdom
V0	Control (no vibration)
V1	0.5m/s² vibration
V2	1.0m/s² vibration
VATS	Vibration analysis toolset
VDV	Vibration dose value
VE	Vibration expert
WBV	Whole-body vibration
WHO	World Health Organisation

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CHAPTER 1: General Introduction

Off-road driving environments now typically expose the operator to multiple occupational health risks. Agricultural vehicles in particular are thought to be responsible for some of the most common, prolonged and severe occupational whole-body vibration (Griffin, 1990) in addition to long duration, high magnitude seated rotations (Bottoms and Barber, 1976). In the UK there are approximately 300,000 active farms and it is estimated these have half a million people currently working on them(UK agriculture, 2009). Agriculture also has a record of poor occupational health, from the self-reported work-related injuries survey (HSE, 2007/08), 18,000 individuals whose current or most recent job in the last 8 years was agriculture suffered from an illness which was caused or made worse by their job. This rate is the highest rate in all industry sectors. The most common injuries experienced are musculoskeletal disorders (MSD). The incidence of low back pain among agricultural workers is known to be in excess of all other occupational sectors (Paoli and Merille, 2005), with other musculoskeletal disorders, such as neck and shoulder pain, recognised as additional risks (HSE, 2008).

1.1. Aims of the thesis

The overall aim of the thesis is to understand the impact of exposure to trunk rotation and whole-body vibration on musculoskeletal discomfort of the neck and trunk. This would increase the knowledge of the risk effects and allow improved representation in risk analysis tools and guidelines. There have been limited studies classifying WBV exposure and operator posture in agriculture and since many of these the agricultural context has changed. A field measurement phase will allow a sample of tasks to be measured to establish current typical exposures. Whilst the professional academic community regularly discuss the anecdotal evidence for the effects of combined exposures in driving environments, capturing this tacit knowledge is difficult and rarely completed. A survey of expert opinion is proposed to educe such opinion and knowledge from experts working in the area.

The subjective and objective effects from exposure to axial rotation and WBV are rarely investigated in controlled laboratory studies. A series of laboratory studies are proposed to investigate the subjective and objective effects as risks for musculoskeletal discomfort development.

The specific aims of the thesis are therefore:

- Classification of the physical exposures typically experienced by operators in agriculture, in a variety of environments and performing a variety of tasks
- Determine current expert opinion on the likely effect of combined exposures to trunk rotation and whole-body vibration
- Evaluate muscular response to trunk rotation and whole-body vibration as single and combined exposures
- Evaluate subjective discomfort response to trunk rotation and whole-body vibration as single and combined exposures

1.2 Thesis structure

The thesis is divided into 11 Chapters, an outline of the Chapters and their contents is provided in Figure 1.

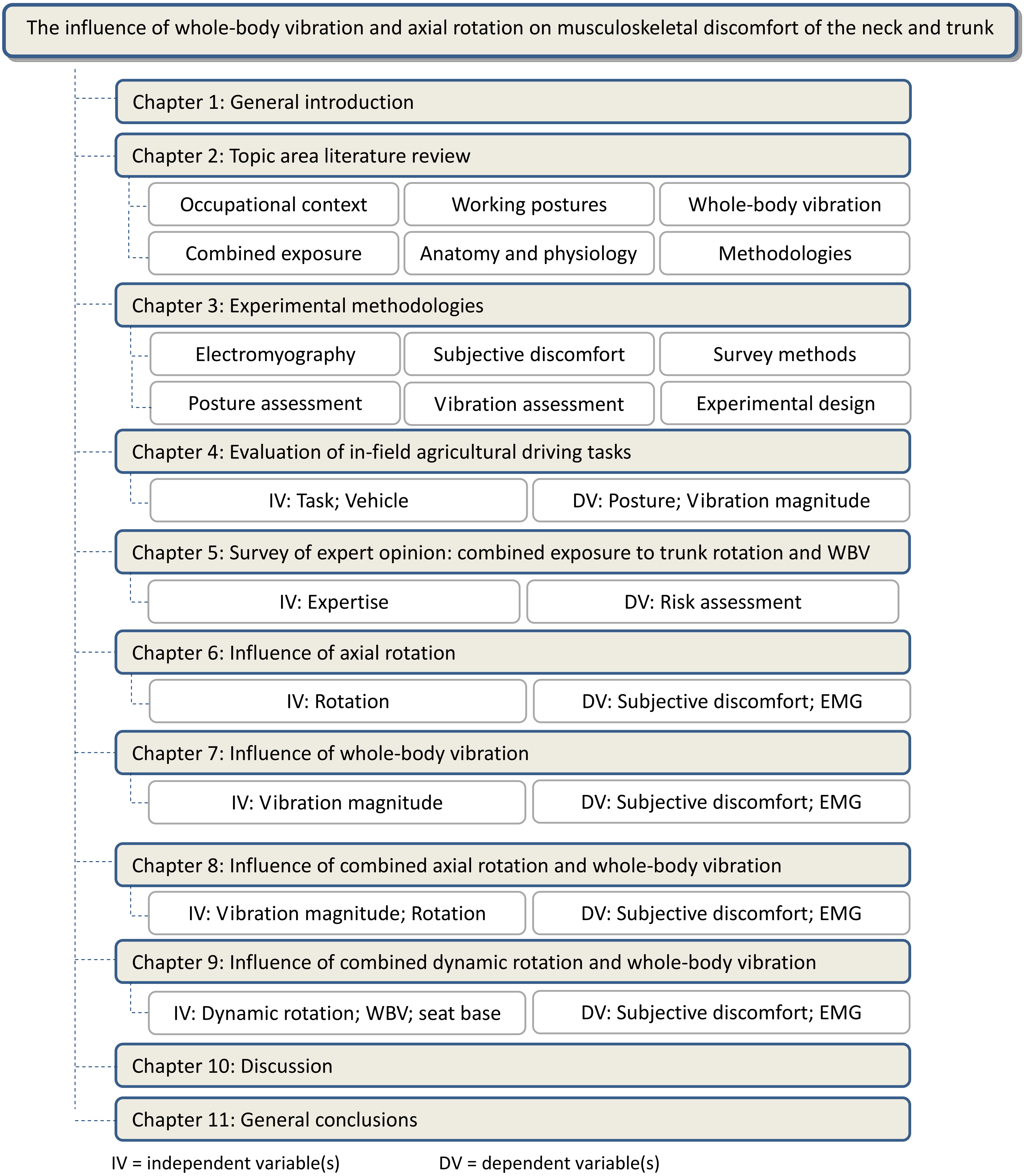


Figure 1 Schematic of thesis structure

CHAPTER 2: Topic area literature review

2.1 Introduction

This literature review describes the context surrounding the proposed research (section 2.2). It also discusses previous research into the effects of seated axial rotation and whole-body vibration, conducted in the laboratory and field (section 2.3 and 2.4). Following this is a discussion of the anatomy of the trunk and how the exposures may affect the musculature (section 2.6). The final section presents the current state of knowledge regarding analysis of the exposures, the common methodologies used (section 2.7 and 2.8).

2.2 Occupational Context

2.2.1 Occupational Health Profile - Agriculture

Agriculture has a record of poor occupational health, from the self-reported work-related injuries survey 2007/08 (HSE, 2009), 18,000 individuals whose current or most recent job in the last 8 years was agriculture suffered from an illness which was caused or made worse by their job. This rate is the highest rate in all industry sectors. The most common injuries experienced are musculoskeletal disorders (MSD). Current estimates suggest that 80% of the worker population in agriculture suffer from a form of musculoskeletal disorder at some point during their working history (HSE, 2009). The results presented in Figure 2 illustrates the high proportion of LBP among agricultural and fishery workers in comparison to other industry workers. The HSE suggests that the high incidence of musculoskeletal disorders in agriculture could be attributed to a variety of causes including work pressures, low training ethos and the high proportion of older workers (HSE, 2008). Occupational safety is also a problem for the sector, for example the recent campaign ‘Make the promise, come home safe’ highlights the serious safety risks associated with working in the industry. Many of the factors outlined by Putz-Anderson (1997) as being antecedents for MSDs, such as low recovery times, high cycle repetition, forceful and awkward postures can be observed within many of the tasks required in the daily routines in agriculture. The biomechanical issues of such peak and cumulative loads, movements and work postures are particularly important when analysing the risk of injury from work exposures (Marras, 2000 and 2005; Dempsey and Mathiannen, 2006).

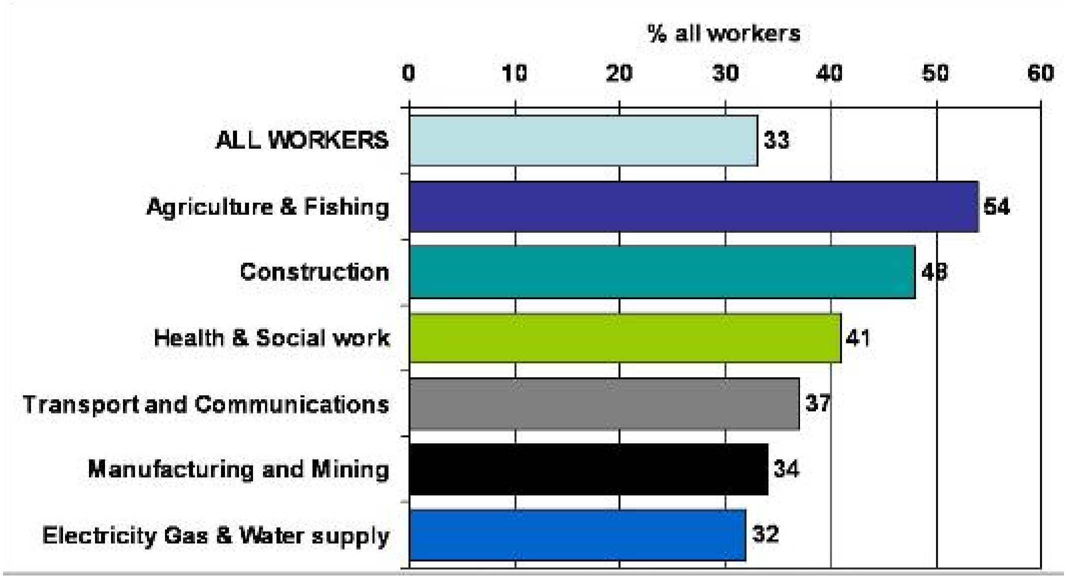


Figure 2 Incidence of LBP in agriculture, from the Third European Survey on Working Conditions (2000)

Much of the work in agriculture is completed with the use of an agricultural tractor. It may therefore be assumed that the tractor use may be responsible for some of the MSD prevalence in the industry.

2.2.2 Agricultural Tractors

The agricultural tractor has evolved since its pre-war introduction. The maximum tractor travelling speed has increased dramatically from 5-10mph in the 1950's to in excess of 30mph today. Current UK agricultural tractor maximum speed limit is 30mph. The introduction of tractor cabs has allowed the steady improvement of this workspace, and these improvements are on-going, including the addition of a joystick (typically located on the armrest) to control multiple functions and power-shift gearboxes reducing the need for clutch usage. In addition, automatic engine revolution control, set on the dashboard removes the need for any pedal control during some. Hydraulic 3 point linkage and power take-offs (PTO) added to the rear of the tractor were developed to add increasing functionality. In spite of the increasing availability of front hitches and PTO, the rear of the tractor remains the main interface for implement attachment, and the number of functions catered for at this interface is ever increasing (Renius, 1992).

In 2010, the number of tractors bought in the UK totalled 13,346. The 'average' farm usually requires at least 3 tractors to operate efficiently, these will be of differing ages and usage will be respective of this. Cultivated land area is not increasing in the UK despite an increasing population therefore each land unit must become more productive. The evidence of this is clear, 65% of farms in the UK are over 100ha, the largest percentage in Europe. Multi-farm machinery use, which allows better exploitation of machine capacity and lower capital tie-up, is particularly important for cost reduction (Kutzbach, 2000). This multi-use requirement of farm machinery will require improving technological solutions.

Much of the research focussed on agriculture, and in particular agricultural tractor use, was conducted at the Silsoe Research Institute. This research was government funded and focused on all areas of agriculture, food processing and environmental engineering. However, after the closure of the institute a gap in this area of industry is left and it is suggested projects such as this are vital in keeping UK agriculture current. Given the extensive use of tractors within agriculture, its effect upon the driver has received limited research attention.

2.2.3 Agricultural Driving Exposures

In other off-road driving occupations, the primary area of focus when considering the health risk of the operator is the transmission of vibration through the vehicle to the operator (Newell and Mansfield, 2006). However, the operation of off road driving equipment may also expose the operator to multiple ergonomic risk factors including static work postures (e.g. neck and trunk rotation, flexion and lateral bending), shock vibration, climatic conditions (e.g. heat, cold), dust exposure and psychosocial factors (e.g. job satisfaction). These ergonomic risk factors have all been associated with musculoskeletal disorder development. Time spent driving tractors has been estimated at 472hrs per annum, with 14% of operators reported driving more than 8 hours per day (Scutter, Turker, & Hall 1997). Therefore any exposures deemed undesirable, will likely be experienced for long durations.

2.2.3.1 Agricultural driving exposures - Posture

The agricultural driving posture is known to contain large twist components (Sjoflot, 1980; Bottoms and Barber, 1978; Boshuizen et al., 1990; Bovenzi and Betta, 1994; Scutter et al., 1997; Oberg et al., 2001; Wikstrom, 1993). Twisted postures are necessary to allow the driver's attention to be focused in many areas, steering of the tractor, rear facing monitoring of the attached machine or implement with additional force required for clutch or brake use.

> "The agricultural tractor driving requires the operators to maintain a stable posture despite dynamic conditions so as to perform the driving task even while looking backwards to observe and control the machine attached to the rear of the tractor.

These requirements may involve a large number of turning movements from looking ahead to behind and vice versa resulting in a poor posture" Mehta and Tiwari (2000)

Surveys of rotation of the head have shown that this movement frequently occurs in certain drivers' jobs (Eklund, 1986), and therefore covering a large section of occupational work, however effects on health of such rotations have scarcely been the focus of investigation (Wilkström, 1993).

The tractor driver has at least two tasks; one in steering the tractor and one in controlling the attached equipment (Sjøflot 1980). The former requires forward attention, and the second task requires attention focused at the worksite of this attached equipment, often at the rear or to the right. The working habits in turning backwards can vary considerably from person to person (Sjøflot, 1980). Whyte and Barber (1985) completed an observational study on the posture of tractor operators, with specific focus on the trunk rotation patterns and showed operators frequently spent in excess of 20%, and up to 59% task time facing rearwards (Table 1).

Table 1 Division of the tractor drivers' time between looking forwards and rearwards whilst undertaking various agricultural tasks, Whyte and Barber, 1985

Driving task	Turns per min (s.d)	Percentage of task time focussing ahead/behind (s.d)
Ploughing	11(5)	56/44 (23)
Rotary Cultivating	9 (5)	79/21 (14)
Spring tine harrowing	2 (2)	96/4 (2)
Power rotary harrowing	6 (5)	78/22 (21)
Disc harrowing	10 (6)	71/29 (20)
Drilling	2 (2)	86/14 (16)
Precision drilling	17 (8)	76/24 (13)
Rotary mowing	15 (7)	72/28 (16)
Cutter bar mowing	29 (9)	56/44 (7)
Forage harvesting	17 (3)	41/59 (8)
Windrowing	11 (0)	75/25 (7)
Baling	15 (3)	40/60 (11)
Mounted sprayer	3 (5)	94/6 (9)

Trailed sprayer	0 (0)	100/0 (0)
Mounted fertiliser distributor	7 (4)	84/15 (11)
Trailed fertiliser distributor	8 (3)	71/29 (10)
Mounted fertiliser broadcaster	6 (3)	89/11 (6)

As illustrated in Table 1, numerous tasks within agriculture require a substantial period of the working time facing rearwards. Baling and forage harvesting both exhibit high requirement for trunk rotation, with the operators observed spending over 50% of the task time in this extreme posture. The posture required for ploughing includes the one shown below in Figure 3.

Figure 3 Typical driver's posture whilst ploughing

The magnitude of rotation through the body seen Figure 3 is not uncommon. From Whyte and Barber's observations, they noted that the degree of twist varied considerably depending upon the task being completed. In general focus on attached implements (often trailed to the rear right) requires a twist of 25-30°, however, for cases in forage harvesting, where observation of the trailer was necessary, a total twist of 130-150° was observed at the head, with 40-50° in the back and 50-70° in the neck. Such twisted postures may have to be maintained for long periods with only short pauses in a neutral position if the driver has to sit twisted backwards in order to supervise and control a rear-mounted or towed implement (Toren, 2001). The recognition that such requirements have adverse consequences have resulted in terms such as 'tractor drivers' neck' been given to such occupational illnesses in the field (Bottoms and Barber, 1978). In a questionnaire study of neck pain in tractor drivers, 33% of tractor drivers experienced neck pain every day, in addition 53% reported that tractor driving increased symptoms of pain (Scutter et al. 1997).

2.2.3.2 Agricultural driving exposures – whole-body vibration

Whilst the operator is seated in the tractor, they are also exposed to WBV. Scarlett et al. (2007) found that virtually all (~ 95%) 'on-farm' vehicles exposed their operators to vibration that exceeded the Exposure Action Value (EAV) during an 8-hour day. Kumar et al. (2001) found that in comparison with ISO 2631-1 (1997) the measured exposure exceeded the 4 hour 'fatigue decreased proficiency limit' on both farm and non-farm terrains. In addition, Servadio et al. (2007) suggested that the values of the r.m.s accelerations are not strictly proportional to the forward speed. The dominant natural frequencies of tractor vibration are 1-7Hz, which lie within the most critical frequency range of the human body, e.g. human trunk and lumbar vertebrae have a natural frequency of 4-8 and 4-5Hz respectively (Pope, 1993; Pope et al., 1987). The results of previous studies on exposures from agricultural driving tasks are summarised in Table 2 below. The range of tasks measured is reasonably varied. The age of the research determines the vehicles available, therefore many include tractors with no suspension, which are reasonably uncommon in UK agriculture. The majority of papers provide details, although limited, on the method of evaluation. It is clear that the r.m.s method of evaluation is favoured, with only one paper presenting results produced with the VDV method. However, the weighting and multiplication factors (if relevant) are only detailed in 2 papers.

Table 2 Vibration emission values from previous studies in the literature

Reference	Method of risk estimation	Vehicles	Tasks	Vibration magnitude (m/s²) axis specified in parenthesis
Scarlett et al. (2007)	PA(V)D worst axis r.m.s with 1.4 multiplication for x and y axis	Variety (included unsuspended, suspended front axle and cab, and front and rear axle suspension)	Ploughing Spraying Plough in transport Trailer transport cultivating	0.7 - 0.9 (y) 0.5 - 0.75 (y) 0.75 - 0.9 (y) 1.05 – 1.35 (x) 1.2 – 1.5 (y)
Bovenzi and Betta (1994)	Vector sum frequency weighted r.m.s	45-85hp, unspecified suspension	Ploughing Mowing Fertilizer spreading Towing trailers Road travelling	1.07* 0.89-1.47* 0.52-1.2*
Paddan and Griffin (2002)	Seat vibration r.m.s (Wb weighting applied)	Tractor, with and without suspension	Variable (incl. mowing and road travelling)	0.29-0.98
Kumar et al. (2001)	r.m.s. values with ISO weighting factors	Tractors, unspecified suspension, 14.9KW As above but with 26.1KW As above but with 37.3KW	Travelling 8-18kph on roads and tilled/harvested grounds	0.56-0.76(x), 1.08-1.86(y), 3.1-3.8(z) 0.48-0.63(x), 0.96-1.64(y), 2.96-3.55(z) 0.47-0.58(x), 0.92-1.6(y), 2.53-3.08(z)
Hostens	VDV	Combine	Combine	1.10-2.03

and Ramon (2003)	harvester	operational, travelling on field	(m/s1.75, y) 4.4-4.99 (m/s1.75, z)
		Combine disabled, travelling on road	1.06-2.0 (m/s1.75, y) 4.27-4.5 (m/s1.75, z)
		Mowing	2.8-3.3m/s2
Mayton et al. (2008)	Tractors, unsuspended	Shrub removal and raking	1.7m/s2
		Road travel	1.7m/s2

* no axis specified

It is clear from the above studies that the vibration measured is often variable between tasks and working surfaces, and often above the recommended magnitudes specified by PA(V)D for 8 hour exposures. There have been numerous improvements in suspension design since many of the studies detailed above. Therefore it is suggested that the measurement and reporting of current vibration exposures in agriculture is revisited.

Work related backache was more common among the tractor drivers (40%) than non-exposed controls (18%) in a study by Kumar et al. (1999). A review study combined the available literature and through a meta-analysis suggested meta-odds ratio for tractor drivers' low back pain association of almost 2.2 (Waters et al., 2008). Additionally, a comparison of the studies by Bovenzi et al. (2002) and Bovenzi and Betta (1994) was used to illustrate that the steady state WBV may not account fully for the associated low back pain. It was suggested that the LBP may be attributed to the mechanical shocks induced during high acceleration events. This is in alignment with the suggestions of Sandover (1998) that mechanical shocks have a greater influence on both human health and subjective discomfort than the long term r.m.s. approach. The Control of Vibration at Work regulations are in place in the UK to minimise risks from exposure to vibration. Despite being introduced in 2005, the exposure limits do not become enforceable until 2014 in forestry and farming, although employers are required to take any exposure reduction action available.

2.2.3.3 Technical developments in agricultural vehicle design

The research directed in this area, stakeholder feedback and competitiveness in the industry have all led to developments in tractor design. Those relevant to the exposures described above (i.e. vibration and posture) will be discussed below.

The main design solutions proposed to reduce the twisted posture of the operator either reduce duration or magnitude of twist. A method to reduce the duration of twists can be achieved with the use of enlarged mirrors (Sjøflot, 1980). Once an initial decrease in work performance was overcome, Sjøflot suggested that the overall work performance increased. Despite such claims, the practice of using big mirrors is not widespread in the UK. Most occupational drivers in the UK can reverse using the view through their mirrors, so it would seem that the skill base is there, but the confidence needs increasing. More functions are now controlled via a joystick on the armrest, it would seem that previous barriers to changing the drivers orientation are slowly being removed. In the future we might expect the driver to be better located for direct viewing of equipment functions, or more aids in collecting the necessary information, i.e. indicators, instruments, television (Sjøflot, 1980).

Alternatively, a reduction in twist magnitude can be achieved through the use of a swivelling seat baseof up to 20° (Bottoms and Barber, 1978). Some authors have advocated increasing the swivel range up to 30° (Sjøflot, 1980). The provision of a swivelling agricultural tractor seat was found to reduce muscle in the trapezius and to a slightly lesser extent in the sternomastoid (Bottoms and Barber, 1978). A tilting seat that allowed the driver to remain an upright position whilst working on an uneven surface, such as ploughing with offside wheels in the furrow, was also raised for consideration (Whyte and Barber, 1985). When ploughing, the number of drivers exposed to extreme twisted trunk postures was reduced by about 50% with the use of saddle chairs in comparison to a conventional chair (Torén et al. 2001). Mansfield et al. (2001) also suggested that a reduction in vibration exposure could be possible if a saddle type suspension seat is used in preference to the conventional suspension seat. Swivelling seats are now a common addition to most tractors sold in the UK, although their benefit has not been evaluated since the prototype studies discussed above. In some manufacturers, the seat base can be rotated up to 90°. However, whilst the seat may be rotated at this level, the requirement of vehicle control, including feet contact with the brakes, remains at the standard position at the front of the cab. This rotation is also much greater than that investigated in the studies discussed above.

The criteria for comfort in a tractor seat are difficult to satisfy because of the conflicting practical requirements. One example is the choice of seatback height. A wide, shoulder height backrest would provide comfort on fairly smooth ground, but it would make it difficult for the operator to turn around and easily see out of the back window (Yadav and Tewari 1998). Donati (1984) suggested that the requirement for rearward attention was often the major contributor in operator’s preference of a seat. He suggested a compromise for adjusting this dimension to take into account the specific working posture of the tractor driver and its postural support role. Seat design based on anthropometric considerations is considered gold standard by ergonomists, however a study on tractor drivers found the dimensions were often not suited to many of the operator population (Mehta et al. 2000).

Off road-driving exposes the driver to multi-axis vibration, as described by the studies in Table 2 and also emphasised in other off road occupations by Newell et al. (2006). However, much of the suspension development work has been focussed on attenuating the vertical axis only (Stein et al., 2008). Tests show that suspension provided in the lateral axes improves operator comfort at higher driving speeds, on rough surfaces (Luger and Nadlinger, 2005). In the tests, the vibration exposure was reduced, however end-stop impacts in the tests reduced the effect of the suspension system. It has also been suggested that suspension in the lateral axes should be disabled during low speed, on road driving (Luger and Nadlinger, 2005). Experience suggests many operators have reported experiencing end stop impacts during off road driving. They also experience the problem of exaggerated seat movements with low vibration exposure, possibly due to resonances in the suspension system. Fore and aft suspension constructs safety risks as the operator may be moved out of the range of the pedals when the suspension is at maximum rearward displacement. Burdorf and Swuste (1993) compared the isolation properties of suspension seats in the laboratory with field measurements and found that 19 of the 24 measurements in-vehicle showed less isolation than predicted by the laboratory tests. Stiles et al. (1994) found that 45% of seats increased the acceleration levels experienced by the operator. It has been suggested that much of this increased exposure is due to end stop impacts (Hostens et al., 2004). Air suspension systems have been favoured to mechanical, within the past 20years. A comparison of the behaviour of the 2 suspension systems and indicated that air suspension was preferable for agricultural machinery (Hostens et al., 2004). This is due in part to the non-linear response of the air spring, resulting in larger stiffness near the ends of travel meaning an end-stop is less likely. The ability to adjust the ride height for the drivers’ weight is an added benefit, with many seats doing this automatically, reducing the need for operator activation.

Active seat suspension has also been explored, which uses non-newtonian fluids in the suspension i.e. their resistance can be varied with the use of electric variables. The first commercial use of the active seat was within agriculture was by John Deere (Dufner and Schick, 2002). This seat requires the operator to self-select the stiffness from 3 options by using a switch placed on the arm rest. Whilst the improvements in active seat suspension must be applauded, when their control is left to the operator, one might question whether they are used to their full potential. New seats must adhere to standards in assessing the operator response to vibration transmitted through the seat (ISO 5007, 1999). This requires laboratory investigations with subjects sat on the new seat. This testing is expensive, and the subjective results gained will not provide detail on which component of the suspension system is not optimised, therefore modelling of suspension systems can be of great benefit (Gunston, 2004). Of course, suspension is not only provided at the seat in tractors, therefore modelling of the whole agricultural tractor allows investigation of the effect of axle suspension developments (Ahmed and Goupillon 1997;Lines et al. 1992;Previati et al. 2007).

2.2.3.4 Driving exposures in agriculture - summary

In agriculture, both trunk rotation and WBV are experienced simultaneously. The effects of such combined exposures have received little attention. It is clear from the studies discussed above that the twisted postures experienced by operators in agriculture are of significant magnitude. Most of the research in the area has focused on classifying the exposures, and not on the effects of such exposures on the operators. Given the high proportion of MSDs, in particular LBP suffered by workers in the industry, it may be surmised that the risks detailed here may be causal. The remainder of this literature review will focus on previous research in the specific areas of twisted postures and WBV exposures.

2.3 Working Postures

Seated postures are often chosen over standing for work purposes due to their lower energy cost, the extra stability gained for completing motor and visual tasks and the lowering of hydrostatic pressure in the lower extremities. It is important to note that no single posture is ideal if maintained for long periods of time, and any seated provision must account for this need to vary the seated posture. The seated posture leads to inactivity, which itself may be injurious (Magnusson & Pope, 1998). When sitting in a conventional seat, the majority of the body weight is transferred to the seat, with the remainder to the floor and arm rests, where this option is available. Seated posture is determined by both the seat and the task to be performed. Poor seated postures are generally considered to contribute to risks of musculoskeletal pain. Newell and Mansfield (2008) found that the inclusion of armrests significantly improved the participants' ability to complete a task with a lower workload demand. The posture of the upper body is less dictated by the seat and more by the task being performed and location of the work area. When the work area is to the rear of the seated position, this requires rotation, which when seated can only be manifested through the trunk, resulting in a twisted posture.

2.3.1 Twisted postures

Twisting whilst seated is a major component of many work tasks and is often seen in the postures required by forklift drivers (Bovenzi et al., 2002; Eklund et al., 1994; Hoy et al., 2005; Wikstrom, 1993), crane operators (Bovenzi et al., 2002; Eklund et al., 1994), subway train drivers (Johanning, 1991; Johanning et al. 2006; Krause et al., 1997), forestry drivers (Eklund et al., 1994; Rehn et al., 2005) and construction equipment (Dupuis and Zerlett, 1987; Kittusamy and Bucholz, 2001; Kittusamy and Bucholz, 2004). A certain amount of rotation of the trunk is normal, however the statistics on injury vary but some authors suggest rotation of the trunk is associated in over 60% and a single causal factor in 33% of back injuries (Kumar et al*.,* 2001). An examination of the compensation claims for LBP in America revealed examples where claimants site twist as the cause of their disability, these include "twisting and turning on forklift" and "long jack and forklift hit each other causing claimant to twist his back" (Murphy and Courtney, 2000). Trunk rotation has also been shown to increase operator self-reported discomfort (Wikstrom, 1993). It is accepted that adverse postures maintained over extended periods increase the risk of development of musculoskeletal disorders (Kumar, 2001). These can be confined to a particular muscle group, or established over the whole body. A rotated working posture is related to higher prevalence of cervical spine disorders (Occipinti et al., 1986). Both bending and twisting have been related to LBP development, in a study that included machine operators, carpenters and office workers, it was found that working in twisted or bent postures increased the occurrence of neck and shoulder symptoms, an association that was most evident for machine operators (Tola et al. 1988). Working with the neck rotated at 45° rotation for 25-30% of working time is suggested to increase the risk for neck pain by 30% (Ariens et al., 2000). A nationwide survey in Denmark, with nearly 10,000 respondents found a predicted odds ratio of 1.71 for LBP of those exposed to frequent twisting or bending (Xu, Bach and Orhede, 1997). For workers who worked with the trunk in a minimum of 30° rotation for more than 10% of the working time, Hoogendorn et al (2000) found an RR of 1.3 with a 95% CI 0.9-1.9 for low back pain in those exposed. Although there are a limited number of studies presented here, the effect of trunk rotation is usually only part of the focus of the research and is usually grouped with other postures for investigation (eg. bending forward, Xu et al., 1997). Research in the golfing arena has suggested that both the high degree of trunk rotation and the velocity of rotation and rate of repetition may contribute to the injury rate (Pink and Perry, 1993).

Considerable muscle effort may be required to keep the back strengthened particularly when seated postures in which the trunk is deviated or twisted more than 20° are adopted (Toren, 2001). Generated muscle tension is known to increase spinal loading (Bonney and Corlett, 2002). Twisting the trunk to face rearwards involves overcoming the passive resistance of the tissues of the trunk. This passive resistance is low at the neutral position, and increases progressively as the trunk is twisted (McGill et al., 1996; Bodén and Oberg, 1998). The precise muscular response to twisting is unclear. External oblique and erector spinae muscles show different activation patterns depending on twisting direction (McGill, 1991). The contralateral external oblique and ipsilateral erector spinae displayed low muscular effort up to 20° twist, however showed linearly increasing effort for rotations beyond this (Toren 2001a). Large activities in the erector spinae, which plays a small role in the generation of axial twist, suggests that stabilization of the spine during twisting may be more important to the lumbar spine than production of axial torque (McGill, 1991, Kumar and Narayan, 1998). Higher levels of coactivity have a significant impact on the spinal loads, since increased antagonistic muscle activity must be offset by the agonistic forces. Therefore, it is suggested by Davis and Marras (2000) that the muscle activity from the antagonistic muscles produced more loading on the spinal structures, without contributing to the ability to offset the external moment imposed on the spine. The rate of fatigue in the muscles of the back results in an uneven pattern of load sharing, which may therefore predispose the trunk to injury (Kumar et al., 2001).

The issue becomes one of motion patterns where the way in which the torso is flexed, either about the hips or in the lumbar spine greatly influences the shear load experienced by the spine (McGill, 2004). The majority of workers with bad backs report exacerbated pain when provoked with anterior to posterior shear (Callaghan and McGill, 2001). In contrast, Duncan and Ahmed (1991) demonstrated that with an intact facet joint, axial rotation does not impose unusual stress on the structure. However, when rotation is combined with bending the axial range of motion is reduced and loading patterns change significantly (Gunzburg et al., 1991). When axial torque is combined with compression, the disc fibres located at the posterolateral and posterior locations of the spine become more vulnerable, particularly when combined with bending moments (Shirazi-Adl, 1989). These suppositions may hold significance for predicting the body's response to WBV exposure, whilst twisted.

In the analysis of the effect of trunk rotation on the body, there appear to be three favoured methodological approaches: subjective assessment; physical measurements (i.e. range of motion) and objective measures (i.e. electromyography). The subjective effect of trunk rotation has not been investigated fully. Direct observations, combined with direct measurement in a laboratory environment provide the clearest picture of the exposures (Van der Beek et al., 1997).

The common methods used to investigate working postures are postural assessment methods. These are evaluated in the section below in order that their evaluation of twisting exposures may be investigated.

2.3.2 Postural Assessment Methods

Posture assessment tools are well developed in ergonomics; however most are not optimised for driving postures. The table below presents the most commonly used methods, their primary references and lists examples of application.

Table 3: Posture assessment methods

Method	Primary reference	Examples of application
Quick Exposure Checklist (QEC)	Li, G. and Buckle, P. 1999	HSE (UK)
Rapid Upper Limb Assessment (RULA)	McAtamney, L. and Corlett, E.N. 1993	Cook and Kothiyal, 1998 and Massaccesi et al., 2003

Rapid Entire Body Assessment (REBA)	Hignett, S and McAtamney, L. 2000	Janowitz et al., 2006
EN 1005-4	Evaluation of Working Postures and Movements in relation to Machinery: EN 1005-4, 2005	
Ovako Working-posture Analysis System (OWAS)	Kahru et al., 1977	De Bruijn et al., 1998; Engels et al., 1994; Li and Lee, 1999; Scott and Lambe, 1996)
The Concise Exposure Index (OCRA)	Occhipinti, 1998	Greico, A., 1998; Mosavi et al., 2005
Computer-assisted Recording and Long-term Analysis of Musculoskeletal Load (CUELA)	Ellegast and Kupfer, 2000	Glitsch, U. et al., 2006
Simultaneous field measuring method of vibration and body posture for assessment of seated occupational driving tasks (Extended CUELA)	Hermanns, I. et al., 2008	

The broad approach of the methods listed above is similar, with the exception of CUELA, and to some extent, QEC. Their method comprises of observation of the task, comparison of the posture observed with reference postures in the look-up tables, combining the scores gained and a comparison of the overall score with risk levels and recommendations. The reliability of these paper-based evaluation methods is sometimes questioned (Li and Buckle, 1999), mainly due to difficulties in classifying the working postures. In addition it is suggested there may be an issue of under-sampling with tasks where motion of a body is a major constituent of the task. With the exception of CUELA, all of the methods can be implemented without specialist equipment. Most use lookup tables in order to provide guidance on whether postures are acceptable or not. No method is specifically designed for use with drivers, for example, the presence of backrests, or armrests, would not alter the scores produced. In addition to this, no method is sensitive to foot pedal pressures.

It is thought that reducing levels of discomfort decreases the risk of an injury occurring (Hedge *in* Stanton, 2005), however, there has been no conclusion reached as to the effect of the level of exertion felt by the subject, and the subsequent role this should play within postural assessment models (McAtamney and Corlett, 1993; Moore and Garg, 1995; Colombini, 1998; Grieco, 1998; Occhipinti, 1998; Hignett and McAtamney, 2000). In addition to this, Jones and Kumar (2004) relate to the fact that little agreement exists as to the physical exposures which should be considered in an assessment of risk and the relative role of those variables in the precipitation of musculoskeletal injury. As a result, it is not usually considered appropriate to produce a method with a high level of resolution in output, but rather provide a qualitative conclusion.

In REBA (McAtamney and Corlett, 1993) and RULA (Hignett and McAtamney, 2000) , trunk rotation is given a weighting equivalence of less than 20° flexion, neck rotation is given equivalence to 0-20° neck flexion. The degree of rotation in both of these conditions is not given consideration. QEC (Li and Buckle, 1999) have three rotation levels for consideration, although this part of the investigation is not meant for seated postures. EN1005-4 (2005) is an ‘evaluation of working postures and movements in relation to machinery’, there is a rotation category for the trunk and for the neck (<45° is considered unacceptable). The Swedish National Work Injury Insurance Criteria states that neck rotation should not be greater than 15° for 80% of a work shift or 45° for more than 50% of the work shift (Eklund et al., 1994). Toren and Oberg after consulting the literature define 0-20° as neutral, 20-30° as moderate and >30° to be severe. As detailed here, most guidelines consider the cut-off for rotations at 30-45°, with anything greater than this classified as ‘severe’ or ‘high risk’, yet it is clear that within agriculture the maximum rotations required are often more than double this cut off. In addition, many of the studies of muscle response focus on short duration rotations of <3min. And although within a task, each rotation duration may be considered relatively short, <3min, in reality, when up to 95% of task time is spent in rotation, this amounts to a largely static rotated posture. It is therefore considered important to explore rotations greater than 45° in the trunk and in the head, and also lengthen the duration of exposure. Trunk rotation is given a proportionately insignificant role in the assessment methods detailed above. It is suggested through the collation of the literature in the posture section 2.3.1 in addition to the proposed research that the effect of trunk rotation in occupational exposures will be recognised and scaled appropriately in the new assessment methods.

Analysis of a simple driving task illustrates that there is little distinction between the outcomes of the methods despite the diverse ways of obtaining the results (Morgan, 2010 for ISO/DTR 10687, 2011). For application in a vehicular environment, some methods proved more practical than others. Driving tasks can involve twisting postures and these are accommodated in all of the methods. However the influence of foot pedals, backrest, armrests, seatbelts, steering wheel, joysticks, etc. are not easily included in any method. For example, segment coding could be identical for an individual sitting in a 'good' seat or for them squatting with no support. Therefore a new method is required, to be based upon the most suitable ones here: EN 1005-4 and REBA. Although not specifically designed for use within driving environments, some posture assessment methods have been used. Massaccesi et al. (2003) found that the neck and trunk scores positively correlated with the self-reported neck and trunk discomfort from the operators. The study was conducted with the drivers of street sweeping machines, who use forward bending rotated postures to monitor the brushes.

Posture assessment tools that exist can provide clear guidance on the level of risk seen within the posture and in addition to this allow for guidance on the remedial actions necessary. Irrespective of whether the effects of simultaneous exposure to adverse postures and whole-body vibration are additive or synergistic, there is a clear need for the development of a tool which can account for both of the quantities and provide an indication of the combined level of risk seen. A clear understanding of the risks present and assessment methods for vibration is needed for this to occur. The lack of a suitable assessment tool allows for rotated working postures to be under evaluated and therefore reduced pressure on the provision of alternative solutions.

2.4 Whole-Body Vibration

From section 2.2.3 it is evident that WBV exposure is common in agricultural driving tasks. The issue of exposure to WBV is not limited to agriculture and is present in other off-road driving environments and has received significant research attention. Several epidemiological studies have demonstrated strong evidence for a relationship between WBV and health effects, in particular low back pain. A national study considering Danish employees resulted in a predictive odds ratio of 1.28 proposed for LBP for those exposed to WBV (Xu et al., 1997). Others (Bovenzi and Hulshof, 1999) have suggested the likelihood of developing LBP is much with a calculated odds ratio of 2.3 in an exposed population to WBV when compared with an unexposed population. The difference between these estimates demonstrates the difficulties in confirming the effects from vibration exposures. An additional challenge is due to the fact that no disorder is uniquely associated with vibration and the many confounding or contributing factors in the relationship between WBV and LBP disorders (Magnusson et al., 1998). In the majority of studies focussing on LBP, the contributory factors most often mentioned are posture, loading of the spine and hand-lever operation (Wikstrom, 1993). The issue of confounding or contributory risk factors has also been acknowledged by others. They suggest there may be concern where a worker is exposed to WBV and then immediately required to perform other activities may be at greater risk for LBP if lumbar stability cannot be assured due to affected active and neural subsystems (Santos et al., 2008). In addition, the exposure duration itself may be associated with LBP to a greater extent than the vibration magnitude (Lis et al., 2007).

Vibration is not necessarily a negative sensation, movements and forces acting upon the body can provide feedback to the individual on the situation in hand. Vibration perception in a tractor for example provides information on the feel of the working surface and allows the operator to make judgements on the appropriate speed for continuing the work.

> "Lack of information on machine movements can negatively affect work performance, especially quality… machines on steep slopes and rough terrain can be a real danger if the operator is not able to act according to the *real* movements of the machine"
>
> (Sjøflot, 1985)

2.4.1 Standards and guidelines on whole-body vibration exposures

The magnitude of the issue of WBV and LBP has been formally recognised. It is now the case in several European countries that LBP and certain spinal disorders are recognised and compensated as WBV-related occupational diseases. The case of Mrs. Robinson (Hulsholf et al., 2002) highlighted the disparities in legislation, at that time recognition and compensation for this particular case would have been given in the Netherlands and Belgium, but rejected in France and Germany. The EU physical agents (vibration) directive (PA(V)D) mandates 'limit' and 'action' values for whole-body vibration (values are also provided for hand transmitted vibration, but not discussed here). The mandate set out in the PA(V)D has been incorporated into the 'Control of Vibration at Work Act' (HMSO, 2005) and is enforceable by law with the HSE taking responsibility for enforcement. An action value of $0.5m/s^2$ and a limit value of $1.15m/s^2$ r.m.s. in the worst axis is specified. The exposure limit values or health guidance caution zones included in some of these standards are not, or only to a limited extent, based on systematic epidemiological investigations (Magnusson et al., 1998)

2.4.1.1 ISO 2631-1 Mechanical vibration and shock – Evaluation of human exposure to whole body vibration: part 1- General requirements

Part 1 of ISO 2631-1 is focused on the measurement and evaluation of WBV exposures and is based on the r.m.s. evaluation method for vibration that does not contain large shocks. The frequency ranges considered within the standard are 0.5 – 80Hz for health, comfort and perception and 0.1-0.5Hz for motion sickness. Frequency weightings are used for each axis of vibration to account for the non-linear response of the human body to different frequencies of vibration (Griffin, 1990). Vibration near the resonant frequencies of the body is assumed to have the greatest potential for injury. The resonant frequency of the sitting person is centered around 5Hz vertically and 1-2Hz horizontally (Wilder et al., 1982; Paddan and Griffin, 1988; Fairly and Griffin, 1989; Kitazaki, 1998; Matsumoto and Griffin, 1998; Mansfield and Griffin, 2000). The weighting factor to be applied in the x and y-axis is Wd, with Wk being applied in the z-axis, these are shown below in Figure 4.

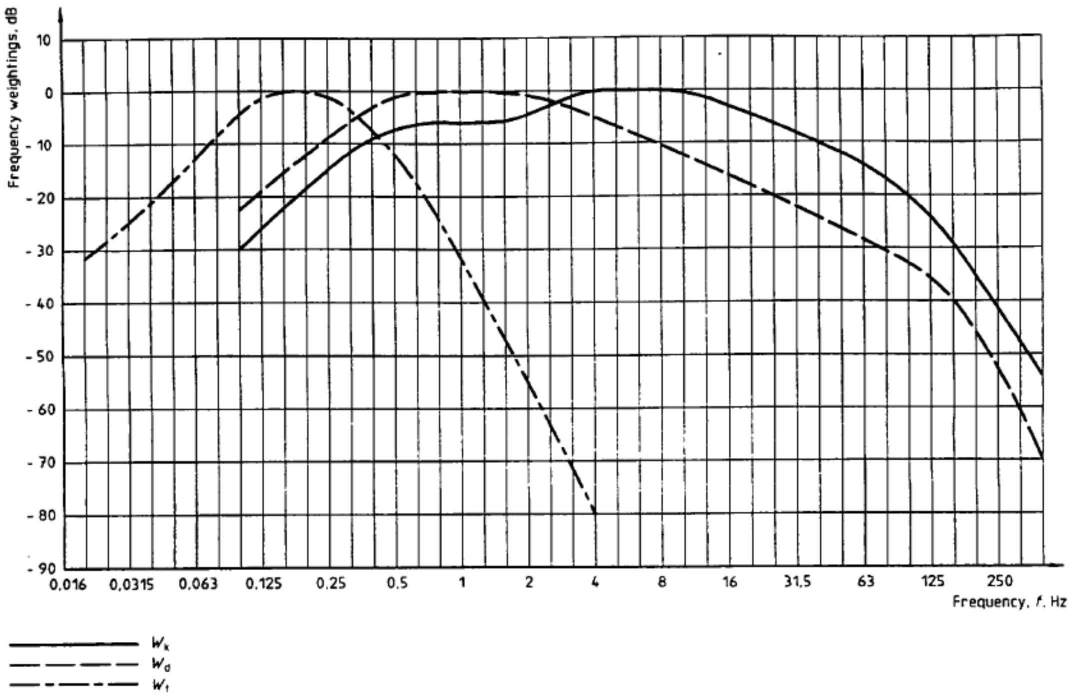


Figure 4 Frequency weighting curves for principal weightings as specified in ISO 2631-1

ISO 2631-1 provides guidance on evaluation of exposure with consideration of health and comfort effects. A multiplication factor of 1.4 is applied to the horizontal axes. An informative annex provides guidance on interpretation with respect to health. The following values are specified in the standard to provide approximate indications of likely reactions to various magnitudes of overall vibration total values in public transport.

Less than 0.315 m/s^2:	not uncomfortable
0.315 m/s^2 to 0.63 m/s^2:	a little uncomfortable
0.5 m/s^2 to 1 m/s^2:	fairly uncomfortable
0.8 m/s^2 to 1.6 m/s^2:	uncomfortable
1.25 m/s^2 to 2.5 m/s^2:	very uncomfortable
Greater than 2 m/s^2:	extremely uncomfortable

ISO2631-1 makes no reference to the posture of the operator and how this may affect the operators comfort and health. However, contained within the annexes is the wording below, which alludes to the possible contributory effect of operator posture:

> "Metabolic and other factors originating from within may have an additional effect on the degeneration. 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."

This guidance, however unspecific is only held within the annexes and therefore not technically part of the standard.

2.4.1.2 ISO2631-5 Mechanical vibration and shock – Evaluation of human exposure to whole body vibration – Part 5: Method for evaluation of vibration containing multiple shocks

ISO2631-5 deals with vibrations mechanical multiple shocks and therefore may also be applicable for exposures in agriculture applying the crest factor evaluation method. Part 5 is specifically concerned with the lumbar spine response to the shock vibration. The standard states:

"The assessment method described in this part of ISO 2631 is based on the predicted response of the vertebral endplate (hard tissue) in an individual… who is maintaining an upright unsupported posture" and then continues "Different postures can result in different responses of the spine". The sentiment of this statement is in contrast to that in part 1 of the standard, where it is 'unknown if these factors can contribute to degeneration of the discs and vertebrae'. Within the calculation of the likelihood of adverse health effects, a constant is used to represent the static stress due to gravitational force. This value, notated 'c' within the standard, is provided at 0.25MPa for a driving posture, although no guidance is given of how one might amend this is the operator is not in an upright seated posture. Contained within the annex of the standard is the statement "A bending forward of twisting posture is likely to increase the adverse health effect." However, again this is purely informative and not technically part of the standard.

2.5 Combined exposure to trunk rotation and WBV

It has been suggested that exposure to WBV and postural stress are co-founding factors in the development of disorders of the spine (Kittusamy and Bucholz, 2004; Kittusamy, 2002; Johanning, 1991). Lis et al. (2007) suggest that co-exposure to WBV and awkward postures increased the risk of LBP fourfold when compared with the risk factors alone. Bovenzi et al. (2002) in a study with port machinery operators found the incidence of LBP was significantly greater in those exposed to WBV and postural load, and in addition, the presence of these two factors gave an excessive risk for lumbar disc herniation. In further studies, Magnusson et al. (1998) demonstrated how the cumulative effect of vibration and adverse posture is not confined to the back, with similar results found for the neck, arm, hip and knee. In a study on subway operators with similar vibration exposure conditions, drivers reported more neck problems than switch board operators, the main difference between the groups attributed to their postures whilst working (Johanning, 1991).

Twisted posture in a vibrational environment has been shown to cause an increased metabolic rate compared to twisted posture or vibration as single exposure variables (Magnusson et al., 1987). Back muscle fatigue has been demonstrated when subjects are exposed to WBV and a twisted posture (Hansson et al., 1991). Newell and Mansfield (2007) found decrements in reaction time and increased workloads in operators with twisted postures exposed to vibration. Seidel's conceptual framework for the effect of posture and WBV stress, in addition to other factors, on the spinal structures is displayed in Figure 5.

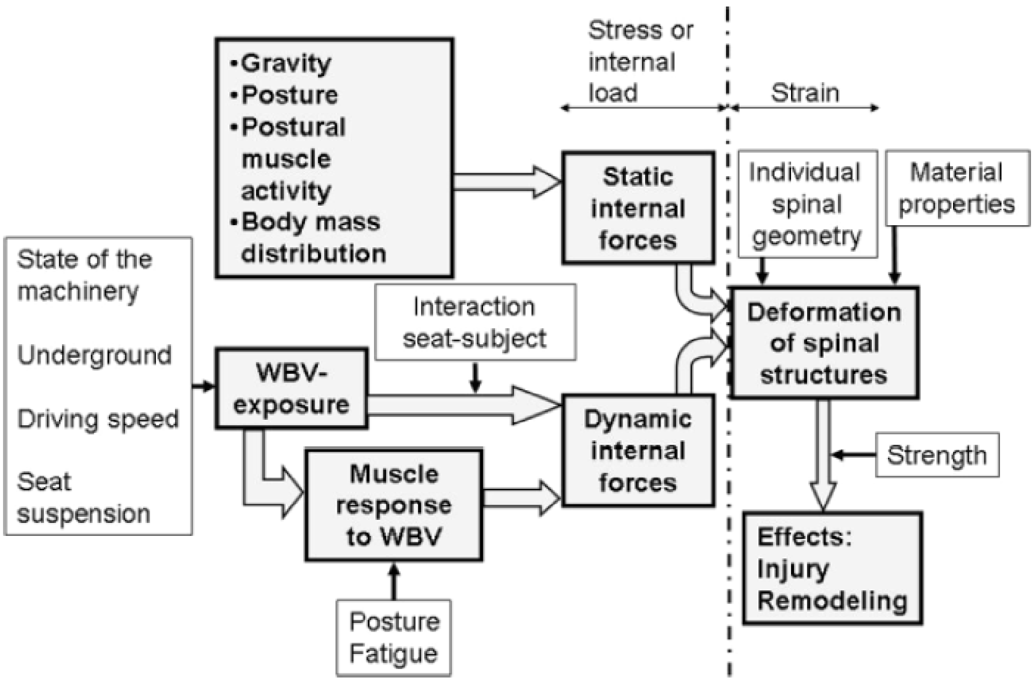


Figure 5 Conceptual framework of the relationship between WBV exposure and spinal health (from Seidel, 2005)

This model was developed from an extensive review of the literature, from epidemiological studies through to biodynamic modelling, and although the resulting framework is presented above, Seidel concurs that more research is required in the following targeted areas.

- The nonlinearity of biodynamics
- The effects of WBV in x- and y-axes

- The strength of the spine for shear
- The contact parameters between the seat and man
- The significances of posture and muscle activity
- The material properties of spinal structures

Structural loading factors would include the biomechanical factors that contribute to loading on the spinal structures, such as intra-abdominal pressure, muscle activity, and the imposed trunk moment, as well as the actual loads on the structures of the spine (Davis and Marras, 2000)

Others researching in the area have acknowledged that an exposure-response relationship is not currently possible to develop for WBV, posture and LBP (Kittusamy and Bucholz, 2004).

Some researchers have attempted to measure both exposures at once, and estimate the resulting risk. Using the Palm-TRAC system to simultaneously analyze WBV and task demands, Tiemessen et al. (2007) were able to acknowledge that there were certain points within the task in which both the magnitude of the vibration exposure and the posture required are undesirable therefore one or both should be avoided at that point. The German Institute for Occupational Health have devised a simultaneous measurement system for vibration and posture(Ellegast and Kupfer, 2000) and have devised a risk matrix which predicts a risk rating of low medium or high for such interactions, although it is suggested that the interrelations detailed in the risk matrix require further consideration.

2.6 Anatomy and physiology of the back and spine

The muscles of the spine are covered by superficial back muscles such as the trapezius and latissimus dorsi. The most superior of the spinal muscles are the semispinalis capitis and the more superficial splenius capitis. Inferior to these are the erector spinae muscles, lateral divisions of these are the spinalis, longissimus and iliocostalis. In the lower lumbar region, the division between the longissimus and the iliocostalis muscle becomes indiscreet, and is often known collectively as the sacrospinalis muscles. The muscles in the lower portion of the back, e.g. the multifidus, provide support for the upright posture. Those in the central portion, adjacent to the spine, provide stability to the spinal column and enable flexion, extension and rotation of the spine. The trapezius, being one of the largest and most superficial muscles of the trunk, provides both postural support and motion. It links the cervical and thoracic vertebrae with the scapula to aid head, neck and shoulder movement. From a mechanical point of view, the spine would be wholly unstable in the sagittal plane if it were not for the support of its ligaments tendons and muscles. Controlled shortening or lengthening of an associated muscle or muscle group allows the movement or stabilisation of the trunk in a given posture. The spinal muscles also play a part in the shock absorbing functionality of the back, which help to relieve the spine of large loads and exhibit a protective function during trauma.

The range of motion when twisting from a neutral position to a maximum trunk rotation in a seated posture varies in the literature between 70° and 82° (Mayer et al., 1985; Kumar et al., 1996). Toren (2001) suggests that considerable muscle effort may be required to keep the back strengthened particularly when seated postures in which the trunk is deviated or twisted more than 20° are adopted. Generated muscle tension is known to increase spinal loading (Corlett, 1989). Twisting the trunk to face rearwards involves overcoming the passive resistance of the tissues of the trunk. This passive resistance is low at the neutral position, and increases progressively as the trunk is twisted (McGill et al., 1994; Bodén and Oberg, 1998).

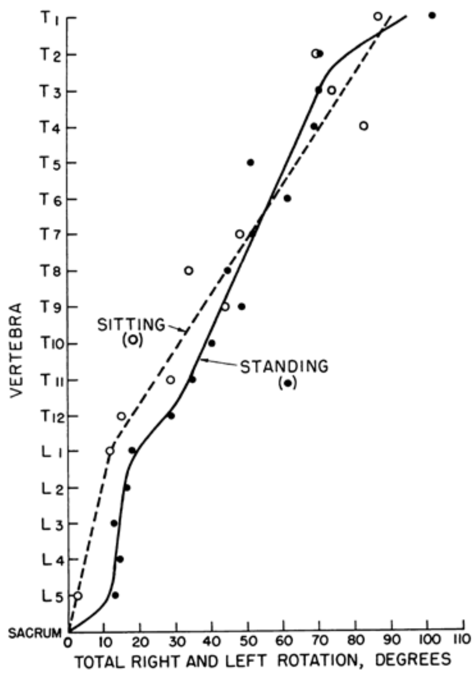


Figure 6 Maximum total axial rotation of the thoracolumbar spine in the standing and sitting positions (pelvis immobilized) in Gregerson and Lucas, 1967

There is discussion about the amount of rotation possible through the spine, with many noting that the lumbar vertebrae do not contribute to rotation (Oliver and Middleditch, 1991). Illustrated in Figure 6 is the results of a study conducted using pins inserted into the human spinal vertebrae, allowing the actual movement to be measured. It can be seen that there is relatively little difference between the contributions of the vertebrae whilst sitting or standing.

2.6.1 Injury to the back and spine

The negative impact of trunk rotation and WBV exposures on the body often results in injury, however back injury embodies a variety of phenomena, few of which can readily be distinguished either in national statistical data or in epidemiologic studies (Troup, 1984). Good muscle health requires the muscle to be supple and flexible with a sufficient blood and nerve supply, a compromise on any of these can result in poor muscle health, possibly leading to an impairment of function and/or injury. It has been shown that muscle dysfunction commonly accompanies degenerative joint disease (Jowlett and Fidler *in* Oliver and Middleditch,1991) the reverse also being true.

> “Mechanical stresses such as those imposed by prolonged asymmetrical postures have a marked effect on the muscles and soft tissues, causing fibroblasts along the lines of stress to multiply more rapidly and produce more collagen”
>
> (Oliver and Middleditch, 1991, p.91).

This increase in collagen reduces the space in the connective tissue of muscle usually reserved for blood, nerve and lymph supply. In the longer term, this increase in collagen reduces the elasticity of the muscle and begins to replace the active fibres present, as collagen is reasonably resistant to enzyme interaction, such changes are consequently irreversible. Injury is suggested to occur with biomechanical perturbations of the tissues and occurs when tissue tolerance has been exceeded. This can be modulated by a sudden load, whether due to mal-coordination or jerky contraction stretching the tissue beyond tolerance. Both of these phenomena are known occurrences in fatiguing muscles (Kumar et al., 2001). In addition Kumar et al. (2001) found a significant difference between the fatiguing rates for different muscles, which suggests a pattern of loading in the back which may be contributory to the development of LBP.

High velocity compression results in vertebral burst fractures, although this is not often associated with injuries gained in an occupational setting (Adams and Dolan, 1995). It is much more likely that and injury such as disc herniation is associated with relevance to work. Herniation is less likely to be produced in one instance and is more consistently produced under many cycles of combined compression, flexion and torsional loading (Adams and Hutton, 1985). This school of thought has been extended to include research linking disc herniation with sedentary occupations and the sitting posture (Videman et al., 1990). It is also recognised in Videmans’ research that occupational factors suspected of accelerating spinal degeneration include heavy physical loading, lifting, bending and twisting, prolonged sitting in sustained non-neutral postures and vehicular driving. Due to the omnipresent nature of LBP, epidemiological studies in the area focus on the visible areas of LBP such as fractures or herniated discs. The graph in Figure 7 illustrates that the prevalence of the visible disorders is proportionately low, therefore making epidemiological studies looking for the visible effects of an exposure particularly difficult.

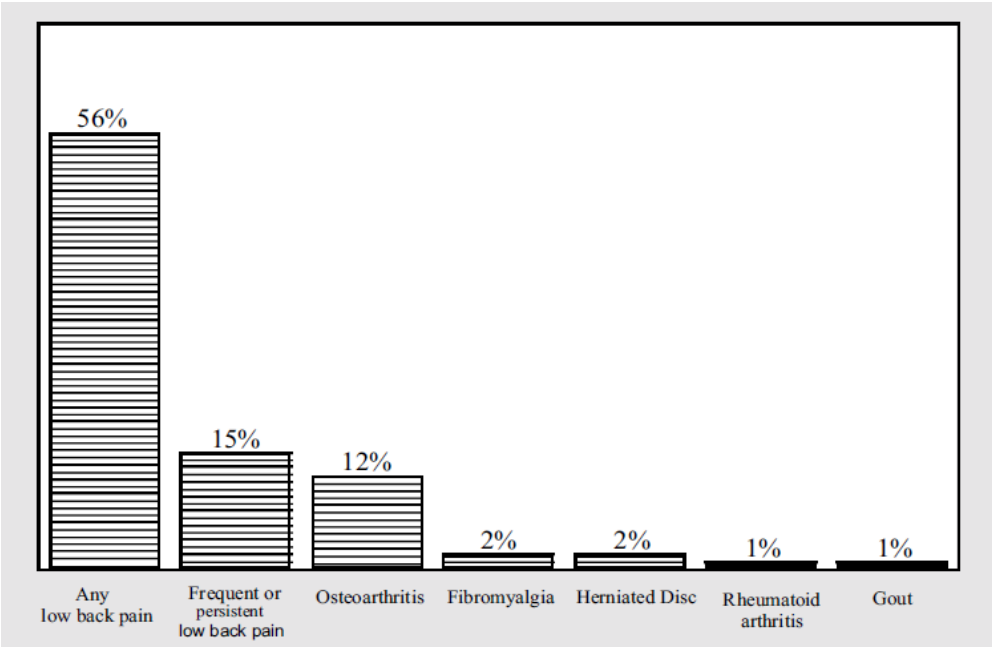


Figure 7 Low back pain ranks No. 1 in musculoskeletal disorders (from Lawrence et al., 1998)

Dr Bruntland, Director General of the World Health Organisation, has suggested that back pain has reached 'epidemic' proportions as we move into the new millennium (WHO, 2003). The social and economic costs are enormous since pain in the low back affects more the 70% of the general population at some time in their life. This economic impact is such as it is associated with high rates of sick leave and disability pensions.

Low back pain is a difficult area of focus due to the many ways in which it can develop. It may be the case that a particular task preformed over a long period of time may instigate the symptoms, or that the combination of stresses placed upon the back from day to day will eventually cause a feeling of discomfort in the lower back. Norman et al. (1998) have shown that, among the physical loading factors, variables tend to cluster in four independent categories: peak spinal loads, accumulated spinal loads, forces in the hands, and trunk kinematic (postural) variables. It is also acknowledged that greater loading on the tissues can contribute to an accelerated failure point (McGill, 1997). In essence, it is felt important to stress that the injury process may not only be associated with very high loads, but rather with cumulative trauma from relatively low loads existing over an extended time frame. Characteristics of the load itself affect the failure development. Load rate, mode of load compression, direction of force progression and properties of the tissue itself are all factors which determine the type and extent of the tissue damage. The discussion of the intricacies of the pathogenesis of low back injury is not included here, it is felt more important to discuss the possible causes of such injury and how these may be manifested in an occupational setting. It is felt important to clarify at this point that injury from herein is not just failure in the gross form where proper function cannot be maintained, but also the smallest form of tissue irritation that may take the form of pain or injury when established.

The different examples of injury causation can be seen in the case examples given by McGill (1997):

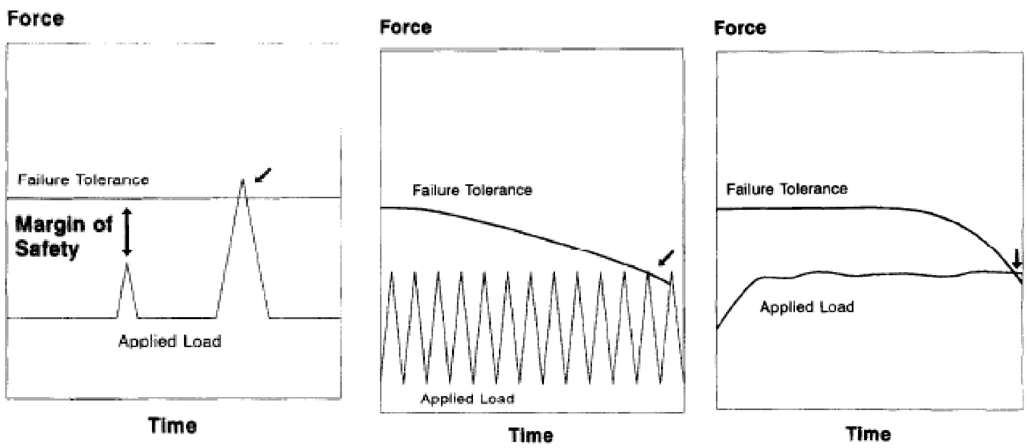


Figure 8 (Applied compressive load exceeds the strength/failure tolerance of the supporting tissues left); Repeated sub-failure loads leads to tissue fatigue and failure on the Nth repetition of load (middle); Loading of passive tissues for a long duration which fail at the Nth% of tissue strain – strain progresses with time, steadily reducing the margin for safety (right), all from McGill (1997)

Unlike those described in Figure 8, most risk factors cannot be described by a single parameter; instead they encompass several parameters which are combined into an exposure metric. For example driving a machine includes postural and vibration risk factors. The relationship between most work-related risk factors and the occurrence of MSDs is not linear, in that an increase in exposure is not always associated with an increased risk. Burdorf suggests that a U-shaped curve is probably a better description of the nature of the association encompassing both an absence of any load and excessive load (Burdorf et al., 1999).

2.6.2 Injury and fatigue

Fatigue is a complex occurrence and it is not uncommon to feel more fatigued after the same event on different days. Historically fatigue has been divided into three main categories. The first being subjective fatigue, characterised by a decline in alertness, mental concentration, motivation and other psychological factors. The second was objective fatigue, characterised by a decline in work output. The third was physiological fatigue, portrayed by changes in physiological processes (Bills 1943 *in* Åstand et al.2003). Physiological fatigue can be manifested in localised muscular fatigue (Chaffin, 1973) and is associated with external manifestations such as the inability to maintain a desired force output, muscle tremor, and localised pain. Fatigue is induced by the required need for sustained muscular contractions, its effects are localised to the individual muscles or synergistic group performing the contraction.

Muscle fatigue is historically recognised as a form of protection (Hough, 1902; McCully and Faulkner, 1986; Friden and Lieber, 1992), preventing overexertion and therefore injury for whole or part of the body. Fatigue can be general and systematic or it can be local and, as a rule, muscular in nature. Åstrand et al. (2003) suggest that subjective feelings of fatigue usually occur at the end of a working day when the average workload exceeds 30-40% of an individual's maximal aerobic power and certainly when the demand exceeds 50%. A simple determinant of muscular fatigue is a loss in muscular performance, and is defined by the 'failure to maintain the required or expected force' (Edwards, 1981) or 'any exercise-induced reduction in the maximal capacity to generate force or power output' (Vollestad, 1997). The nature of fatigue is complex due to the multiple factors involved in its manifestation and the relative importance of each is dependent on the fibre type composition of the contracting muscles, the intensity, type and duration of the contractile activity and the individuals degree of fitness (Fitts, 1994). Basmajian and de Luca (1985) equate muscular fatigue to that of a bridge collapsing, that is the fatigue in the steel casual of the collapse may only be visible at the last point, however, the crystalline structure of the steel will have been undergoing chemical and physical changes prior to the failure point. In muscles, the failure point may be observed by the inability to maintain a certain workload, however, the biomechanical processes leading to this point may well be visible before the contractile fatigue becomes visible.

> "Time integrated fatigue may lead to different types of injuries during the operation of [the machine], such fatigue stretched over a period of months and years may cause physical, physiological stresses manifested in MSDs in the long run"
>
> (Tiwari and Gite, 2006).

Possible causes of fatigue cited in the literature (Kumar and Mital, 1996; Fitts, 1994), include the depletion of the muscles' energy supplies and the subsequent accumulation of metabolic products such as lactate and hydrogen ions. However, as demonstrated by Sjøgaard (1990), that although such factors may be influential in the development of fatigue, no major depletion of ATP stores is seen even when large forces are generated. In addition, in cases where the loading of the muscle is far below the maximum and where energy stores should suffice, an indication of muscular fatigue (an increase in the muscle electrical activity) is still seen (Jørgensen et al., 1988). A disturbance in the spread of the action potential across the muscle fibre membrane and a reduction in the electromechanical coupling are two suggested reasons for this increase.

McCully and Faulkner (1986) found that the extent of muscle injury was dependant not upon the velocity of lengthening, but on the degree of force developed during lengthening contractions. This theory has been developed to include the hypothesis that injury occurs in the first five minutes of contractile activity, due to the fact that once past this point, the muscle in question will have suffered sufficient fatigue to reduce the fibre force below what is required for development of injury (Jones et al., 1989; Leiber et al., 1991).). McCutcheon et al. (1992) and Friden and Leiber (1992) illustrated that the degree of muscle injury appears dependent on the nature of contraction rather than the duration of work, which proves interesting when contrasted with current tools for posture evaluation that centre on activity duration in addition to force (Hignett and McAtmney, 2000; EN 1005-4, 2005). Recent studies (Yokoyama et al., 2007) show that muscle fatigue can enhance the likelihood that one develops pain to a mild exposures. Clinically this could relate to the development of pain from such conditions as repetitive strain injury (RSI), and may relate to the interrelationship between chronic pain and fatigue.

2.7 Electromyography (EMG)

Electromyography (EMG) is a widely used method for investigating muscular response to stimuli. It provides a non-invasive index of the level of muscular activation present (Duchêne and Goubel, 1993). The ability to measure many muscles at once, and match this to investigation of subjective discomfort are the primary reasons for choosing this method. There are two primary considerations when choosing EMG as a methodology. One option is to measure the muscle activity and the other to measure muscular fatigue. The former illustrates the immediate response to a load, and can illustrate which muscles are activated by a particular task. The latter provides a more descriptive analysis of the effect of the activation, therefore is chosen as the primary method of investigation here. Secondarily, EMG can be measured intra-muscularly with fine wire electrodes, or more commonly on the skin surface with surface electrodes. The latter is almost solely used in the investigation of occupational exposures, and therefore the only method considered herein.

2.7.1 EMG signal processing methods

There are two main methods considered for investigating the EMG signal and its nature. The signal is normally a function of time and is describable in terms of its amplitude and frequency. In work-physiological and ergonomic studies, both indicators have been applied in order to identify the fatiguing process during occupational work and to derive recommendations for work design (Örtengren et al., 1975; Christensen, 1986; Jørgensen et al., 1991, Luttmann et al., 1996). These methods are discussed below.

2.7.1.1 Time domain processing methods

The main indicators of EMG amplitude are the mean absolute value (MAV), also called the average rectified value (ARV), and root-mean-square (RMS) value. The amplitude is derived from the raw EMG by rectification and low-pass filtering. The increase in electrical activity (EA) is a well-used method of fatigue identification (Ng et al., 1997, Van Dieen et al., 1993, Van Dieen et al., 1996; Luttmann et al., 1996). A uniform functional relationship between the mechanical force production and the EMG amplitude is not entirely settled (Kumar, 1996). Laurig (1975) demonstrated a relationship between the possible duration of interrupted work or 'endurance time' and the fatigue induced increase in the electrical activity, EA. He suggested that a shallow increase in the EA indicates slow fatiguing, whereas a steep increase in the EA suggests a fast fatiguing and therefore a shorter endurance time. A regression function can be produced, in order to provide a method for predicting corresponding endurance times to the EA seen for the task. Analysis of the changes in EA in a specific frequency band (5-30Hz), the 'frequency banding' technique has been suggested to increase reliability of measures (Dolan et al., 1995). The linearity seen in this section of the EMG can also be of assistance to frequency analysis parameters. However, non-linear behaviour is also seen within this frequency band, therefore the usefulness of the method is questioned (Kumar et al., 2001).

EMG is often normalised to, or expressed as a percentage of, the maximum electrical activity obtained during a maximum electrical activity (MEA) obtained during static maximum voluntary contraction (MVC). However, whereas voluntary efforts that produce MVCs from some muscles have been published (Yang and Winter, 1983), the method to achieve maximum signals for normalisation from the trunk musculature remains to be established (McGill, 2005). No single trunk muscle is specifically designed to produce axial rotation because the generation of axial torque is coupled with the production of either lateral bending or sagittal plane torque or both (McGill, 2005), therefore establishing a MVC with a test contraction would be impractical.

2.7.1.2 Frequency domain processing methods

In muscle fatigue, the power spectral density function (PSD) of the myoelectric signal undergoes a frequency shift and compression due to sustained contractions (Basmajian and DeLuca, 1985; De Luca, 1984; Kogi and Hakamada, 1962; Merletti et al., 1990, 1991; Oberg et al., 1990, Kumar et al., 2001). Mean power frequency (MPF), median frequency (MF) and zero crossings are the spectral shift indicators most frequently used in the literature (DeLuca, 1984; Hägg, 1981; Knaflitz et al., 1991; Merletti et al., 1991; Luttmann et al., 1996) where usually only one of the characteristics is used. The zero crossing rate or zero-crossing frequency of the signal is defined as half the number of zero crossings of the signal per second (Hägg, 1981; Inbar et al., 1986, Cifrek et al, 2009). A Gaussian distribution of the EMG signal to its derivative is necessary for the zero crossings method, and it is highly affected by noise therefore is not a favoured choice (Cifrek et al, 2009).

Dedicated studies have focused on the specific properties of both the MF and MPF indicators. It is suggested that the MF should be the preferred measure due to its low sensitivity to noise (Stulen and de Luca, 1981).Others (Hary et al., 1982) have concluded that MPF is more stable and more sensitive to changes in the underlying spectra, and therefore is a more reliable indicator of fatigue. In addition, a study by Nagate et al. (1990) reveals that the MF is less sensitive than the MPF in the detection of differences in the power spectra and that MPF reflects changes occurring at even low levels of percentage maximum voluntary contraction (MVC) which would be important for the seated driving tasks as these are unlikely to reach the MVC. Some studies have been made into the relationship between MF and MPF and muscular force level on static and dynamic contractions (Luttmann, 1996). The rate of decline of MF during sustained contraction is the most used index of muscle fatigue (Mannion et al., 1997; Roy et al., 1989; Lariviére et al., 2002). Merletti et al., (1990) found that in slowly fatiguing muscles these variables showed a linear decrease with time. However, in a rapidly fatiguing muscle a curvilinear pattern was reported. Due to the lack of clear distinction between the MF and MPF parameters, both will be calculated in the first instance, until a preference is clear.

2.7.1.3 Joint Analysis of Spectrum and Amplitude

Since 1912 and the work of Piper, the frequency components of the EMG signal have been known to decrease when a contraction is sustained. In addition Cobb and Forbes (1923) observed a consistent increase in the EMG amplitude during such contractions. Lindström et al (1970) and de Luca (1979) noted that both phenomena are linked. They explained this by noting that during a sustained contraction the low-frequency components of the EMG signal increase and therefore more EMG signal energy will be transmitted through the low-pass filtering effect of the body tissue. Consequently, the magnitude of the two related phenomena depend of a number of factors, the contraction force level, time into the contraction, type of electrode used, thickness of subcutaneous tissue and the muscle of investigation.

Oberg (1995) in a comparative study on trapezius, found that measures of fatigue based on amplitude alone jeopardized both the calibration and estimation of muscle load obscuring assessment of fatigue. Thus he argued against the EMG amplitude without simultaneous accounting for spectral parameters. A shift in the frequency towards the lower end of the spectrum and the level of electrical activity are both indicators of fatigue, however, both are also indicators of muscle activity. Therefore in a task where muscle usage varies, fatigue may be incorrectly suggested, or missed in the evaluation. To reduce the likelihood of this occurrence, Luttmann et al. (1996) propose a method by which both the spectrum and level of activity can be jointly analysed. Time-related changes in the MF are plotted as a function of the time related changes in the EA. Using Figure 9 to illustrate, it is clear to see that when both are analyses simultaneously in this way, fatigue can be isolated as the cause for the change in EMG.

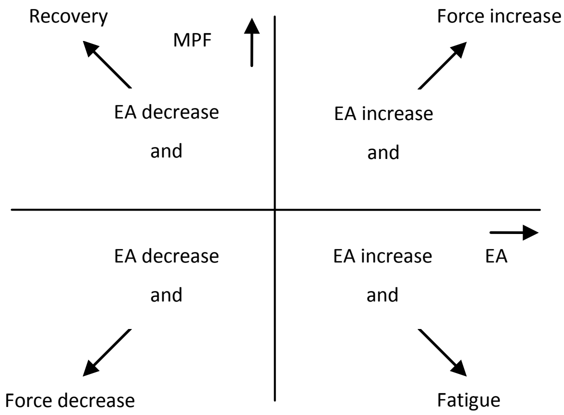


Figure 9 Joint analysis of spectra and amplitudes, from Luttmann et al., 1996

In the ideal situation, the contraction level of the muscle concerned will remain constant, so that this interaction can be ruled out from the analysis. In the laboratory, this is often possible because the contraction can be controlled; however it is often not the case in field measurements. One possibility of obtaining sections with a constant contraction is to include test contractions within the work sequence (Hägg et al. 1987, Hägg, 1991). However it is often not possible to interrupt the work sequence with such requirements, therefore an alternative method is suggested by Ballé et al. (1982) and Luttmann et al. (1988) where work sequences are coded according to their content and evaluation is limited to these sections.

2.7.2 Muscles proposed for investigation

The back muscles are composed of several fascicles that act synergistically to produce movement. Even if a load is kept constant, there will be load sharing between the muscles of the back. To account for this in analysis, some authors advocate the averaging of bilateral or homologous muscles (Nargol et al., 1999) or even of several muscles (Van Dieen et al., 1998; Kankaapaa et al., 1998) to get EMG indices with better measurement properties in terms of validity and reliability. This is not a possible solution here due to the requirement for detailed analysis of the effects of the twist which may require bilateral comparisons.

The muscles used in the evaluation of the effect of trunk rotation are varied. In addition, coupled with those used in the evaluation of WBV the muscles investigated in the literature are varied. Bjurveld et al., (1973 in Wilder, 1993) showed that the trapezius and erector spinae are activated most under exposure to WBV. The list of the muscles therefore chosen for investigation is listed in Table 4 combined with the studies these muscles have been investigated in and the types of work where they were investigated.

Table 4 Muscles chosen for investigation

Muscles	Based on studies	Type of work
Trapezius upper	Hagberg, 1981; Kadefors et al., 1994	Shoulder flexion and elevation
Trapezius decendens	Blüthner et al, 2001; Åström et al., 2009	WBV during relaxed, upright and bent forward postures; vibration effects at the neck
Erector spinae	O'Brien and Potvin, 1997; Kumar et al., 2001; Kumar et al., 1999; Kumar et al., 1998; Lavender et al., 1994; Pope et al., 1987; Marras et al., 1998; Marras and Granata, 1995; Torén, 2001; Zimmerman and Cook, 1997; Wilder et al., 1985; Magnusson et al., 1988; Santos et al., 2008; Seroussi et al. 1989; Seidel, 1988; Blüthner et al, 2002; de Oliviera et al., 2004; Hansson et al., 1991	Prone extended postures; Isometric twists; WBV
Multifidus	Bajmajian, 1978; Santos et al., 2008	WBV

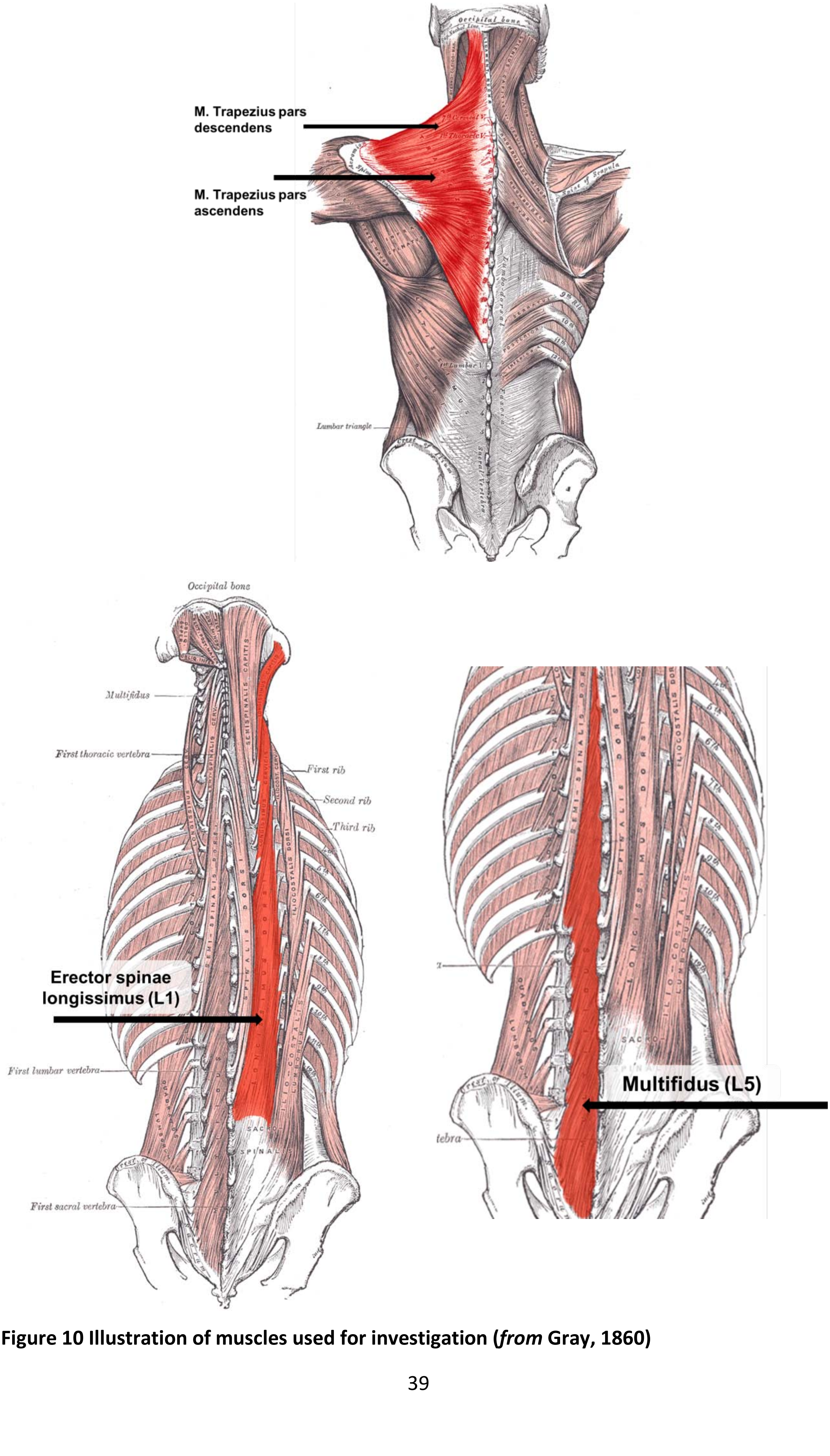


Figure 10 Illustration of muscles used for investigation (*from* Gray, 1860)

2.8 Subjective methods

Pain intensity ratings appear to parallel the development of muscle fatigue, as demonstrated in the graph shown in Figure 11.

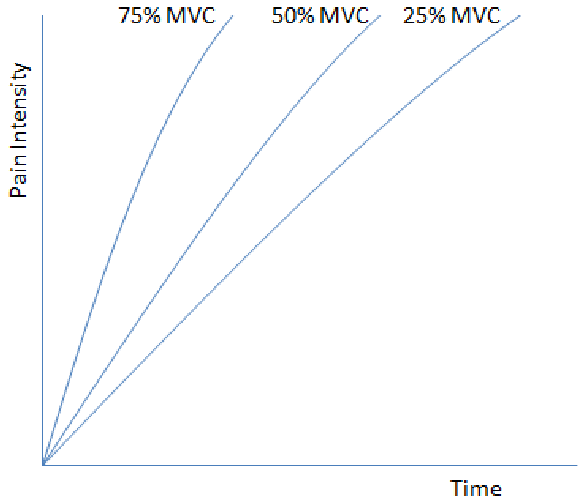


Figure 11 Pain intensity-time curve adapted from (Heyward 1973)

Discomfort is a generic and subjective sensation that arises when a human physiological homeostasis, psychological well-being, or both, are negatively affected (Shen and Parsons 1997). Both postural and vibration discomfort are physiological aspects of human discomfort. Subjective discomfort is widely used in the automotive industry to differentiate between seat designs (Gyi and Porter, 1999; Kyung et al., 2008). In laboratory settings, the use of subjective discomfort is commonly used alongside objective measures, often as a reference point for more variable experimental techniques, such as EMG. Discomfort may be assessed during the task, at regular pre-defined intervals, before and after an exposure, or as a one off survey of the comfort of the operators. Much of the body part discomfort work is based on that of Corlett and Bishop (1976) who introduced their body map and a 7-point rating scale anchored at extremely uncomfortable and extremely comfortable at opposing ends as a way of assessing subjective discomfort.

Seated discomfort increases over time (El Falou et al., 2003; Na et al., 2005), and this increases further with an undesirable operator posture (Pope et al., 1986). The use of subjective body part discomfort in the evaluation of operator exposures is often limited to subsequent questionnaire analysis of operator health status. The use of subjective discomfort is discussed further in the Methodologies (Section 3.3.2).

2.9 Summary

There are two main areas of concern in agricultural driving exposures: the posture of the operator and their vibration exposure. There is no clear recommendation in the Physical Agents (Vibration) Directive on how to control for the posture of the operator when assessing vibration exposures. There is little provision in the physical ergonomics assessments of posture for driving tasks, in particular for seated rotated postures, or for how to account for vibration exposure. Therefore, no clear recommendation can be made to operators, employers, or manufacturers on acceptable exposure magnitudes, or durations. There is little acknowledgement of combined risk effects within the literature, epidemiological studies are particularly difficult to complete with such complex interacting risk factors. An estimation of the likely risks from experts within the research areas would provide an indication of the likely health effects. Developments in cab design have been made, with the introduction of twisting seat bases, although the evaluation of their effect upon the operator has not been completed. The occupational exposures themselves will have changed with the introduction of new seats and suspension systems; an assessment of typical current exposures is needed.

The method of subjective discomfort rating is widely used in the automotive industry, and in the laboratory based investigation of exposures. Electromyography is common in the investigation of specific muscular responses, but less well used in the investigation of occupational exposures. A combined methodology based on these two methods is proposed to allow for the full investigation of twisted exposures in a vibrational environment.

CHAPTER 3 - Experimental Methodologies

This Chapter describes the experimental design, equipment used, the test configurations, calibration and validation methods. The analysis methods used are described, and include electromyography (EMG) activity and frequency analysis, statistical comparisons of data, posture and task analysis. Table 5 provides an introduction to the studies that are included in this thesis, including details of the equipment used and methods of analysis employed.

3.1 Experimental Overview

Three lab studies, a field study and a survey were conducted for this thesis, and 6 Chapters of this thesis are dedicated to reporting the results and analysis of these studies. The experimental laboratory work was carried out in the Environmental Ergonomics Research Laboratory at Loughborough University. The laboratory studies investigated the biomechanical and subjective responses of the subjects to the stimuli. The field study examines the ergonomic risk exposures in typical agricultural driving tasks; in addition, the survey of expert opinion assembles current knowledge and opinion on exposures including vibration and twist elements.

3.2 Experimental Development

Table 5 Outline of field and laboratory studies main objectives and measurement conditions

Study	Objectives	Equipment	Measurements	Conditions
Evaluation of in-field agricultural driving tasks (Chapter 4)	To target specific agricultural driving tasks in order to determine the magnitudes of vibration and driving postures present. To investigate situations where trunk rotation and WBV may be experienced simultaneously. To collect informal data on exposures from the operators.	Biometrics data logger, NexGen triaxial accelerometer x2, digital video camera, Geko GPS logger	Floor and seat acceleration, posture assessment, vehicle location and speed, task analysis	Round baling, square baling, forage harvesting, ploughing, buck-raking, trailer towing
Survey of expert opinion (Chapter 5)	To assess current expert opinion on exposures on symptom display, current guidelines, assessment methods and recommendations for environments with both WBV and twisted postures	Paper-based questionnaire	Statistical comparison of responses	Operators, ergonomists (posture experts) and whole-body vibration experts

Influence of axial rotation (Chapter 6)	To improve understanding of the musculoskeletal discomfort response of the neck shoulders and back to axial rotation. To determine subjectively judged discomfort and objectively judged muscle fatigue for the exposures, and to establish if a correlation between subjective and objective measures exists	Biometrics EMG sensors (SX230) x8, Biometrics datalogger, digital camera	Subjective measurements (Porter's body map), Electromyography, Posture assessments	P0 (control); P1 (110°); P2 (170°)
Influence of whole-body vibration (Chapter 7)	To improve understanding of the musculoskeletal discomfort response of the neck shoulders and back to WBV. To determine subjectively judged discomfort and objectively judged muscle fatigue for the exposures, and to establish if a correlation between subjective and objective measures exists	6 DOF vibration simulator, triaxial accelerometers x5, Biometrics EMG sensors (SX230) x8, Biometrics datalogger x2, digital camera	Subjective measurements (Porter's), Electromyography, floor and seat acceleration	V0 (control); V1 (0.5m/s² r.m.s); V2 (1.0m/s² r.m.s)

Study	Objectives	Equipment	Measurements	Conditions
Influence of both axial rotation and WBV (Chapter 8)	To improve understanding of the musculoskeletal discomfort response of the neck shoulders and back to axial rotation and WBV. To determine subjectively judged discomfort and objectively judged muscle fatigue for the exposures, and to establish if a correlation between subjective and objective measures exists and to investigate the possibility of an interaction effect between WBV and axial rotation exposure	6 DOF vibration simulator, triaxial accelerometers x5, Biometrics EMG sensors (SX230) x8, Biometrics datalogger x2, digital camera, CUELA posture measurement system	Subjective measurements (Porter's), Electromyography, floor and seat acceleration, widaan risk assessment	PV0 (control); P1V1 (110°, $0.5 m/s^2$); P2V1 (170°, $0.5 m/s^2$); P1V2 (110°, $1.0 m/s^2$); P2V2 (170°, $1.0 m/s^2$)

Influence of WBV and dynamic axial rotation (Chapter 9)	To improve understanding of the effect of trunk motion on discomfort manifestation and muscle fatigue, whilst under exposure to WBV. To assess if assumptions for static postures can be applied for those where motion is also present, to assess if seat base rotation reduces discomfort and muscle fatigue	6 DOF vibration simulator, triaxial accelerometers x5, Biometrics EMG sensors (SX230) x8, Biometrics datalogger x2, digital camera, CUELA posture measurement system	Subjective measurements (Porter's body map), Electromyography, floor and seat acceleration, widaan risk assessment	Control (control); SB0 P0 (0.5m/s², seat base 0°, forward facing posture); SB0 Pmov (0.5m/s², seat base 0°, dynamic rotation); SB30 P0 (0.5m/s², seat base 30°, forward facing posture); SB30 Pmov (0.5m/s², seat base 30°, dynamic rotation); SB90 Pmov (0.5m/s², 90° seat base, dynamic rotation)

The studies were designed so that, where possible, the results and conclusions from one study could inform the design of the next. Due to the levels of discomfort experienced in the single exposure studies (Chapter 6 and Chapter 7), when planning the experiment into the combined effects of twist and WBV, the decision was taken to reduce the duration to 7 minutes for each exposure. In addition, as a result of the operator responses in the expert opinion review and informal discussions with operators in the field study, Porter's body map was amended to include the buttocks and thighs. The expert opinion review questionnaire was designed to encompass tasks seen in the field study, so there may be some comparison of recommendations for tasks, and what was in use in the field. The dynamic rotation study was based on the task analysis results from the field study and also utilised the newly modified Porter's with buttocks and thighs.

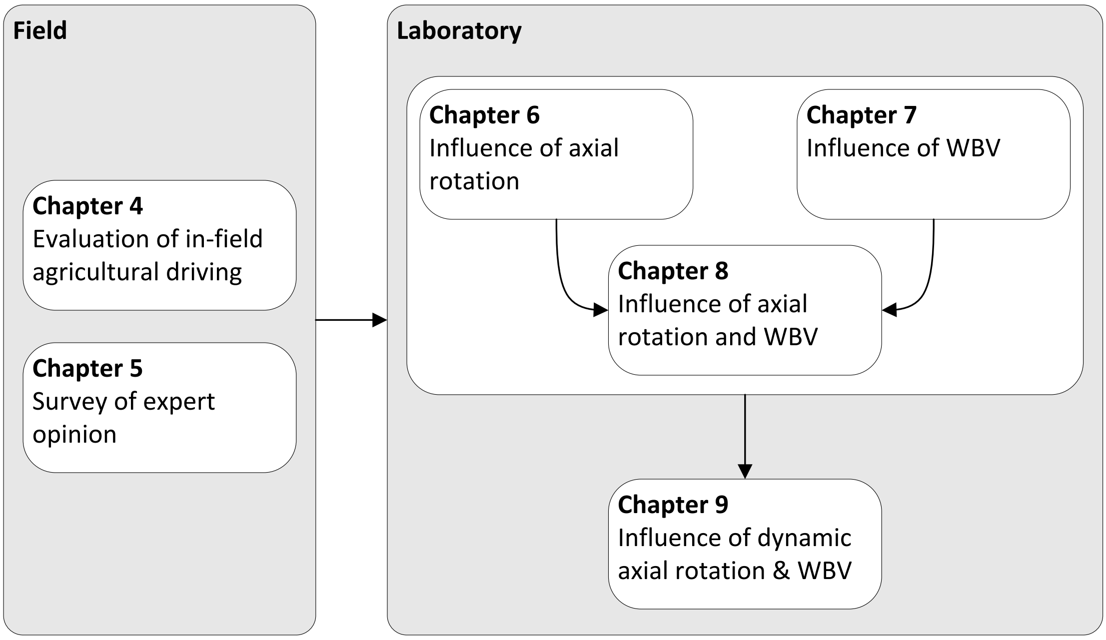


Figure 12 Diagrammatic of experimental conditions and interactions. Dotted lines indicate influence flow, full lines denote information flow

Unfortunately, due to the seasonal nature of agricultural work, the field study was restricted to March-July to encompass the widest range of tasks. Trunk rotation levels are relatively well defined for off-road environments (Whyte and Barber 1987) and therefore it was decided that these would form the basis for developing the experimental plan. Therefore, the vibration magnitudes were limited so that when subjects were exposed in addition to trunk rotation they would not reach levels of unacceptable risk. The vibration was based on a nominally flat spectrum so that the results would not be biased to any particular environment and the conclusions would not be limited by this factor.

Much of the data collected on vibration exposure in agriculture is out of date, modern tractors often have 2-4 wheel or even cab suspension. It was felt important to collect new data for these vehicles. In addition, vibration data is not often captured synchronously with task data, therefore the opportunity was taken to film the operator and synchronise the film with the vibration data to give a full description of exposures.

The groups for the expert opinion review were chosen as they were key stakeholders for the exposures. Others have consulted expert opinion to consider whether the research area justifies further investigation (Sandover, 1998). Particularly in the field of whole-body vibration, the vibration magnitudes are often measured, and prevention strategies prescribed, but the evaluation of these methods over time is not often considered, therefore recommendations from the literature would be posed to the operator and other expert groups for reflection. In addition the experts were asked to consider the areas they felt discomfort would present, so that these results may be compared between groups and with the experimental conclusions. The experimental conditions are more fully described in the respective Chapters.

3.3 Laboratory Studies – Chapters 6, 7, 8 and 9

Included within this section are the methodological issues for the laboratory studies, including the trunk rotation, whole-body vibration, combined WBV and rotation study, and also the dynamic rotation study.

3.3.1 Electromyography Methodology

Electromyography (EMG) is a widely used method for investigating muscular response to stimuli. It provides a non-invasive index of the level of muscular activation present (Kumar and Mital 1996). And although the activation of muscles may be of interest, in terms of the effect of a stimulus, the development and progression of fatigue is considered a more descriptive index (El Falou et al., 2003). The ability to measure many muscles at once, and match this to investigation of subjective discomfort is the primary reason for choosing this method. A detailed methodology of the EMG used in the experiment is outlined below, for a discussion on the methods available for EMG analysis; the reader is referred to the literature review, Section 2.7. The details of the methodology outlined here are in accordance with the standards for reporting EMG data (Merletti 1999). A European project called Surface Electromyography for Non-Invasive Assessment of Muscles (SENIAM) project was commenced in 1996 with the aim of attaining consensus on key items in EMG (Hermens et al. 2000) where applicable reference to this project conclusions are taken as best practice.

3.3.1.1 EMG Equipment Configuration

The data acquisition system for EMG consisted of 8 bipolar dry reusable electrodes with integrated pre-amplifier (SX 230) and a datalog data capture unit (W4X8). The electrodes used were integral, dry and reusable of material Ag/AgCl. The electrodes were circular, mounted on a rectangular base (20 x 35mm), with a 20mm inter-electrode distance. Due to the input impedance of > 10,000,000 M Ohms, minimal skin preparation is required. However, the skin was cleansed with alcohol and shaved where hair was visible. Electrodes were attached to the skin surface using medical grade die cut adhesive tape. In addition medical tape was applied over the electrode and wires to hold in position.

3.3.1.2 Electrode placement

Many trunk muscles are involved in twisting because no single muscle generates a pure axial torque (McGill, 1991; Marras and Mirka, 1992). Fatigue is often seen in muscles serving both antagonistic and stabilising roles during the generation of axial torque (O'Brien and Potvin, 1997). Preliminary investigations and informal interviews with operators suggested that the main areas for musculoskeletal discomfort in agricultural work scenarios involving vibration and twist are the neck, shoulders and low back. The muscles for the study were chosen based on these findings, various studies on axial rotation, whole-body vibration and general ergonomics studies (literature review, Section 2.7.2).

Muscle activity was recorded bilaterally at the m.trapezius pars decendens (TD); m.trapezius pars ascendens (TA); erector spinae pars longissimus (ES); and multifidus (MF) in accordance with the SENIAM recommendations (Hermens et al., 2000). When specifying electrode placement, it is considered best practise to align the electrode with muscle fibre direction and avoid the innervation zone (Mesin et al., 2009). Research has shown a single main innervation zone of the TD being 52-54% of the distance between the acromion and the seventh cervical vertebrae (C7) (Farina et al., 2002). In addition, it is specified an ideal electrode placement with a lateral distance of approximately 25mm from the mid-point of acromion to C7. Therefore, electrode placement was specified at 40% of the C7 – acromion distance (being closer to C7) and in line with the line between C7 and acromion.

For TA, electrode placement is at 2/3 on the line from the trigonum spinea to the 8^{th} thoracic vertebra, in line with the line between these two points. For the erector spinae longissimus, the electrodes are placed two finger widths bilateral from the proximal spine of L1, in parallel with the spine. Electrodes covering the multifidus are placed on and aligned with a line from caudal tip posterior spina iliaca superior to the interspace between L1 and L2 interspace at the level of L5 spinous process (i.e. about 2 - 3 cm from the midline). The reference cable was placed over the styloid process and fixed with an elasticated strap. Figures 13-16 illustrate the electrode placement, with '**X**' marking the attachment point, and the arrows depicting alignment with fibre direction.

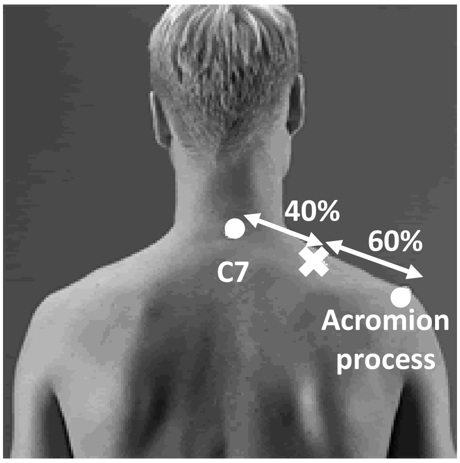


Figure 13 Electrode placement over trapezius decendens (upper), adapted from Hermens et al. (2000)

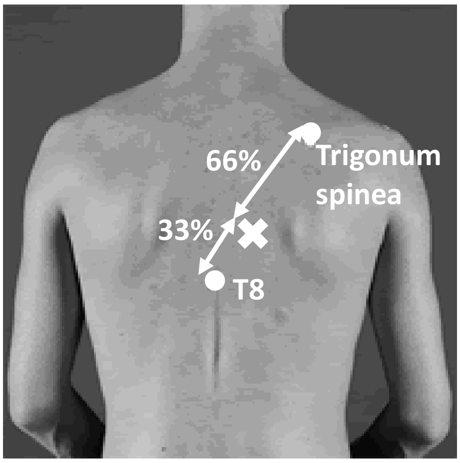
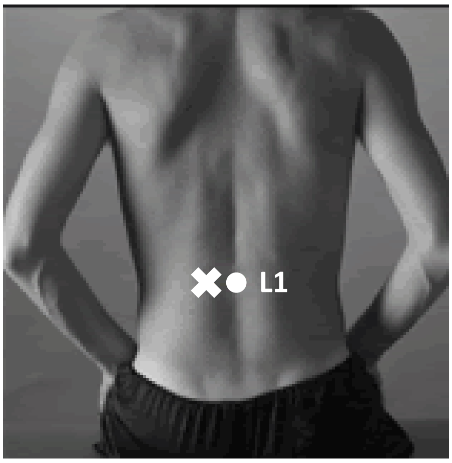


Figure 14 Electrode placement over trapezius acendens (lower), adapted from Hermens et al. (2000)



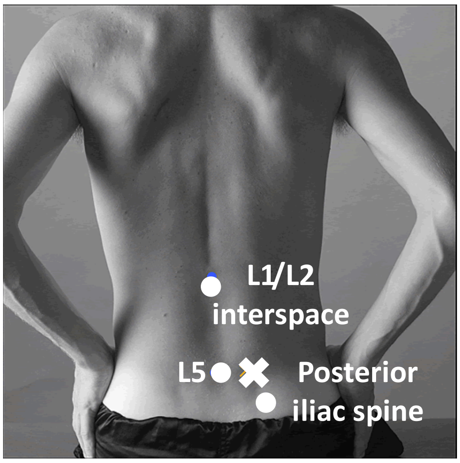


Figure 15 Electrode placement on erector spinae longissimus, adapted from Hermens et al. (2000)

Figure 16 Electrode placement on multifidus, adapted from Hermens et al. (2000)

3.3.1.3 Amplification

The sensors used were bipolar, with a differential amplifier. This serves to amplify the difference between the signals at each electrode (there are 2 on each sensor) and ignore any 'common' signals to both electrodes. Essentially, differential amplification subtracts the potential at one electrode from that at the other electrode and then amplifies the difference. Correlated signals common to both sites, such as from power sources and electro-magnetic devices. Cross talk may be experienced where signals from more distant muscle sources may interfere with the signal sources close to the muscle under investigation (Gerdle et al., 1999), this is also suppressed with the use of differential amplification. The amplitude of the bipolar sEMG signal decays exponentially with increased distance from the recording electrode (Day, 2002), therefore sensor size and inter-electrode distance affect the cross talk measured. Decreasing the size of the conductive area reduces the effective EMG measurement distance (i.e. depth). Similarly, decreasing the inter-electrode distance decreases the effective recording distance (Lindstrom et al., 1977). For the muscles under investigation here, recommendations in SENIAM dictate an inter-electrode distance not greater than 20mm. The electrodes used in the following Chapters have this inter-electrode distance therefore it is suggested that the effect of cross-talk will be minimal. The gain provided by the biometrics sensors is 1000, which is in the range recommended by Basmajan and DeLuca (1985).

3.3.1.4 Filtering and Sampling

In order to prepare the myogram for fatigue analysis, signal processing and noise removal are required. The majority of the power in EMG signals is within the frequency range of 5-500Hz at the extremes (Farina et al., 2002). Redfern et al. (1993) found that to remove the artefacts caused by electrocardiographic (ECG) contamination that a high pass filter of 30Hz was optimum. It is also suggested that a 30Hz high pass is necessary to reduce the potential influence of skin movement on the muscle (Hansson et al. 2000; Santos et al. 2008). This also has the additional benefits of reducing the amplitude and smoothing the signal. Signals above 300Hz are considered outside the anatomical range (Dolan et al. 1995) it is also apparent that the power above 200Hz in the spectrum is nominal. The low pass filter is therefore set at 250Hz. The sampling rate employed in the data collection was 1024Hz.

3.3.1.5 Analysis

In order for the two methods of fatigue analysis to be continued, the data is required to be analysed in two separate methods. This is described below in Figure 17. The data acquisition and processing has been detailed above, the amplitude and frequency analysis will be described herein.

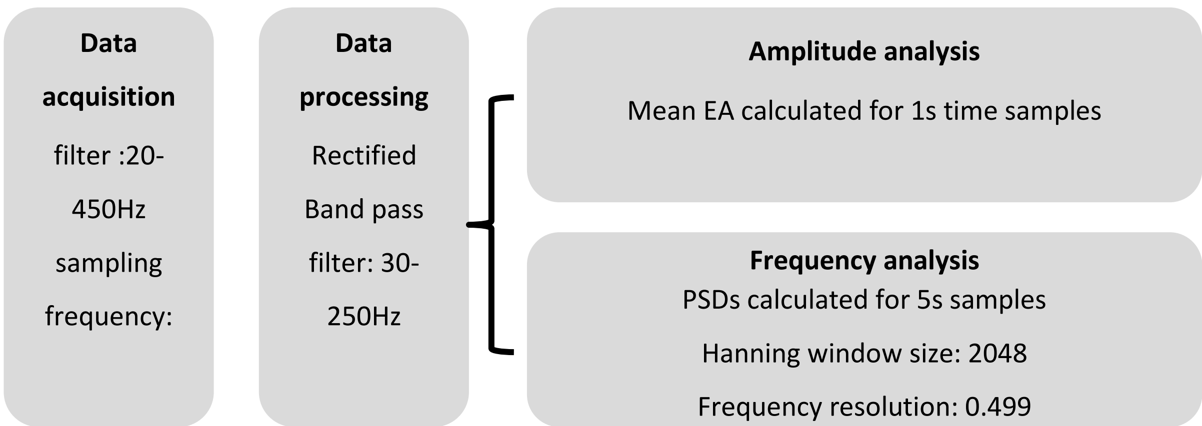


Figure 17 Schematic of EMG signal processing methods

The joint assessment of spectrum and amplitude (JASA) method (Luttmann et al. 2000) is chosen as the most comprehensive method for investigating muscular responses. This requires both analysis of the electrical activity (EA) and the frequency in the time domain. In the ideal scenario that the contraction of the muscle can be kept constant, it may only be necessary to consider one variable, amplitude or frequency (Luttmann et al. 1996). However, within these scenarios, joint assessment of spectrum and amplitude can still be utilised to confirm the analysis.

For analysis, the raw EMG is rectified and filtered. Shown below is the process of rectification and averaging the raw EMG signal so that the EA may be analysed. The occurrence of muscular fatigue was proven by analysing time-related changes in the EMG amplitude and spectrum. For analysis of the EMG amplitude, the electrical activity (EA) is rectified and the mean EA is calculated for successive 1s samples. Regression analysis allows the initial and end values to be determined, along with the gradient of any change (Wilder, 1994). A Wilcoxon statistical comparison of the initial and end values in addition to a t-test of the gradient are utilised to investigate significance of any results. For frequency-domain spectral analysis, PSDs were calculated at 5s intervals with a window size of 2049 samples and a resolution of 0.488Hz. A Hanning window was applied to each data segment. Statistically, the spectral data is treated the same as the EA data described above.

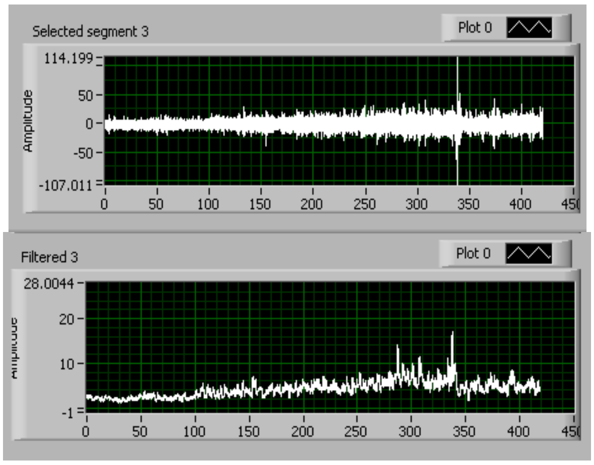


Figure 18 Typical raw (upper) and rectified and averaged (lower) EMG data

3.3.2 Subjective Methods

Porter's body map was developed at Loughborough University for assessing discomfort in a vehicle scenario. Porter's body map was based upon an original by Corlett and Bishop (1976) where instead of assessing overall discomfort, as was the previous norm, body parts could be assessed in isolation, allowing the identification of possible problem areas and therefore causal factors. They asked workers to mark on a body map where they felt most uncomfortable, next most uncomfortable etc. The original body map was of a standing individual, however, in an attempt to reduce subject effort and therefore error, the idea was transposed to a seated figure, asking subjects to rate all body parts sensation rather than ranking in terms of discomfort experienced.

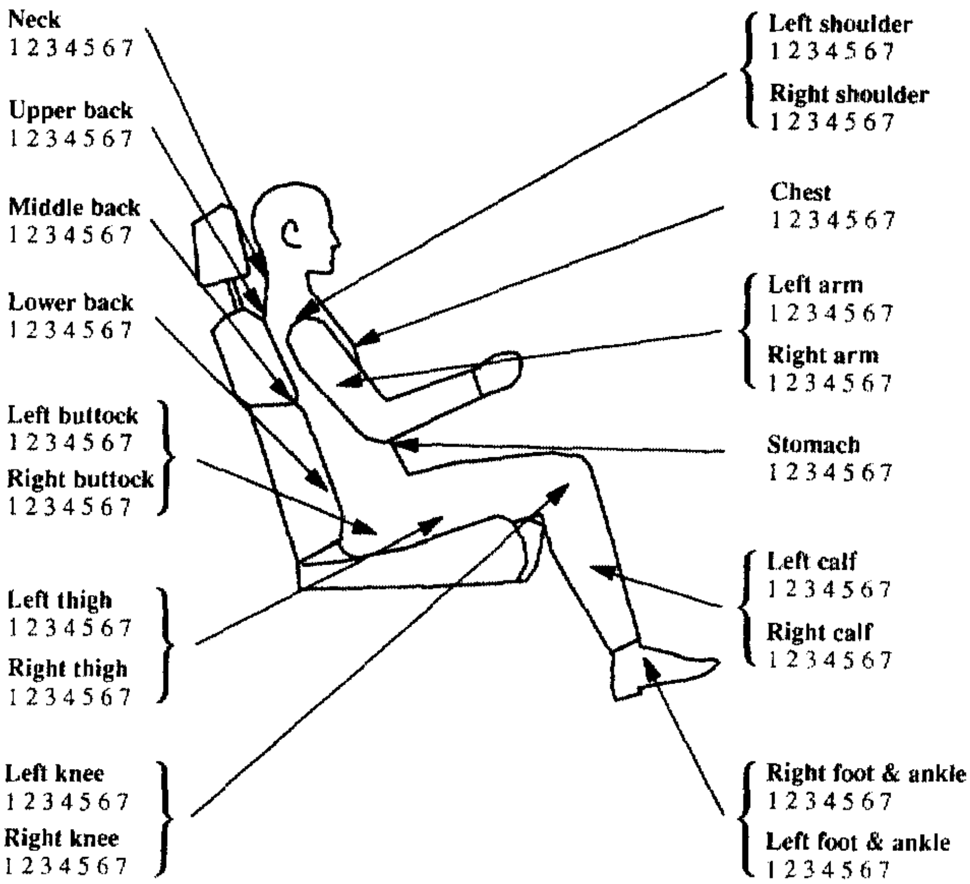


Figure 19 Porter's body map (1999): 1. very comfortable; 2. moderately comfortable; 3. fairly comfortable; 4. neutral; 5. slightly uncomfortable; 6. moderately uncomfortable; 7. very uncomfortable. Reproduced from Gyi and Porter (1999).

Porter and Gyi's experience in using this evaluation techinique exceeded 20 years, in which time it was found to be simple to administer, with little training required before use (Porter et al., 2003).

It has previously been noted the fact that people frequently and naturally distinguish ordered levels of their subjective responses across the entire continuum from strongly positive to strongly negative (Richards 1980). This is the principle that underlies the graded scales (eg. Porter et al., 1993). In Porter's discomfort questionnaire, the ratings range from extremely uncomfortable to extremely comfortable. However, several studies have indicated that comfort and discomfort are based on different variables, summarised in (Zhang et al., 1996).Others (De Looze et al. 2003; Shen and Parsons, 1997) suggest that in the light of this research, comfort and discomfort need to be treated as different and complimentary dimensions when assessing specific seating discomfort.

ISO 2631-1 (1997) provides descriptives of the levels of discomfort that can be expected from increasing levels of vibration. Therefore, the descriptive verbal anchors in Porter's body map were replaced with those from ISO 2631-1 (1997), as illustrated in Figure 20. This was the format used for all investigations reported in this thesis.

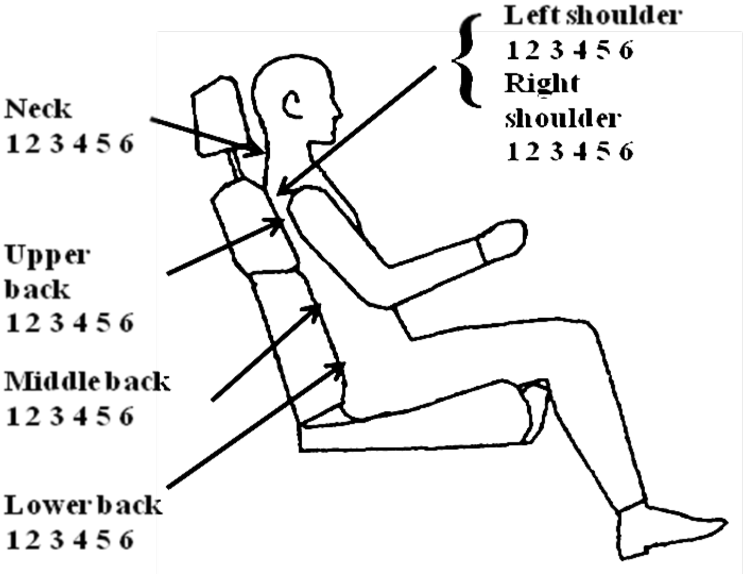


Figure 20 Modified Porter's body map (with ISO 2631-1, 2005); 1. not uncomfortable; 2. a little uncomfortable; 3. fairly uncomfortable; 4. uncomfortable; 5. very uncomfortable; 6. extremely uncomfortable

The focus of this research is on the neck, shoulders and back, consequently the chest, left arm, right arm, stomach, left thigh, right thigh, left calf, right calf, left knee, right knee, right foot and ankle, left foot and ankle categories were removed from the evaluation.

Sufficient information on the ratings should be provided to the subject so learning the scale is not an additional effort required by the subject (Shen and Parsons, 1997) therefore the body map was printed onto A2 sheets and placed around the laboratory to facilitate the subject in rating their discomfort, when requested. After introduction to the body map, the participants were asked to orally rate their discomfort for each specified body region every 60 seconds throughout the experiments. The ratings were recorded after each rating.

3.3.2.1 Analysis

The subjective data collected cannot fulfil the assumptions required for parametric tests, and therefore non-parametric testing is employed. Tests will be conducted to consider differences over time for each condition, and also the differences between conditions at specified time points.

The limitations of the laboratory studies will be discussed together at the end of the 4th laboratory study, Chapter 9.

3.4 Experimental Design

In order to investigate the influence of axial rotation and WBV on musculoskeletal discomfort development, these factors must be categorised into experimental conditions which can be investigated utilising the methods outlined above.

3.4.2 Investigations of axial rotation

In agriculture, axial rotation is a major task component. Tractor engine power is transferred through the power take-off (PTO), which is located at the rear of the vehicle to the working attachment e.g. mowers, balers, ploughs etc. These often require monitoring which involves rotation of the driver. The magnitude and duration of rotations is documented in the literature (Torén and Öberg, 2001; Whyte and Barber, 1985) and discussed in the introduction (Section 2.3.1). It is also important to consider the vehicle dimensions and the influence these may have upon the driver and task completion, this is less discussed in the literature. A number of studies that have investigated axial rotation have used 90° rotation condition, however in many agricultural vehicles the side pillar is placed at 90° to the driver as shown in Figure 21. This restricts the field of vision at this point meaning the operator is rarely rotated at 90°.

Figure 21 Typical agricultural tractor cabin (taken from Valtra 'Direct' model, Valtra, 2010)

In addition to the pillar at 90° is the corner pillar at 130° to the forward facing neutral. As discussed previously, most tractor attachments are made at the rear, but not all follow the tractor directly to the rear, e.g. a baler would remain directly behind the tractor, however a mower, although attached at the rear, would operate behind and to the right of the tractor, therefore requiring the operator to monitor the work area out of the rear-side window. To reflect these working scenarios, the two angles of rotation chosen for investigation were 110° and 170°. In addition to the requirement for out-of-cab monitoring, banked to the right of the operator is the location of the majority of non-steering column based controls. The operator is often required to operate these controls in response to the machinery and or/ground conditions. This direction of rotation was replicated in the studies.

Combining the research from the literature, field observations, and vehicle dimensions, the direction of rotation will be to the right, with rotation at 110° and a maximum rotation of 170° to the forward facing neutral position.

The myoelectric activity of the ES has been shown to decrease with increasing backrest angle (Magnusson and Pope, 1998), and therefore the impact of this is minimised in the study by maintaining a constant backrest angle of 110°, as from Figure 22 this is the point at which the EMG signal amplitude shows the least distribution, yet is likely to be replicable of those seen in tractor cabs.

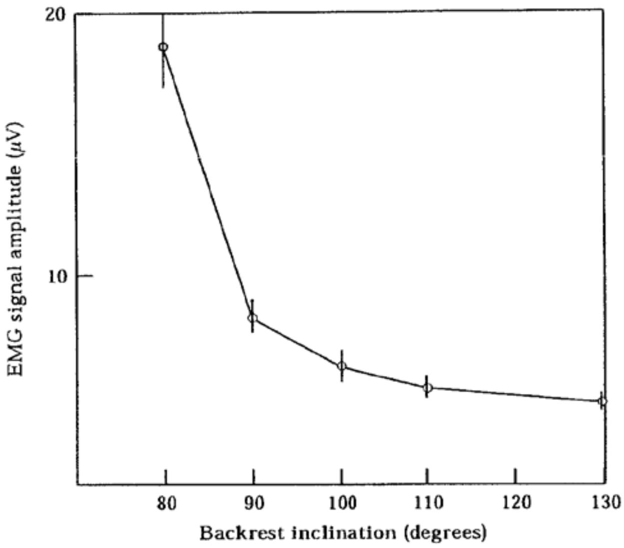


Figure 22 Myoelectric activity of erector spinae in relation to backrest angle (Magnusson and Pope, 1998)

3.4.3 Investigation of whole-body vibration

Previous studies investigating tractor vibration have found high vibration magnitudes (0.47-0.76x, 0.92 - 1.86y, 2.53 - 3.80z m/s^2 weighted r.m.s) in an investigation of 3 tractor powers with ride suspension travelling both on and off-road (Kumar et al., 2001). Bovenzi and Betta (1994) measured vibration at the seat pan of 53 tractors finding a range of 0.89-1.41 m/s^2 weighted r.s.s. The tractors were carrying out normal tasks (with machinery attachments), it is not known if the seats were suspended. Boshuizen et al., 1990 calculated an average of 0.6 m/s^2 and 1.1 m/s^2 weighted r.s.s for on- and off-road tractor driving respectively. Many vibration measurements have been made below the seat (Crolla et al., 1990) or without the attachment of implements. Implements attached to the rear can have the effect of attenuating (ploughs/harrows) or exaggerating (trailers, spreaders) vibration (Crolla, 1976). It is acknowledged that suspension has improved considerably since the majority of these studies, and therefore the full extent of the exposures detailed here will not be replicated.

Two vibration conditions and a control (no vibration) were chosen for the study. These were V0 (no vibration), V1 (0.32 x; 0.23 y; and 0.39 z-axis, m/s^2 weighted r.m.s.) and V2 (0.73 x; 0.60 y; and 0.82 z-axis, m/s^2 weighted r.m.s.). These were deemed high enough to be representative of current exposures, yet not exceeding the guidelines for safety outlined above. The vibration was 1-20Hz random vibration, based on a nominally flat spectrum.

3.4.4 Experimental conditions

To minimise any order effects, all conditions in each study were balanced across the study for each subject using a Latin Square. The investigation of the influence of rotation and WBV was split into 4 experiments to facilitate completion; these are explored in separate Chapters.

- **Chapter 6:** Influence of axial rotation on musculoskeletal discomfort
    - Control with no rotation (P0)
    - 110° rotation (P1)
    - 170° rotation (P2)
- **Chapter 7:** Influence of whole-body vibration on musculoskeletal discomfort
    - control with no vibration (V0)
    - 0.5m/s² r.m.s (V1)
    - 1.0m/s² r.m.s. (V2)
- **Chapter 8:** Influence of simultaneous axial rotation and whole-body vibration exposure on musculoskeletal discomfort
    - Control, no rotation, no vibration (PV0)
    - 110° rotation with 0.5m/s² r.m.s (P1V1)
    - 110° rotation with 1.0m/s² r.m.s (P1V2)
    - 170° rotation with 0.5m/s² r.m.s (P2V1)
    - 170° rotation with 1.0m/s² r.m.s (P2V2)
- **Chapter 9:** Influence of whole-body vibration and dynamic rotation on musculoskeletal discomfort
    - 0° seat base rotation, static posture, no vibration (control)
    - 0° seat base rotation, static forward facing posture, with vibration (SB0, P0)
    - 0° seat base rotation, dynamic rotation, with vibration (SB0, Pmov)
    - 30° seat base rotation, static forward facing posture, with vibration (SB30, P0)
    - 30° seat base rotation, dynamic rotation, with vibration (SB30, Pmov)
    - 90° seat base rotation, dynamic rotation, with vibration (SB30, Pmov)

The interaction between the conditions in Chapters 6, 7 and 8 are illustrated in Table 6

.

Table 6 Summary of exposure conditions

	0° rotation	110° rotation	170° rotation
0m/s² r.m.s.	P0; V0; PV0	P1	P2
0.5m/s² r.m.s.	V1	P1V1	P2V1
1.0m/s² r.m.s.	V2	P1V2	P2V2

A repeated measures design was employed within each of the experiments, although the subjects varied between experiments. The conditions were balanced using a Latin square design. Recovery time between exposures was 10 minutes in accordance with recommendations by Lariviére et al. (2003).

The level of rotation was defined by placement of a visual target at the three degrees of rotation. Participants were free to determine how they achieved the rotation (wholly trunk, neck or both) more information is provided on seated posture in section 3.4.5 below. The relative position of the body segments was recorded digitally on camera. Reflective markers indicated specified anatomical landmarks for comparison. Markers were placed on the acromion process, vertebra prominens (C7), external occipital protruberance, and squamosal sutre superior to the ear.

3.4.5 Laboratory setup

A bespoke mock-up of a tractor cab including seat, steering wheel and pedals was manufactured at Loughborough University. The dimensions were taken from the guidelines outlined in ISO 3462 'Methods for determination seat reference point of agricultural tractors' (1980). The seat was a taken from an off-road vehicle with air suspension, arm rests and a full backrest seat. The rig can be seen in Figure 23. The seat was adjustable in the fore-aft direction, to the individual participants' discretion. The backrest was maintained at 110°, as discussed in previously. Once the participant was positioned, the seat suspension was adjusted to the centre of vertical travel. The steering wheel and pedals were fixed in position throughout the studies. Participants were instructed to place hands and feet on the steering wheel and pedals for the experiment. For the study investigating trunk rotation, the rig was mounted on a wooden platform, on the floor. For all other studies, the rig was mounted on the multi-axis vibration simulator.

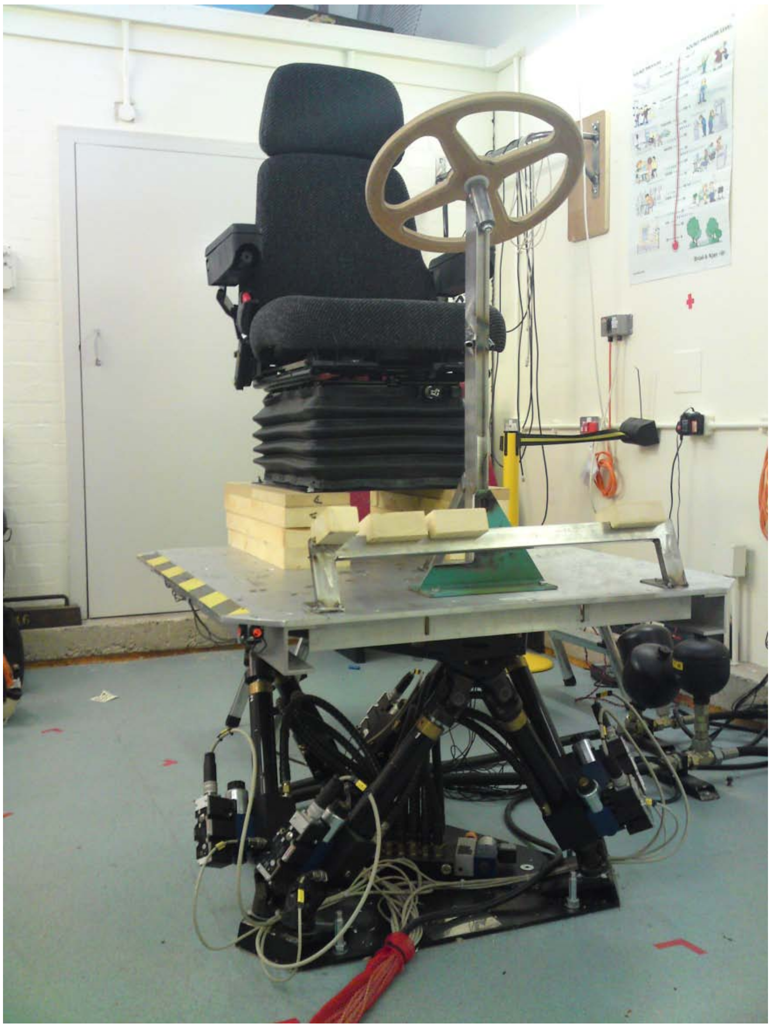


Figure 23 Mock-up of agricultural tractor cab mounted on the multi-axis vibration simulator at Loughborough University

3.4.6 Vibration Platform

All vibration conditions were conducted on the vibration platform, situated in the Environmental Ergonomics Laboratory at Loughborough University. The platform is a Rexroth Hydraudyne B.V. Micro Motion 600-6DOF-200-MK5 multi-axis vibration simulator capable of producing motion in the frequency range 1-25Hz. Vertical, lateral and fore-aft peak to peak displacement is 180mm, roll, pitch and yaw peak to peak angles are 20 degrees. The distortion for single axis sinusoidal motion is specified at <10% displacement and cross talk between axes <10%. The maximum payload for the system is 600kg.

Normal operation of the platform would be as follows:

- subject seated on seat on seat fixed to platform with safety belt fastened

- area around platform cordoned off with safety barrier
- vibrator pressurised and set to neutral position (from -0.15 to 0.0m)
- vibration exposure, set by operator
- vibrator set to settled position and depressurised
- subject removed from shaker

3.4.6.1 Safety aspects when using the vibration platform

Experiments conducted on the vibrator were in accordance with ISO 13090-1 (1998) 'Mechanical Vibration and Shock – Guidance on safety aspects of tests and experiments with people'. Safety barriers are installed around the shaker to mark an 'inner zone'. This zone is designed to avoid any possible contact by personnel with the motion base, or any parts fixed to it. No entry into the inner zone is permitted whilst the shaker is pressurised. Emergency stop buttons are in reach of the experimenter at all times, although in the case of a non-emergency stop request, (for example a participant request), the system is brought to a settled state without the use of the emergency button to avoid the shock exposure caused by bringing all rams to a neutral position at once.

The platform is controlled with a dedicated computer with no general purpose software or networking capability to ensure sole control. A mechanical end-stop cushioning system is built into actuators to avoid end-stop shocks. Additional accumulators added to hydraulic system to dampen motion during depressurisation in the event of a power or mechanical failure.

Eight accelerometers are mounted to the vibration platform, and the real time data from these are monitored on a lab PC throughout the experiment. This will enable the exposure to be monitored and modified if necessary. These accelerometers are also used to confirm that the exposures of the participants are below the thresholds of risk outlined above.

3.4.6.2 Accelerometers

In addition to the platform accelerometers, two tri-axial accelerometers are used to record the vibration at the seat surface. These accelerometers (S2-10G-MF, Biometrics Ltd, UK) weigh 15g. The sensitivity of the accelerometer is ±1V and the operating range is ±10g.

A recorded time history from two calibrated accelerometers being inclined at 0° to the vertical, turned through 180° to the vertical and back to 0° over the duration of 30s is shown in Figure 24. The accelerometers were fixed together and turned after 10s, then after another 10s returned to the start position. The shocks evident at the 10 and 20s times are as a result of accelerometer contact with the horizontal surface.

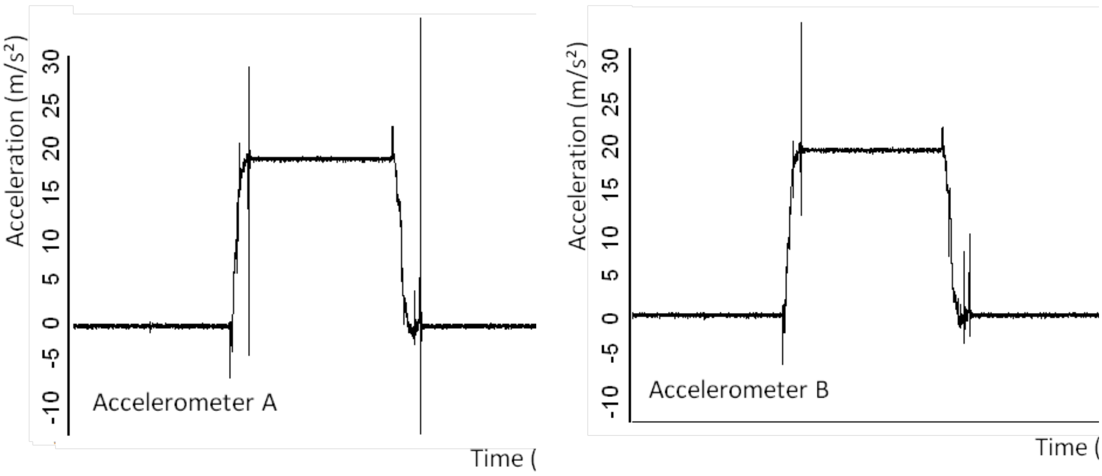


Figure 24 Example calibration time histories for two accelerometers mounted together and inverted through 180°

3.4.7 Subjects

3.4.7.1 Ethical Clearance

The methods for all experiments undertaken for this research are described under generic experimental protocols which were approved by Loughborough University's ethical committee: G05-P1, use of a multi-axis vibration simulator; G04-P3, subjective and objective measures of human response to whole-body vibration; G02-P1 quantification of vibration exposure of vehicle occupants vibration collection; G99-P7, electromyography and electrocardiography.

The greatest magnitudes of vibration to which participants were exposed were similar to those experienced by operators in off-road driving in industry, with the total vibration dose not exceeding the lowest criteria for risk specified in the EU physical agents (vibration) directive $0.5 m/s^2$ r.m.s A(8). The risks from vibration exposure were controlled by monitoring the vibration dose. Some stimuli will feel uncomfortable to participants; this is a requirement for this investigation.

Participants were referred to by number. Records of vibration exposure were kept and archived; the collection and storage of data complied with the Data Protection Act.

Participants were informed of their right to withdraw from experiments in the instruction sheet provided at on commencement of experiment, also posters were displayed to this effect around the lab. Written consent was obtained before commencement of the experiment. Exclusion criteria are provided in Appendix (Section d). Furthermore, to facilitate surface EMG measures, subjects were excluded if their body mass index exceeded 30kg/m² (Santos et al., 2008). Participants were chaperoned at all times during the studies. Experiments only took place during office hours whilst the laboratories are occupied

3.4.7.2 Informed consent and health screen questionnaire

All participants were provided with a 'participant information sheet' informing them of the aims and procedure of the experiments. They were encouraged to familiarise themselves with the environment and to clarify any queries they may have before signing an informed consent form.

3.4.7.3 Recruitment

Participants were primarily recruited from the student and staff population at Loughborough University via e-mail advertisement. Additional participants were recruited via the 'research participation scheme'. This required first year psychology students studying a psychology practicals module to participate in department research. Students were free to choose which research they participated in. Agreeing to participate did not affect the students' right to withdraw at any point during the research. Participants were not paid for their time

3.4.7.4 Participant data

Participant's date of birth and gender were collected on commencement of the experiment. Stature was recorded in cm using a free standing stadiometer and weight recorded in kilograms (kg) using an electronic scale (Mettler Toledo kcc150). This allowed body mass index to be calculated using the standard formula

$$BMI = \frac{h^2}{m}$$

Where h = height (m) and m = mass (kg)

3.5 Field study – Chapter 4

This section discusses the methodology applied throughout the field data collection period.

The methodology involves the observation of operator's posture (Section 3.5.1), the measurement of vibration (3.5.2) and the details of participation (3.5.3).

3.5.1 Observation of Posture

The observation of posture through video recording is a widely used method (Eger et al., 2008; Hoy et al., 2004) for the measurement and later classification of postures. There are no known formal guidelines on the use of video to capture working postures, therefore the published methodologies in the literature are taken as a basis for this methodology.

3.5.1.1 Observation equipment

The video recorder purchased for the study was a Sanyo Xacti, vpc HD700. This featured high definition recording for clear images, and image stabilization to cope with the moving environment. The export format of the video was mpeg4. The videos were saved onto an 8MB SDHC card, then saved on a PC for later analysis.

To mount the video camera in the tractor cabin, a suction mount was utilised (Panavise 809). This mounting allowed the camera to be fixed firm to the tractor cabin, whilst focussed the operator.

Figure 25 Video camera (left) and mount (right) used in the study

3.5.1.2 Video processing

The videos were loaded onto the computer and converted to mpg in WinX v4.1 (Digiarty, 2009). Videos were opened in VLC media player (VideoLan, 2009) and played at 0.25 speed to allow for inspection.

3.5.1.3 Posture Assessment

The videos were inspected at 30s intervals. The video was paused, and the posture of the operator was recorded. Following the OWAS coding technique (Kahru et al., 1977), the following was utilised in the posture and task analysis of each work segment. This allowed a picture of the task to be built up and the posture of each operator to be classified, including frequency and duration of twist.

Table 7 Guide for observation of postures (from Kahru et al., 1977)

Trunk twisted	Controls	Task component	Task activity
1 - 0° 2 - 30° 3 - 45° 4 - 110° 5 - maximum	1 – steering wheel 2 – side bank 3 – hand accelerator 4 - other	1 – driving fwds 2 – observing crop through door window 3 – observing through rear-side window 4 – observing through rear window	Eg. unloading bale/reversing/forward driving

3.5.2 Vibration assessment

The vibration measurements were conducted according to ISO 2631-1 and the Physical Agents (Vibration) Directive (2007). Equipment specification and calibration is described earlier (Section 3.4.6), the accelerometers and datalogger described in this section are used throughout this test period. One accelerometer was fitted in a Society of Automotive Engineers (SAE) flexible disc (as defined in ISO 10326-1, 1992) and positioned on the seat pan beneath the ischial tuberosities, see Figure 26.

Figure 26 Typical location of mounting for the seat surface accelerometer, shown mounted in the SAE pad

The accelerometer was mounted so that the axes were aligned correctly in all vehicles. That is the x axis was directed in the fore-aft direction, y-axis in lateral and z-axis in the vertical direction of travel. If the seat base was rotated, the accelerometer was aligned with the tractor, not the seat base (this was the case in 3 of the trials). A second accelerometer was mounted on the floor of the vehicle close to the seat base. The floor accelerometer was aligned in the same axis as those described above. The accelerometer was fixed in place using superglue and a high strength adhesive tape. The Biometrics DataLogger was wrapped in fabric cloths and stored at the rear of the cabin, behind the operator's seat. The raw vibration signal was recorded with a 500Hz sampling rate. A date and time stamp of the collection period is added to the data within the DataLogger.

3.5.2.1 Analysis of whole-body vibration data

The vibration was collected for periods of constant driving, no break periods were present. Vibration analysis was conducted in accordance with ISO 2631-1 and carried out with the Vibration Analysis Toolset (VATS version 7.5) software (NexGen Ergonomics, 2009), which is compliant with ISO 8041 (2005). Frequency weighted root-mean-square accelerations in the x, y and z axis were calculated, along with the crest factor, and any other additional methods if crest factor value of 9 is exceeded, as specified in the standard. Weighting factors used were W_k (frequency range 0.5-80Hz) for the vertical W_d (0.5-80Hz) for horizontal directions. The principle method for evaluating exposure to WBV is the frequency weighted root mean square method (r.m.s). This method is prescribed by ISO 2631, where the appropriate weighting factors are also illustrated, the horizontal axis are weighted with W_d and vertical axis W_k. In the assessment of health effects, multiplication factors of 1.4 are recommended for the horizontal axis vibration. Therefore these are applied to the data during analysis. In addition to the calculation of r.m.s, the Seat Effective Amplitude Transmissibility (SEAT) value is also calculated. The formulas and workings of these methods are explored further in the relevant experimental Chapter (Chapter 4).

3.5.3 Participants in Field Study

3.5.3.1 Ethical Clearance and informed consent

The methods for all experiments undertaken for this research are described earlier in Section 3.4. The same procedure of informed consent and health screening was adhered to. The operators were not asked to alter their normal exposure in any way, and were therefore exposed to the same risks that would normally be prevalent in their daily working tasks.

3.5.3.2 Recruitment

Participants were primarily recruited from around the investigator's home. Posters advertising the research project were placed on local notice boards and invitations to participate were read out in local farming group meetings. Participants were not paid for their time

3.5.3.3 Participant data

Participant's date of birth and gender were collected on commencement of the experiment. Stature was recorded in cm using a free standing stadiometer and weight recorded in kilograms (kg) using a portable electronic scales.

3.5.4 Equipment setup

Camera and accelerometer placement was conducted during a suitable rest period, identified by the operator. This ensured minimum interference caused by the setup process. Details of the operator, machine, attachment and work tasks were also collected during this period. After the measurement period, the equipment was removed from the cabin, and the operator was debriefed and thanked for participation. Any clarification of task details was also done at this point.

3.6 Survey of Expert Opinion – Chapter 5

Questionnaires offer a flexible way of gaining specific data from a large population sample. They can be designed and administered to answer specific experimental aims (Stanton et al., 2005). A recognised method for reviewing available knowledge on a topic is to gather expert opinion. This method is widely used in the medical profession and within standards development, however is not commonly published on less specific topics in ergonomics. A combination of these two methods has been used before (Sandover, 1998), and the basic methodology is followed herein.

The aim is to consider if current expert opinion on the issues of trunk rotation, WBV and combined exposures are in agreement among the key parties. The main experts in the fields were clearly defined. The first group consisted of those with experience in the field of WBV measurement and assessment. The second group were ergonomists, particularly those with experience in postural assessment. The third group were operators commonly exposed to both trunk rotation and WBV. Further details on the questionnaire development and dissemination are discussed in the relevant Chapter (Chapter 5).

3.6.1 Participant information

3.6.1.1 Ethical Clearance & Informed Consent

The methods for this expert opinion review are described under generic experimental protocols which were approved by Loughborough University's ethical committee, and are described earlier in Section 3.3. Participants were referred to by number. Completed questionnaires were kept and archived; the collection and storage of data complied with the Data Protection Act. Participants were informed of their right to withdraw from experiments in the instruction sheet provided with the questionnaire. Written consent was obtained before completion of the questionnaire.

3.6.1.2 Recruitment

Participants were not paid for completion of the survey. Further details on the recruitment of participant groups is considered in the relevant Chapter (Chapter 5).

3.6.1.3 Participant data

Participant's relevant occupational experience was recorded as part of the demographics information collected. In addition operating duration and number of breaks taken per day was also collected from the operator group.

3.6.2 Questionnaire Development

When developing the questionnaire, it had to be considered the diversity in the intended audiences. Therefore diversity in the methods available for completion were employed to increase participation levels. The survey took the form of a questionnaire to elicit direct responses on particular topics with open ended comment boxes for additional information which respondents felt important. The postural ergonomics expert (PE) and WBV expert (VE) response groups completed the same questionnaire, which was split into five main categories. A demographics section contained questions on the area and length of expertise of the respondent. The second section required respondents to rate the risk of common vibration and posture combinations seen within off-road driving industries. Experts marked an outline of the body where they considered discomfort would be experienced in common combinations of posture and vibration. This data was then coded by body segment, as defined by Kuorinka et al. (1987) to facilitate comparison between response groups. Those with experience in assessing WBV exposure were asked whether they considered the posture of the operator should be reflected as part of the assessment of WBV exposure. Previous research has suggested possible additions to agricultural tractors to avoid the stresses put upon the body (e.g. large mirrors, Sjofløt, 1980; swivelling seat, Bottoms and Barber, 1978). Respondents were asked to consider how effective they would perceive such additions to be. An operator expert (OE) group completed a largely similar questionnaire, however questions about risk assessment were removed, and supplementary questions on working durations and least preferred tasks were added.

CHAPTER 4: Evaluation of in-field agricultural driving tasks

This Chapter discusses a field study designed to establish current typical vibration exposures and operating postures in agricultural driving tasks. Research was carried out under real operating conditions to investigate the magnitudes of occupational exposure to vibration and classify the working postures whilst under this vibration exposure. The study aimed to give a snapshot of some of the common driving tasks in agriculture in order that a lab study may be developed to include greater purchase to real-life exposures. The study was not designed to be an exhaustive evaluation of the many driving tasks carried out in agriculture.

4.1 Introduction

Various studies have investigated the exposure profiles of in-field driving operations. Agriculture is unique to many other off-road driving scenarios in that one machine is developed, i.e. the tractor, and to this a variety of working attachments are added. The use of these will have an extensive bearing on not only the vibration transmitted to the worker, but also the posture of the worker during this task. It is clear that operators are often exposed to high magnitudes of vibration (Scarlett et al., 2007; Bovenzi and Betta 1994; Scutter et al., 2007). Many of the studies investigated a limited task range or are constrained by tractor type. The solutions that are commonly employed in agricultural vehicles to reduce vibration transmission from field to seat surface include damping seat suspensions, front and rear axle suspension systems, suspended cabs and shock absorbers for cabs (Servadio et al., 2007; Scarlett et al., 2007).

It would seem the case that with the advancement of suspension systems and vehicle design that the vibration emission of the vehicles would be reduced in comparison to past studies. However it is suggested that there is a degree of discomfort homeostasis attached to the exposures (Mansfield, 2004). That is as improvements are made to the driving environment, either through improvements to the tractor design, or to the work surface, the operator will adjust to their acceptable comfort or risk level by increasing the working speed, or duration of working (Wilde, 1982).

Specific standards are set up for the analysis of vibration effects, namely ISO 2631 parts 1 and 5 (1997). Tractor WBV emission values are normally assessed in accordance with ISO 5008 (2002) methodology, where the tractor is driven over a defined 100m (smoother) and 35m (rougher) test tracks at a prescribed range of speeds. The vibration emission can then be measured at the seat in line with ISO 2631-1 (1997).

Previous studies have each considered different range of tasks, those common to each are detailed below.

- Disc harrowing and hay making (Matthews, 1984)
- Ploughing, mowing, road travelling etc. Bovenzi and Betta (1994)
- Ploughing, spraying, trailer transport, cultivating (Scarlett et al., 2007)

For a more exhaustive review of the studies in agriculture, the reader is referred to the literature review. In addition to the vibration exposure, the tractor operator is also required to adopt specific working postures. Previous investigations of working postures in agriculture have been conducted to evaluate the effectiveness of an intervention (Sjoflot, 1980; Toren and Oberg, 2001). Various methods have been developed to assess the working postures of a worker. Investigation is via observation, video recording, or by worker self-reports (Drury, 2001). Previous investigation of postures during a driving task have utilised diaries (Van der Beek et al., 1994), video observations (Eger et al., 2008; Toren and Oberg, 2001) or with a system of goniometers and accelerometers (Raffler et al., 2000). Whichever method is used for capturing the posture, the method of analysis is similar for all; that is the posture is classified against a series of guidelines. These may be predetermined posture categories, or bins (Eger et al., 2008 ; Hoy et al., 2005) or with the use of various posture assessment tools eg. RULA (Hignett and McAtmney, 2000)

4.2 Aims & Hypothesis

The main aims of this study are to quantify WBV emission levels found upon modern agricultural tractors whilst performing a range of typical in-field operations; and to investigate the nature, frequency and duration of any postural deviations from the neutral forward-facing driving position. The findings will provide an insight into the tasks and will allow for specific features to be built into future laboratory studies.

The main hypotheses of this study were:

H_1: Ploughing and cultivation tasks will produce the greatest WBV emissions (Sjoflot, 1980;

H_2: Fore-aft vibration will dominate the exposure profile for field tasks (previous studies have demonstrated this is the worst axis for off road driving profiles, Newell and Mansfield, 2007)

H_3: The posture of the operator will be determined by the task, those with greatest durations of rotation will be ploughing (Whyte and Barber, 1985)

H_4: The largest frequency of rotations will occur during baling operations (Whyte and Barber, 1985)

4.3 Methods

The methods utilised in this study were designed to answer the hypotheses outlined above. This involved the measurement vibration exposure at the seat for a selection of tractor types and tasks, whilst completing real world operations. In addition, the posture of the operator was recorded and analysed. The operators were experienced, and used familiar equipment.

4.3.1 Selection of operators

Subjects were recruited in Mid Wales. Timing of the field study was organised to coincide with the busiest part of the harvesting season in Wales, June-August. In April, a number of posters advertising the study were placed around the area, on local notice-boards. The local young farmers group were asked for participators, also local contractors were phoned and invited to participate. The twelve operators who volunteered to participate signed the consent form, height and weight details were recorded for each participant. Due to the demographic of the operator population, only males participated in the study.

Table 8 Operator characteristics

N	Age	Weight	Height
12	37 (±12)	84.6 (±12.1)	1.8 (±0.09)

Operators were also given the opportunity to participate in the survey of expert opinion, the results of which are presented in Chapter 5.

4.3.2 Selection of test machines and tasks

The test machines and tasks were in part driven by the availability within the operator population. A range of modern, medium/large (100-360 horsepower) two- and four-wheel-drive tractors, embodying different levels of suspension system capability were sought. In addition, a range of suspension seats types, namely mechanical and air suspension, are also investigated. Some tasks were actively sought as they had previously been shown to cause discomfort, these are listed below:

- Ploughing (Sjoflot, 1980)

- Baling (Bottoms and Barber, 1994)

4.3.3 Measurement of whole-body vibration

WBV exposure measurements were conducted in accordance with ISO 2631: Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part 1: General Requirements (1997). The vibration was measured on the cab floor (close to the seat mounting) and at the seat surface using an SAE pad placed on the seat surface under the ischial tuberosities. Accelerometer setup is described in more details in Methodology, Section 3.5.3. The vibration data was stored on the Biometrics data logger (WX4X8). WBV emission levels were calculated during the completion of normal tasks, with trained operators. The study was designed so that minimal interference was made with the work. The equipment was fitted to the machines before the commencement of any activity. During this period, information about the machine and operator was also collected. Vibration analysis was conducted in accordance with ISO 2631-1 and carried out with the Vibration Analysis Toolset (VATS version 2.3.3) software (NexGen Ergonomics, 2005). Frequency weighted root-mean-square accelerations in the x, y and z axis were calculated, along with the crest factor, and any other additional methods if crest factor value of 9 is exceeded, as specified in the standard. Weighting factors used were W_k (frequency range 0.5-80Hz) for the vertical W_d (0.5-80Hz) for horizontal directions. The principle method for evaluating exposure to WBV is the frequency weighted root mean square method (r.m.s). This method is prescribed by ISO 2631, where the appropriate weighting factors are also illustrated, the horizontal axis are weighted with W_d and vertical axis W_k. In the assessment of comfort, no additional multiplying factors are applied, none are applied here.

$$\mathbf{r.m.s} = \left[\frac{1}{T}\int_0^T a^2(t)dt\right]^{1/2} \quad (\mathbf{0})$$

4.3.4 SEAT values

Of particular concern is the ability of the seats to react to the variety of applications and provide sufficient damping in these conditions. This can be investigated with the seat effective amplitude transmissibility (SEAT) value (Griffin, 1990), where the vibration amplitude at the seat can be compared with the floor to provide an indication of the effectiveness of the seat at isolating the operator from the vibration. SEAT values less than 100% indicate a reduction in vibration transmitted to the operator through the seat, however those greater than 100% indicate an amplification of the vibration experienced by the operator at the seat. The SEAT value can be calculated from either the r.m.s or the vibration dose value (VDV) or the frequency-weighted acceleration. VDV and r.m.s have been shown to give similar results (Paddan and Griffin, 2002) therefore only results calculated from r.m.s are presented here. $SEAT_{r.m.s}$ is the ratio of the frequency-weighted acceleration on the seat, $r.m.s._{seat}$, to the frequency-weighted acceleration on the vehicle floor, $r.m.s._{floor}$

$$\mathbf{SEAT_{r.m.s}}\,(\%) = \frac{\mathbf{r.m.s_{seat}}}{\mathbf{r.m.s_{floor}}} \quad (1)$$

It is also possible to calculate the SEAT value using the VDV evaluation,

$$\mathbf{SEAT_{VDV}}\,(\%) = \frac{\mathbf{VDV_{seat}}}{\mathbf{VDV_{floor}}} \quad (\;)\;\mathbf{0}$$

Both methods will be used to allow for comparison between the techniques.

4.3.5 Operator posture and task analysis

To collect information on operating postures, a video camera was utilised to record the postures so that they could be analysed after the event. All the vehicles investigated in this study had an enclosed cab. The tractors under investigation included medium class tractors, whose power and sixe is sufficient to engage in cultivating work on a farm. The aim is to collect data from a variety of tractors within this category, from a range of manufacturers. The video camera (Sanyo Xacti, vpc HD700) was attached in the top right rear corner on the rear side, or rear window, depending on roof height and operator position within cab. The camera was attached to the window using an anti-shake suction mount with ball head (Panavise 809). This attachment mechanism provided adjustability to obtain the best field of view and monitor the operator's posture and movements. The camera had an external viewfinder which allowed the positioning of the camera to be finalised once the operator was seated.

The task itself was also observed with key features noted, along with the posture of the operator at that time. This was completed for the same task with the observer in the vehicle, when a seat was available, but not during video data collection. The video and observer data was then compiled to build a complete picture of the task and task components with associated postures. The operator's posture was coded into posture categories to classify the level of trunk rotation. The categories for rotation are set according to the cab layout (i.e. placing category boundaries in-line with standard pillar placements). Additional categories were provided for the specific activity being completed e.g. activating hydraulics and any controls being activated.

Once loaded onto a PC, the videos were sampled every 30s and the posture of the operator recorded on a sheet. In addition a shorter section of work, 5 minutes sampled at 1s intervals, was taken and the frequency and duration of twists was investigated in more detail. To this, task specific information, such as what the operator was doing/why he was in that posture is added. The method loosely follows the OWAS coding technique (Kahru et al., 1977) where the main risk factors are:

- number of movements
- static muscle work
- force
- work postures determined by the equipment

The coding technique is discussed in greater detail in Section (3.5.1)

4.3.6 Data collection procedure

Data collection was completed during real-time tasks. The accelerometers and video camera were fixed in the cab either at the start of the task, or during a break. The operators were then briefed on the location of the equipment, and asked to perform their task as normal. The amount of time recorded for each operator varied depending on the task under investigation, although all recordings were in excess of 30mins to collect a representative sample of the vibration (Newell and Mansfield, 2006). Data collection was subject to operator's availability and the environmental conditions (weather etc.). The operators completed a minimum of 5 repetitions of the task under investigation, e.g. 4 bales wrapped, to allow for full analysis of the task.

4.4 Results

4.4.1 Test machines and tasks

12 machines being operated for 7 different tasks were measured for the investigation. The average duration of measurement was 35mins (range 23mins - 1hr 23mins). Where possible the task was observed from a safe position at the side of the field before/after measurement if further observation of the task was needed. An illustration of the tasks is provided in Figure 27.

Round Baling

Mowing

Heston baling

Seeding

Wrapping

Ploughing

Forage harvesting

Buckraking

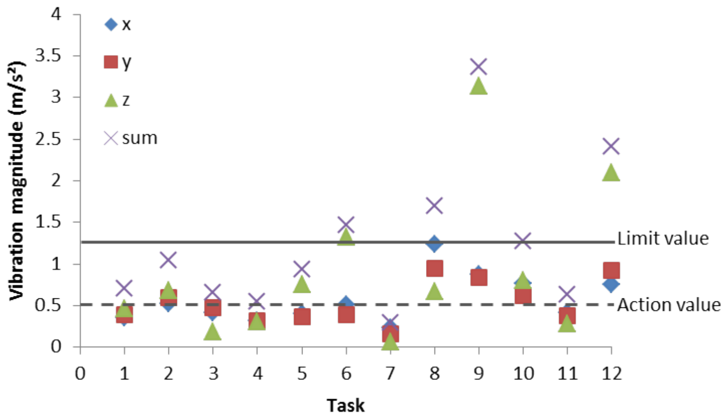
Figure 27 Illustration of tasks investigated (from actual observations where possible)

Table 9 Details of machines and tasks used for investigation

Tractor *Make, model*	Suspension *Axle, seat*	Task	Reference for Figure 28
New Holland TS115	Air seat	Round Baling (1)	1
Massey Ferguson 6260	Air seat	Round Baling (2)	2
John Deere 6630	Air seat	Round Baling (3)	3
New Holland TS115	Air seat	Round Baling (4)	4
Case CVX 160	Air seat	Round Baling (5)	5
John Deere 6800	Air seat	Square Heston Baling	6
Case CS78	Air seat	Wrapping	7
John Deere 6620	Front axle and air seat	Forage harvesting	8
Case Maxxum 5100	Air seat	Mowing	9
John Deere 5820	Mechanical seat only	Buckraking	10
Massey Ferguson 3600	Air seat	Seed laying	11
New Holland T7000	Front axle and air seat	Ploughing	12

4.4.2 Vibration analysis with ISO 2631-1

Frequency weighted r.m.s. accelerations, crest factors, vibration dose values and vibration frequency spectrums are all presented and discussed below. Unfortunately, there are inconsistencies with the floor data collected, meaning it is not available for analysis in this section. The vibration presented here covers the seat vibration for these 2 cases, and seat and floor vibration for the other cases. The emission values include natural pauses in the investigated work phases, but do not include periods where the machine is idling for prolonged periods or when the operator has left the cab.



1 baling (1)	7 wrapping
2 baling (2)	8 forage harvesting
3 baling (3)	9 mowing
4 baling (4)	10 buck-raking
5 baling (5)	11 seeding
6 heston baling	12 ploughing

Figure 28 Emission values measured during 12 agricultural tasks, vibration measured at the seat. The vibration is weighted as per ISO 2631 weighting, with 1.4 multiplication factors applied to the horizontal axes

Figure 28 illustrates the emissions, interpreted by r.m.s. method. Five operations exceed the 1.15m/s^2 limit value as specified by the physical agents (vibration) directive (2005). Most operations, with the exception of the wrapping task, exceed the 0.5m/s^2 action value, assuming these activities are carried out for 8 hours a day.

It is specified in ISO 2631 that a crest factor should be calculated for each axis. This is specified at the ratio between the highest frequency weighted acceleration peak divided by the aforementioned r.m.s value. The crest factor is said to identify emissions where the r.m.s would likely underestimate the vibration dose. Therefore if the crest factor value of 9 is exceeded, then additional methods of evaluation must be used. The vibration dose value (VDV) is a cumulative emission value, based on 4th power dose method, therefore emphasising any peaks, or shocks in the vibration (shown in equation 4)

$$VDV = \left(\int_{0}^{T} [a_w(t)^4 dt \right)^{\frac{1}{4}} \quad (1)$$

Where a_w is the frequency weighted route mean quad (r.m.q) value at time t and T is measurement period (s)

The additional methods required are specified as 'running r.m.s.' where a maximum transient vibration value (MTVV) is calculated. This is typically the highest single acceleration in 1s samples. If the crest factor threshold is exceeded, then either MTVV or VDV values can be compared to the r.m.s using the flowing criteria:

$$\frac{\mathbf{MTVV}}{\mathbf{a_w}} = \mathbf{1.51}$$

$$\frac{\mathrm{VDV}}{\mathrm{a_w} . \mathrm{T}^{1/4}} = 1.75$$

Where a_w is the frequency weighted r.m.s value and T is the measurement period (s)

It is specified in the standard that these should be calculated, and if exceeded then both the r.m.s and additional evaluation values should be reported. Unfortunately no guidance is provided in the standard on how to use the running r.m.s, VDV or MTVV methods, or which to favour (Marjanen, 2010). Table 10 illustrates the r.m.s. values and the calculated crest factors. Due to the high proportion of crest factors over the threshold value, additional analysis methods are used. The results of these are displayed in Table 11.

Table 10 r.m.s. emission and crest factor values calculated with ISO 2631 weighting factors

Operation	r.m.s (m/s²)				Crest Factor			
	x	y	z	SUM	x	y	z	SUM
Baling (1)	0.35	0.39	0.47	0.70	9.62	6.35	13.33	11.62
Baling (2)	0.53	0.59	0.68	1.04	10.05	7.22	6.78	8.03
Baling (3)	0.42	0.47	0.18	0.66	11.89	6.31	8.42	9.05
Baling (4)	0.32	0.32	0.30	0.55	9.00	7.26	39.01	25.16
Baling (5)	0.40	0.36	0.76	0.93	8.51	10.85	10.80	9.90
Heston Baling	0.51	0.39	1.32	1.47	6.28	6.95	21.79	12.01
Wrapping	0.23	0.16	0.07	0.29	14.72	18.39	43.42	31.00
Forage Harvesting	1.24	0.95	0.67	1.70	10.15	8.56	23.68	11.13
Mowing	0.87	0.83	3.14	3.36	7.74	6.03	10.39	8.97

Buck-raking	0.77	0.62	0.80	1.27	6.02	7.20	12.20	7.31
Seeding	0.41	0.38	0.28	0.63	11.96	7.61	8.74	9.47
Ploughing	0.75	0.92	2.09	2.41	7.01	6.31	11.97	7.98

In the r.m.s method of evaluation highlighted cells mark instances exceeding the PA(V)D action value, black cells with white text indicate tasks where the limit value is exceeded. These values are calculated with the 1.4 multiplying factors specified in PA(V)D. The highest magnitude vibration exposure is seen in the mowing task.

Table 11 VDV emission values, calculated for 1 hours exposure; VDV/r.m.s and MTVV/r.m.s

Operation	VDV ($m/s^{1.75}$) (1hr)			VDV/r.m.s			MTVV/r.m.s		
	x	y	z	x	y	z	x	y	z
Baling (1)	4.8	4.4	6.1	1.74	1.47	1.64	8.32	6.34	3.18
Baling (2)	6.3	6.8	4.5	1.53	1.48	1.46	6.56	5.19	4.70
Baling (3)	6	5.6	2.5	1.84	1.50	1.54	8.26	6.25	3.69
Baling (4)	4.1	3.8	5.2	1.65	1.54	2.43	8.71	8.60	6.77
Baling (5)	5.1	4.3	2.2	1.67	1.53	1.43	9.00	8.60	6.00
Heston Baling	5.6	4.4	3.6	1.44	1.47	1.82	5.92	7.84	3.48
Wrapping	4.1	3	4.1	2.29	2.38	2.98	13.07	8.86	5.33
Forage Harvesting	16.5	12	7.3	1.71	1.62	2.23	5.17	7.14	7.75
Mowing	9.7	9	9.9	1.43	1.39	1.38	9.18	5.41	5.04
Buckraking	9	7.7	2.8	1.51	1.59	1.51	6.23	10.32	4.31
Seeding	5.1	4.6	4.9	1.59	1.56	1.53	6.09	5.04	5.55
Ploughing	8.3	10.3	4.8	1.44	1.44	1.44	7.81	5.10	3.59

The outlined cells mark the worst axis in the VDV evaluation

The VDV values shown here are calculated for 1 hours exposure to allow comparison between the exposures. The dependency on duration has to be considered a fault of the VDV analysis method. Assuming the measurement period is typical of the daily task, the r.m.s. results can easily be extrapolated to give a daily exposure value, and can easily be compared across tasks. This is not the case for the VDV results.

There is no conclusive ‘worst axis’ amongst the operations evaluated above. Among the 3 baling operations, the worst axis varies between x, y and z for the 5 measured tractors.

Unfortunately there is not enough vehicles of the same type measured to allow for possible trends among operation type to be evaluated. There are differences between the worst axis defined by the r.m.s and VDV evaluation methods. Baling tasks 3 and 4 and seeding all differ in the calculated worst axis between the 2 methods. With VDV methods, there seems to be a greater tendency for x axis to be the worst axis, and from the frequency analysis below, this is also the axis with the greatest power.

4.4.3 Frequency analysis of vibration data

Figure 29, Figure 30 and Figure 31 illustrate the PSDs from the vibration collected during the field tasks.

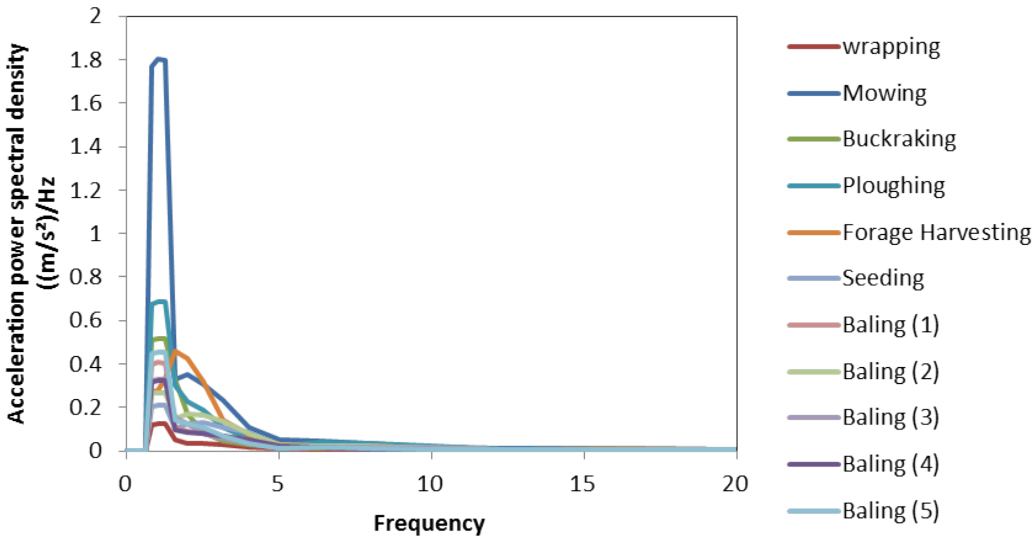


Figure 29 Weighted PSD of vibration for all operations (x-axis)

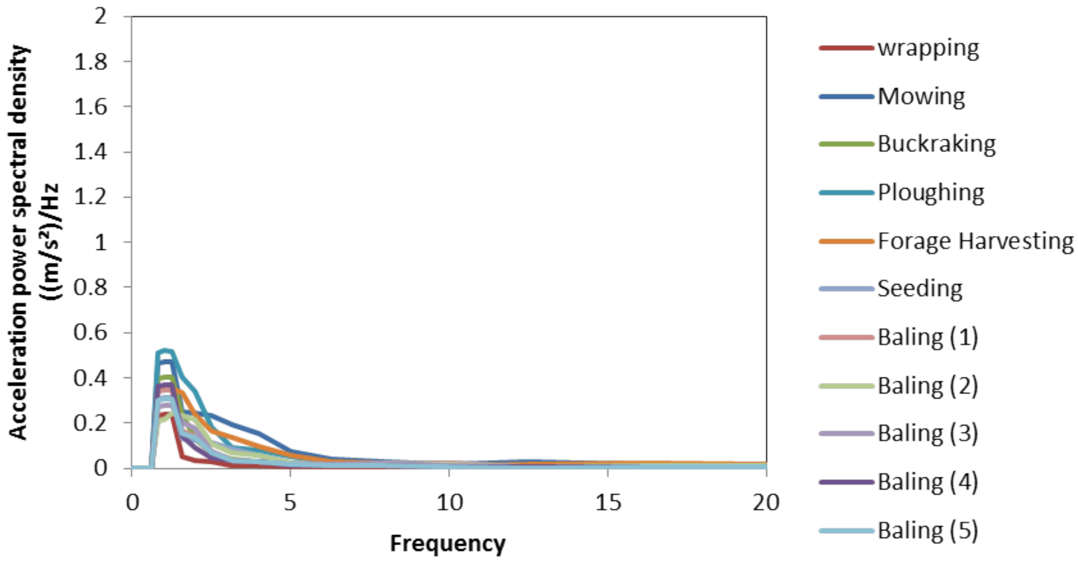


Figure 30 Weighted PSD of vibration for all operations (y-axis)

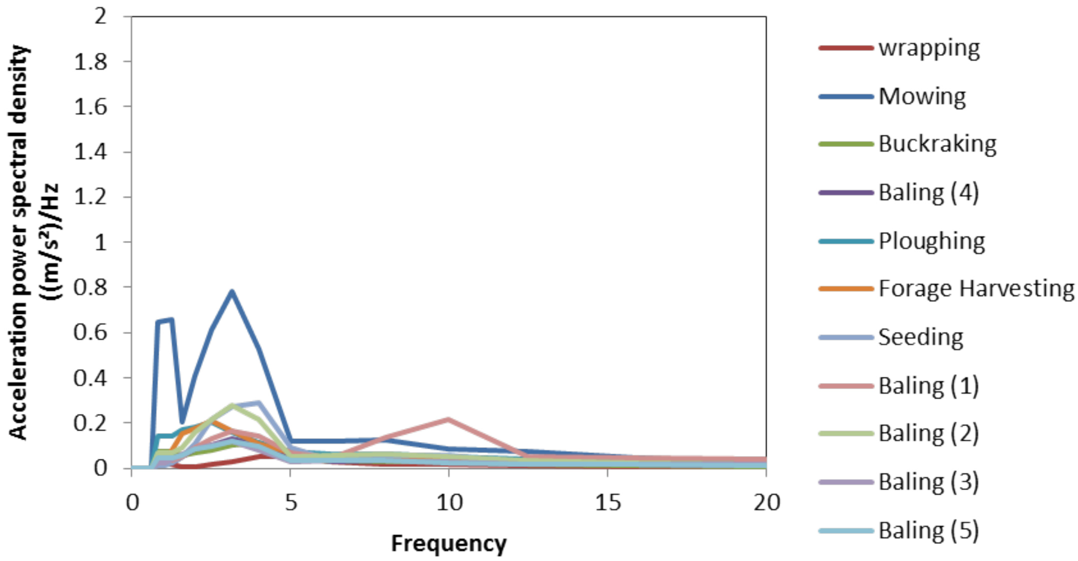


Figure 31 Weighted PSD of vibration for all operations (z-axis)

One operation, mowing had a dominant frequency of 2-3Hz in the fore-aft direction. This operation also had a different profile to the other operations in the vertical direction with dominant frequencies at 2 and 4Hz. Despite the dominant frequency in the x axis, the greatest r.m.s values are seen in the y-axis. The power spectral densities of the other operations are all similar, with dominant frequencies between 1-5Hz in all axes. In addition, all operations have greatest power in the x-axis,

4.4.4 Operator posture and task analysis

The percentage of operators spending time with different levels of rotation differed greatly between the tasks, as expected, Figure 32 below. The greatest levels of rotation are seen in the wrapping (85% task time at maximum rotation) and ploughing (90% task time between 110° and maximum rotation). Tasks with the lowest levels of rotation are Heston baling and mowing.

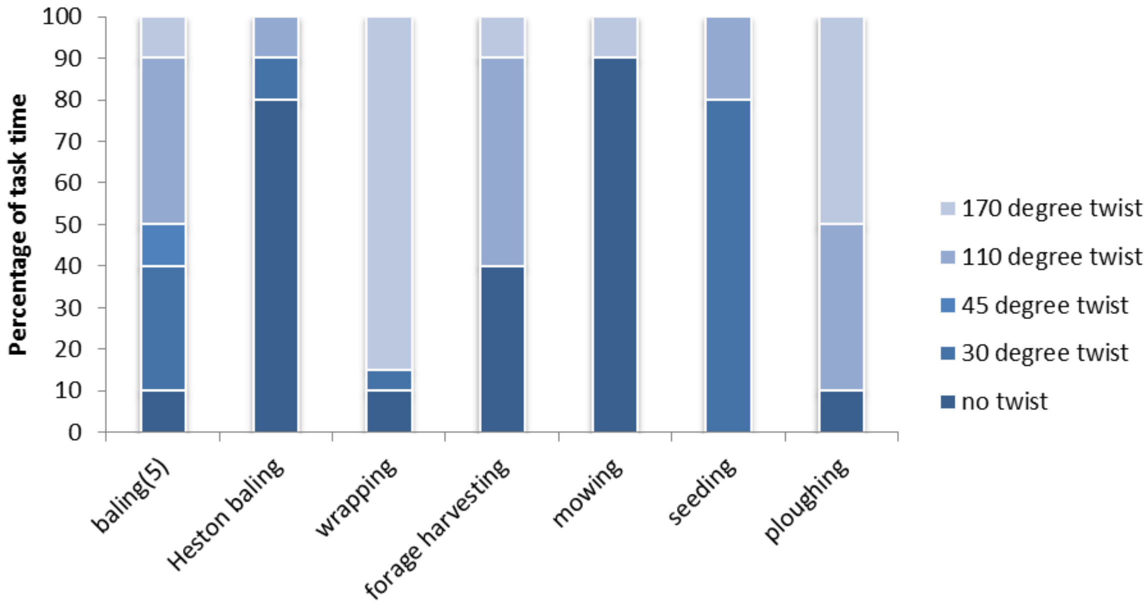


Figure 32 Percentage of task time spent with specified levels of rotation

In addition to the percentage task time spent rotated, information was also collected as to the frequency of rotations and the cycle time (where appropriate). These are illustrated Table 12 below. As can be seen, the tasks with the greatest frequency of rotations are the baling (exception Heston) and forage harvesting tasks. The lowest frequency of rotations is seen with the ploughing and mowing tasks. The combination of the magnitude and frequency of rotation allows for a greater insight into the task. For example ploughing and mowing, although both reasonably static tasks, it can be seen that operators mowing typically spend the majority of task time in a forward facing neutral posture, however operators ploughing spend a large duration in static heavily rotated postures. Although the operations of baling and ploughing may have similar proportions of time spent at particular levels of rotation, it can be seen the baling consists of much less task time in a static rotated posture.

Table 12 Breakdown of rotation frequency and cycle time by operation

Task (subject)	Turns/min	Cycle time (min)
Baling (1)	11.4	2
Baling (2)	11	4
Baling (3)	10.6	3
Baling (4)	9.8	5
Baling (5)	4	4
Heston baling	0.5	6
Ploughing	0.5	5
Mowing	0.5	n/a
Wrapping	4.5	3-4
Forage harvesting	15	15-18
Seeding	3	n/a

These results can be compared to the results collected by Whyte and Barber (1985)

Table 13 Task analysis, shortened version, from Whyte and Barber (1985)

Task	Total time (min)	Turns/min (s.d)	%time ahead/behind (s.d)
Ploughing	71	11(5)	56/44 (23)
Rotary mowing	7.1	15 (7)	72/28 (16)
Cutter bar mowing	6.7	29 (9)	56/44 (7)
Forage harvesting	15.7	17 (3)	41/59 (8)
Baling	18.5	15 (3)	40/60 (11)

As can be seen from comparing Table 13 and Table 12, the results are similar. For baling, the turns per minute is reduced from 15 in Whyte and Barber's study to between 4 and 11 in the present study. The results for forage harvesting are also similar between the two studies. However, the results for both mowing and ploughing are different between the two studies. Whyte and Barber found these tasks to include many more rotations than in the current study.

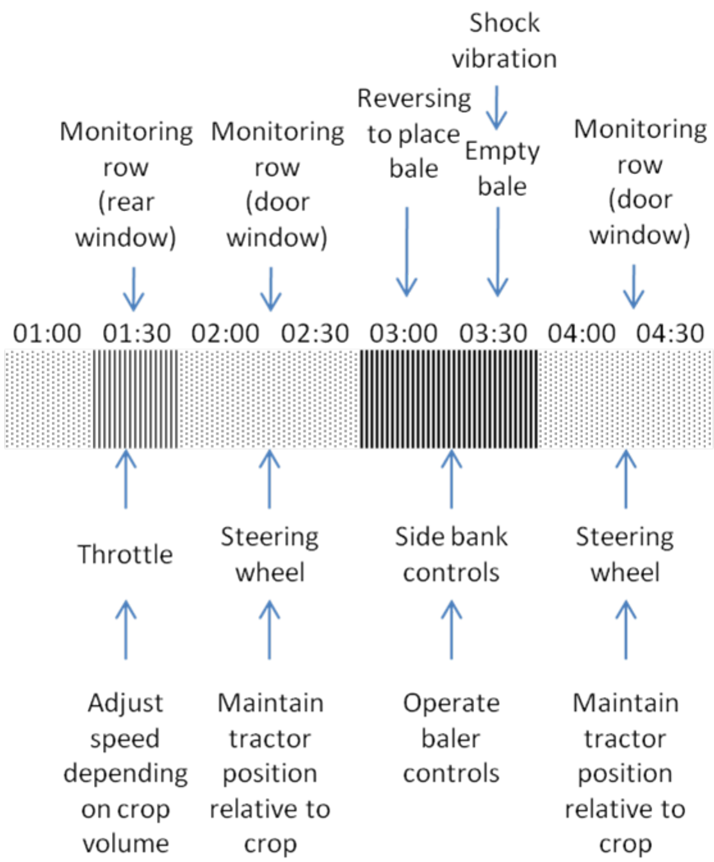


Figure 33 Example of task breakdown (baler 1)

Figure 33 illustrates an example of a typical task breakdown. This allows the complete picture of the task to be built, with the control activation and the posture of the operator to be built in. The conclusions of this analysis are given in Table 14 below.

Table 14 Task descriptions, including interactions between operator postures, control activation and vibration exposure

Task	Posture	Control activation	Shock vibration
Baling	Twisted posture to observe crop entering pick-up-reel, twist for reversing to place bale (particularly issue on steep ground)	Control activation needed for applying string to bale and emptying bale	Shock vibration as bale empties whilst twisted and activating control
Heston Baling	Forward facing, infrequent monitoring of crop entering pick up reel	Controls placed to front right of operator	
Ploughing	Static monitoring of	Spool control (for	Large shock caused

	ground, particularly to avoid stones;	lifting and turning plough) placed on side bank, requires activation at end of field	when turning plough, operator faces backwards during this to monitor its completion
Mowing	Observation mainly out of front-side window to ensure tractor placement in-line with crops, rotating only to reverse at end of row	Spool control (For lifting mower) only needed at end of rows	Operator travels across headland to turn around, which causes vibration. Mowing is also fastest operation measured
Wrapping	Twisted posture required to monitor amount of wrap on bale	Control activation required throughout this duration, controls placed next to back window, both hands required	Shock vibration as bale is placed on wrapper, and when emptied off. Momentum of bale rotating on wrapper creates movement of the tractor
Forage Harvesting	Rearward observation is required to direct grass placement in trailer, this is interspersed with periods of forward facing as operator drives back to farm	Joystick control of grass chute, this is placed to front right of operator, observation is required to rear during its use	
Seeding	Screen control panel is placed to front right of operator, this is monitored throughout, except when changing direction	Changes to seed volume is made on control panel	

Much of the requirement for twist is driven by the requirement for observation. The controls for the Heston baling included a measure of crop moisture content. The crop bulks, and creates blockages in the machines when the moisture content is high, therefore by monitoring driving speed and therefore crop volume in response to moisture content, the operator could negate the requirement for rearward attention. A simple solution for many of the issues could be negated with a little consideration in the design phase. The controls for all of the round balers and the wrapper were placed to the right and rear of the operator. This is because the spool control hose would not reach further into the cab, and also there is no platform for placement anywhere else in the cab. For the Heston baler, the spool hose was lengthy, allowing for choice in placement, and had its own stand to fit on the right door. It is not a matter of age, the Heston baler was probably the oldest attachment measured.

4.5 Discussion

Previous studies have highlighted the levels of rotation and vibration in agriculture (Sjoflot, 1980; Bottoms and Barber, 1994). In order to understand how the exposures have changed over time, the present field study was conceived to investigate current exposures. The aim was to consider the driving environment as a whole, how the twist and vibration exposures are combined. The sample set was small, in part due to the availability of the sample population, and due to equipment failings. An additional 2 operators with full cab suspension tractors were measured but the vibration data corrupted and therefore the data is not available for analysis.

4.5.1 Vibration exposure magnitudes

Previous studies have shown that cultivating tasks subject the operator to the greatest vibration exposure (Bottoms and Barber, 1994; Scarlett et al., 2007). The tasks with the greatest vibration exposure in this study were the four who exceeded the PA(V)D limit value in the worst axis, these were mowing, ploughing, heston baling and forage harvesting (in descending order, see Table 10). Only one of these could strictly be considered a cultivation task (ploughing). The worst task measured here was mowing, which has not been identified in any previous research, and was the first hypothesis identified for this study. In this task the operator was highly trained and the field condition was not particularly poor in comparison to those where the other tasks were measured. It appears the main distinction between this task and others measured here, besides the operation, is the speed of the tractor ride. The mower itself was a trailed mower conditioner, where the grass is not only cut, but beat with flails to extract the juice out of the grass to aid wilting. This addition to the mower requires a high powered tractor and is quite brutal in its operation, which may contribute to the reason for the high vibration emissions transmitted to the tractor, and therefore the operator.

It was hypothesised that 50% of the operations measured would exceed the action levels set out in the physical agents (vibration) directive of 0.5m/s^2 worst axis. 4 out of the 12 operations measured exceeded the limit value in the worst axis, with all but 2 exceeding the action value. This illustrates that little improvements have been made if this is compared to previous studies. Figure 34 illustrates the results of the current study in comparison to previous studies. The range of vibration seen in this study is lower than previous studies, however only Mayton and colleagues report clearly increased ranges. The vehicles used in the study by Mayton et al. (2008) included smaller utility vehicles, and these appear responsible for the higher vibration emissions seen in their study.

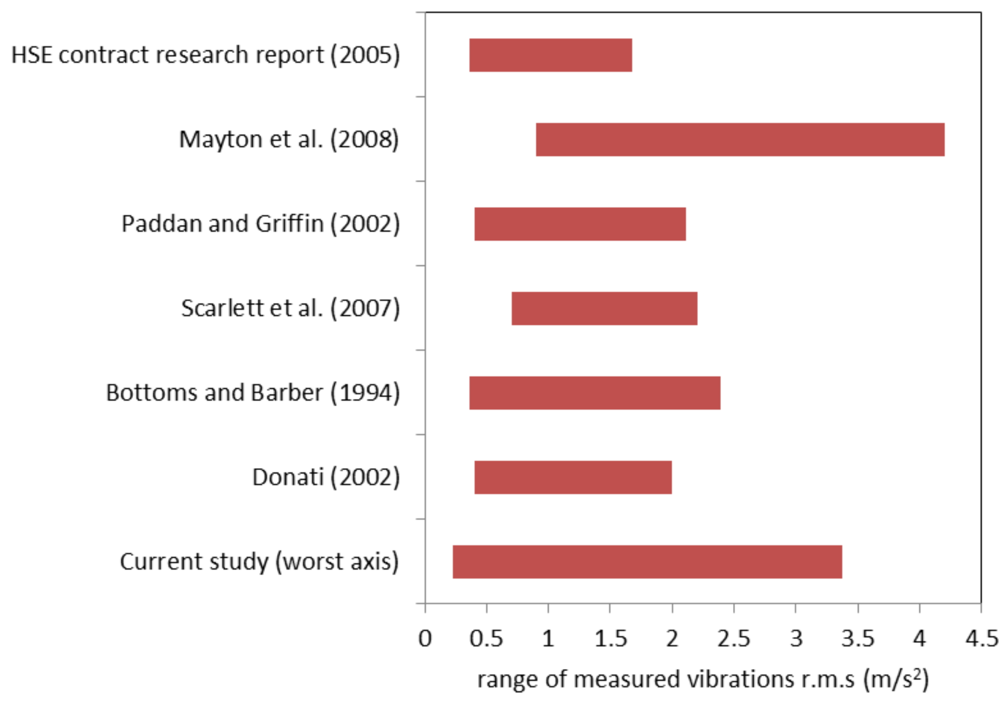
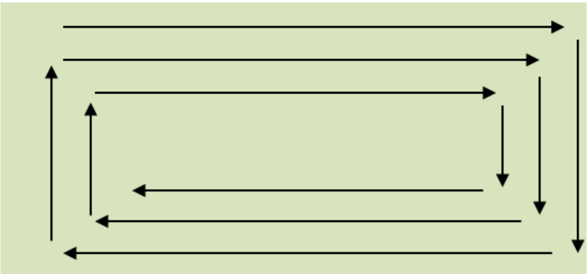


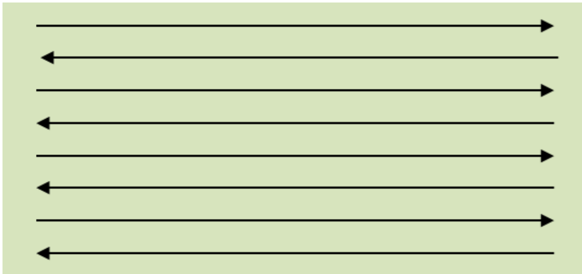
Figure 34 Vibration emissions for previous and current studies. Vibration presented is range reported in paper, weighted r.m.s.

In other off-road driving occupations such as quarrying and mining, much of the vibration emission reduction strategies have focussed on improving the work surface. However, this is not the case in agriculture. Improvements *have* been made to the working surface, but this is a consequence of developments in cultivation attachments and methods (e.g. disking and power harrowing), rather than a targeted action. An insightful conversation with 1 operator illustrated the issue that still exists. There is a varying number of machines that are used on the fields. Smaller vehicles tend to circulate the field more times, finishing by doing the centre section in longer lengths. When a larger machine is used on the field, they cannot turn the sharp corners that the smaller machine has, so will turn around at end and only travel up and down the field. The result is that the travelling lines (caused by the smaller vehicles) are at right angles to the direction of travel of the larger vehicle, essentially causing a cross over, and an uneven working surface.

e.g. 1. smaller machines go round and round field to avoid turning round



e.g. 2. larger machines cannot turn corners, so would rather turn around



Result: areas of concern are where both travelling routes coincide

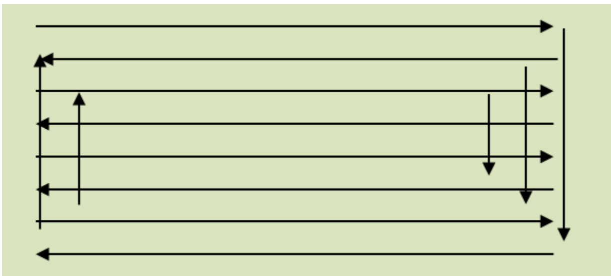


Figure 35 Areas of concern when different machines are used to cultivate the same piece of land

The example provided in Figure 35 was the case for the mowing task investigated in this study, and could go some way to explaining the higher than expected measured vibration magnitudes.

An understanding of the frequency components is vital to fully understand the nature of the exposure, particularly if the dominant frequencies lie within those thought to have the greatest detrimental effect upon the body (Manusson et al., 1992). The hypothesis that fore-aft vibration would dominate the vibration, as found in other off-road vehicles (Newell, 2007). From the PSDs it is clear that the greatest power is held in the fore-aft axis, this is not represented in the worst axis of vibration in the vehicles though. Newell (2007) specified that the dominance of the fore-aft axis was a result of the travelling carried out during the off road operations investigated. The majority of the power in all axis was focussed between 1-5Hz. This is in concurrence with the results from Bovenzi and Betta (1994) who found dominance at 2.5-5Hz,narrower than the 1-7Hz found by Kumar et al. (1999). Crolla (1976) suggest that the tractor and plough behaviour are altered when they are combined. Tractor ride vibration is reduced when ploughing because tractor pitch and bounce are damped by the vertical force on the plough, the damping forces are transmitted to the tractor through the linkages. Crolla also suggests that the vertical motion components of a tractor alone centre on 4Hz, whereas when connected to a plough these are reduced to 1.5Hz.

4.5.2 Posture of the operator

In the hypothesis, it was predicted that the posture of the operator would be greatly determined by the task. In fact it seems that although the task plays a large role, another key determinant is control placement and operator trust in machinery and crop. As an example, out of the balers one (5) had a low frequency of twists in comparison to the others. This operator had the most favourable harvesting conditions, therefore a low moisture content in the crop. This meant the likelihood of blocking the machine was low, in addition the baler had the ability to 'reverse', reducing the impact of any blockage. These two factors combined meant the operator only had to rotate to monitor occasionally and for bale placement. In contrast, the posture of the wrapper operator was exacerbated by the placement of the controls so close to the rear of the cabin, and the requirement for constant observation of the bale to monitor the amount of wrap applied. The requirement for better control placement has been raised previously by Donati (2002). Donati's sentiments that machine operation should be possible without requiring the operator to adopt awkward or unusual postures cannot be echoed more clearly than by the conclusions of this study.

4.5.3 Combinations of vibration and adverse postures

This thesis is tasked with investigating exposures with both vibration and twist components. The results of the current study indicate that these factors do not occur in isolation, and in fact particular tasks i.e. ploughing include high components of both. In addition, the results of this study illustrate that not all rotations are static and held for relatively long periods of time, but in tasks such as baling, there is a high frequency of rotations per minute. The postures of the operators and the dynamic rotation warrant further investigation within the laboratory studies.

4.5.4 Limitations of the study

The study presented here had high external validity, however the time and preparation required for such data collection has restricted the number of operations available to be investigated. Environmental conditions were unfavourable for the collection period, with unusually high levels of rainfall (Met Office, 2010). This meant a number of operators who had originally agreed to participate ended up operating in simultaneum. In addition, due to the added pressure that small windows in the weather gave, some withdrew as they perceived the data collection would delay their harvest.

The loss of the floor vibration data was unfortunate. Consideration of the SEAT values would have added to the understanding of the exposures.

Ideally the vibration measurements and tasks analysis would have covered a whole working day. This was not a practical option due to the operator availability. The measurement durations were maximised where possible, and did include a representative sample of the task on that day. Also, a variety of operators completing the same task with a variety of vehicles would allow a wider application of the data. Nevertheless, the results are interesting and provide evidence of the exposures.

There are a number of different kinds of variability that can have an impact on the assessment from WBV exposure (Newell, 2007). Studies by Marjanen (2006) indicated that vibration magnitudes measured on one day were not representative of the vibration profile experienced throughout the working week. This was further confirmed by the studies by Newell (2007). Furthermore it is acknowledges that additional variability is caused by operators, vehicles and working surfaces. Therefore it cannot be suggested that the field study is necessary typical of vibration exposures in agriculture. However, it may be considered that they will be representative of similar exposures. The field study proved problematic due to the limited weather window available to the operators to complete the harvesting tasks investigated. This issue limited available operators, and reduced possible measurement times. The floor vibration data was removed from evaluation due to issues within the vibration data, possibly due to operator contact with the accelerometer on the floor, or possibly due to contact issues of the accelerometer with the measuring surface.

4.6 Conclusions

The measures of vibration magnitude and operator posture revealed both exceeded what could be considered as acceptable. Forage harvesting is a task of particular concern due to both the high frequency of twists and the high magnitude vibration exposures. The original hypotheses are accepted or rejected below.

H_1: Ploughing and cultivation tasks will produce the greatest WBV emissions (Sjoflot, 1980)

If assessed with the r.m.s worst axis method, as specified in PA(V)D, the tasks with the greatest measured WBV emission were mowing, forage harvesting and ploughing respectively. Therefore the hypothesis is rejected.

H_2: Fore-aft vibration will dominate the exposure profile for field tasks (previous studies have demonstrated this is the worst axis for off road driving profiles, Newell and Mansfield, 2007)

Using the r.m.s. method of evaluation, there are more tasks with higher vibration magnitudes in the vertical axis than the for-aft and lateral. However, when using the VDV method of evaluation, the fore-aft axis dominated the worst axis exposure profiles. The PSDs of the vibration does not clearly discriminate between the axis, therefore the hypothesis is rejected.

H_3: The posture of the operator will be determined by the task, those with greatest durations of rotation will be ploughing

The greatest length of task time spent twisted was observed in the round bale wrapping task, the hypothesis is therefore rejected. The control placement also had an effect on operator posture.

H_4: The largest frequency of rotations will occur during baling operations (Whyte and Barber, 1985)

The largest frequency of rotations occurs during forest harvesting, followed by the baling tasks. The hypothesis is therefore rejected, although it is noted that forage harvesting was not measured in the study by Whyte and Barber (1985).

CHAPTER 5: Review of expert opinion on occupational exposures containing both trunk rotation and WBV elements

5.1 Introduction

The fields of whole-body vibration and postural ergonomics are well founded, and extensive literature is present for each area. However, the cross-over area covering occupations with both risk factors is less well developed. Due to the complexity of each area, experts tend to specialize in one or two areas (Keyserling and Wittig, 1988). The literature for both is discussed in many of the previous sections of this thesis. However, many experts in the areas have thoughts and ideas that cannot be elicited from a literature review. The skills used by an expert to formulate an opinion are the result of concentrated training and research (Keyerling and Wittig, 1988). Therefore it was considered that a survey of the key experts in the area would allow a rapid review of available knowledge on key areas.

The method of expert opinion is well utilised in healthcare where a selection of treatment methods can be considered by experts in the field. Through this consideration, a wealth of knowledge on procedures or treatment combinations may be shared between the contributors. This method is an iterative process and is grounded in the Delphi technique (Dalkey, 1969). Experts in the field of ergonomics are often called upon to visit workplaces and use their knowledge and experience to evaluate and rate ergonomic stressors which may cause fatigue, discomfort or injury. Whilst in agreement that the Delphi technique is a good technique for problem solving, this was not the aim for this survey and therefore only the first stage is completed, i.e. the opinions once collected are not disseminated back to respondents for feedback and improvement.

The method of surveying expert opinion on issues in ergonomics is less utilised, however it has been used by some when exploring areas less covered in the literature e.g. Sandover (1998). Sandover considered three linked investigations to uncover the whole picture surrounding high acceleration and shock events. This included a literature review, field data, and a review of expert opinion. The other areas of investigation, literature review and field data are covered elsewhere in this thesis, this section will focus on expert opinion review.

5.2 Aims and Hypothesis

The objective of this study was to collate unpublished knowledge and opinions of experts on the presence and magnitude of the impact of simultaneous exposure to trunk rotation and WBV on musculoskeletal discomfort development. A secondary objective was to determine where conflictions in opinion/judgement may occur between the expert groups. A final objective was to determine how well the experts' ratings agreed with objective measures of ergonomic strain.

H_1 The risks of musculoskeletal discomfort from WBV and axial rotation, judged by the experts, will be greater when exposures are combined
H_2 The areas of perceived discomfort as judged by the experts will match subjective results gained in laboratory studies (Chapters 6, 7 and 8).
H_3 Those with experience of posture and vibration assessment will recommend recognition of combined exposure risk in risk assessment techniques
H_4 Recommended technological developments in agricultural tractor design from the literature (Bottoms and Barber, 1978; Sjoflot, 1980) will be considered apposite for reducing the risks from trunk rotation and WBV.

5.3 Methods

5.3.1 Subjects

The three expert groups chosen for analysis are

1) Vibration experts (VE) - those working with assessment and teaching of the effects of WBV
2) Postures experts (PE) – those with experience with assessment and teaching of the effects of working postures
3) Operating experts (OE) - operators with experience of driving exposures likely to include exposure to axial rotation and WBV

A questionnaire was developed to facilitate completion by the three expert groups, however it was appropriate to remove/supplement some questions in the operator (OE) questionnaire. This is discussed in more detail below. The questionnaire was formulated for completion either online or on a paper based form. It has been suggested that this combination of collection methods allows a wide range of respondents and maximises the response rate (Gosling et al., 2006). Various methods of recruitment were utilised to ensure a fair representation of the target population. Methods of recruitment along with the target method of completion are detailed in Table 15.

Table 15 Methods of recruitment for the target respondent groups.

Target group	Recruitment method	Target method of completion
OE	Trade shows – opportunistic sample of operators visiting tractor stands at Royal Welsh Show 2009	Paper
	Field study participants – those participating in field study investigation were invited to complete the survey	Paper
	Online – a discussion thread was opened on Farmers Weekly online, a link to an online version of the survey was posted	Online
VE	Human Response to Vibration conference 2009	Paper
PE	Ergonomics Society conference	Paper
	Transport special interest group – members of the transport special interest group were e-mailed with an online version of the survey	Online

An e-mail message and posts on discussion forums asked professionals to participate in a survey of occupational exposures in agriculture. The e-mail also contained information on the average time required for completion (10-15mins), information on the confidentiality of answers and the method of access to the survey (a link to the survey's host website). The author's contact information was also provided. Survey Monkey (2009) was utilised to facilitate the survey due to the flexibility in survey design and format, the ability to add images to the survey and the provision for anonymity. The survey introduction included an overview of the topic area, thanked participants and contained Loughborough University logo and contact details to reinforce the source of the questionnaire. Participants were also notified of the presence of comment boxes throughout the survey and encouraged to write any additional information in these that they felt appropriate. The confidentiality and withdrawal information was repeated along with researcher contact details. The paper based questionnaire included the same introduction and was essentially a reproduction of the online form, with some additional formatting where appropriate.

Dillman (2000) asserts that people's motivation to respond to surveys is vested in the Social Exchange Theory that by responding in the survey respondents will be compensated in a way that meets some of their needs. No monetary incentives were provided to participants. Although in the introduction to the research to the operators, the interest in the research of tractor manufacturers was stressed. For academic and practitioner experts in vibration and ergonomics, it was hoped that the incentive for these groups would be contribution to research within their fields. Keith (1996) considers the core methodological problem of combining expert opinion is based on a simple unavoidable truth: the fraction of experts who hold a given view is not proportional to the probability of that view being correct. One may safely average model parameters, but not models. The approach here, therefore is not to know what "the answer" is, but rather what the leading sources of uncertainty and concern are, what is the potential for conflicts in the future conclusions of study.

The survey was organised into separate categories. It had become clear that there were 5 main areas that were ambiguous in the literature, or had not been visited in recent years. These are discussed below along with the questionnaire development.

5.3.2 Survey Content

5.3.2.1 Respondent demographics

A demographics section contained questions on the area and length of expertise of the respondent.

The ergonomist specialism groupings were taken from the primary knowledge areas recognised by the Institute for Ergonomics and Human Factors (IEHF, 2008). Respondents were asked to indicate their main area of expertise, the categories are as follows:

- Anatomy, anthropology and physiology in human activities (incl. postural and biomechanical loading)
- Environmental stressors (incl. vibration)

- General psychology & organisational psychology (incl. cognitive ergonomics)
- Socio-technical systems (incl. systems evaluation)
- Survey and research methods (incl. measurement techniques)

For operator respondents, the areas of expertise were taken from the main sectors in agriculture defined by Department of Farming and Rural Affairs (DEFRA) with the addition of contractors, as although not considered 'farmers' by DEFRA, will have extensive experience of the exposures being discussed. The categories are listed below:

- Arable
- Contractor
- Dairy
- Livestock
- Poultry
- Pigs

An option for 'other' was also provided in both cases, although respondents choosing this box were asked to specify. Subjects were asked to indicate their length of experience in the above areas in broad response categories, (none; < 1 year; 1-2 years; 2-5 years; 5-10 years; >10 years).

Operators were asked to estimate their typical driving time (per day) during busy periods. Due to the variable nature of work in agriculture it was considered necessary to specify 'busy periods' to get a true representation of time spent on tractors when using them. The operators were also asked to estimate the number of rest periods typically taken during this driving activity.

5.3.2.2 *Health risks*

One of the main aims of this research thesis is to categorize the risk to musculoskeletal health from exposure to posture and vibration stress. At the least, to provide some form of ranking between exposures. Much of the literature is rightly detailed and complex. However, to combine the research to provide an answer to the simple question of which exposure is worse, and to what magnitude is just as detailed and complex. The conclusions of many risk assessment procedures involves the ranking of exposures, whether with a traffic light green, low risk – red, high risk (EN1005-4, 2005) or with a numerical risk score (REBA). In the development of RULA and REBA, McAtmney et al. (1993, 2000) collated the data on MSD development from the literature. They also considered the opinions of ergonomists and physiotherapists on a number of standard postures (within the health profession) on their level of risk for MSD development. The professionals were provided with images of the working postures and required to code the risk for predefined areas i.e. trunk, neck, arms etc. The results of all the risk coding then led to the development of REBA (Hignett and McAtmney, 2000). A similar method is employed here, although illustrations of postures were not provided, as vibration magnitude could not be easily conveyed via this method and this may have caused unnecessary bias. Experts in this study were provided with written explanations of the exposures. These are detailed below:

- No twist, low vibration (smooth driving ~$0.25m/s^2$)
- No twist, medium vibration (rough driving ~$0.5m/s^2$)
- No twist, high vibration (off road driving ~$1m/s^2$)
- Medium twist (70°), low vibration
- Medium twist, medium vibration
- Medium twist, high vibration
- High twist (170°), low vibration
- High twist, medium vibration
- High twist, high vibration

The experts were asked to consider each of the exposures and to rate how risky they felt each exposure would be for the development of an MSD. The verbal descriptives for risk level are the same as used for the body part discomfort, a unipolar 5 point scale, ranging from not at all to extremely. The response categories are detailed below:

- Not at all
- Slightly
- Moderately
- Very
- Extremely

Only PE and VE were asked to complete this question.

All experts were asked to classify whether they thought a risk for low back pain was posed by trunk rotation and by WBV separately. They were also asked to consider if they felt the risk increased if the exposures were combined.

The use of exposure limitation is a common method of risk control. Guidance and standards often prescribe a limit on exposure duration e.g. physical agents (vibration) directive (2005). The acceptable exposure duration is inversely proportional to the perceived risk, i.e. in the case of the PA(V)D, higher vibration exposure results in shorter acceptable exposure durations. A method often employed to determine the severity of exposure it to ask subjects to consider "how long would you do this for?". Wikstrom (1993) asked experienced operators this when considering vibration and twist exposures. Here, experts were asked to consider what they felt acceptable exposure durations would be for a variety of twist and vibration combinations, these are given below:

- No twist, no vibration
- Medium twist, no vibration
- High twist, no vibration
- No twist, with vibration
- Medium twist, with vibration
- High twist, with vibration

No response categories were provided, to avoid biasing the responses.

5.3.3.3 Discomfort development

Subjective discomfort is used in many studies to rate exposures. More specifically, body part discomfort has been used to investigate patterns of discomfort (Kuorinka et al., 1987). Experts were asked to mark on a body outline where they felt discomfort would manifest. An example of this question is illustrated below (in bold).

Please indicate on the body maps below any areas you feel the operator may experience discomfort either during, or after exposure to vibration or twisted postures. Mark as many areas as you feel appropriate.

e.g. ***The mark below would show discomfort in the elbow.***

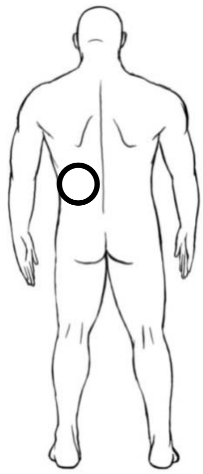


Figure 36 Body outline for marking of discomfort

Once compiled, the body maps for the separate respondent groups can be compared. These can also be compared to the responses from the laboratory studies, and also equivalent studies in the literature.

5.3.3.4 Guidance and standards

The creation of formal, international standards is an arduous process, consisting of many meetings between experts within the area, and consideration of vast amounts of literature. There is a wealth of guidance (PA(V)D, 2002) and standards (ISO 2631-1, 1997). Those with experience in assessing WBV exposures were asked whether they considered that the posture of the operator should be reflected as part of the assessment of WBV exposure. The level at which posture should be considered was also examined within this section. This question was omitted from the OE questionnaire, as it was deemed unsuitable.

5.3.3.5 Evaluation of previous research

Within agricultural tractors, the focus for development has been directed at reducing vibration exposure. Better suspension systems are now present on many tractors, extended from the seat to wheel and cab suspension. Relatively small progression has been made to impact the requirement for twist whilst completing many tasks in an agricultural driving environment. Sjofløt (1980) proposed the addition of large mirrors to reduce the need for operators twisting in monitoring tasks. A swivelling seat base was first recommended by Bottoms and Barber (1978), and has been the subject of a number of experiments in the literature (Toren, 2001). This development has been widely deployed by the main seat manufacturers for tractors including Grammer and Kab, and is seen in many of the major

UK tractor manufacturers (incl. John Deere, Case, New Holland, Massey Ferguson). The use of CCTV within vehicles has been used to allow the operator to view the area behind the vehicle when reversing (waste collection vehicles, busses, lorries) and also to cover any blind-spots around the vehicle (busses). To our knowledge, only one manufacturer selling into the UK market have introduced this into their top models (Valtra – models from Vario 700 upwards).

The use of full backrest seats are often recommended by those investigating vibration exposures (Control of Vibration at Work Regulations, 2005). However, the issue within agricultural tractor cabs is the requirement for rearwards observation which a full backrest seat may interfere with.

To investigate the perceived effectiveness of these recommendations and additions, a common task scenario was put to the experts and they are asked whether they would recommend, would not recommend, or felt unqualified to comment for each of the additions discussed above. The common task was selected so that it would deliberately include high duration and frequency of twists. The task descriptions are given below:

- An agricultural driver is required to plough an uneven field. This task requires constant rear and forward attention. The task will take approximately 8 hours, during which time the driver will leave the cab for 30mins to have lunch.

A box for comments was also provided.

At the end of the questionnaire, participants were thanked for their time, reminded of the contact details should they have any enquiries about the research, and also invited to add any further comments about the research area in general which had not been covered by the questions. The full questionnaire is included in the Appendix a) and b).

5.4 Results

5.4.1 Demographics

A response rate is only possible to determine from the VE and PE response groups. 35 questionnaires were handed out during the HRV conference with a response rate of 37% (13 VEs completed). 50 e-mails were sent out to ergonomists, 33 responded, with an additional 4 targeted respondents from the IEHF conference. These were targeted due to the in-depth experience in the field of agricultural ergonomics, or trunk rotation and WBV environments. Due to the nature of recruitment for the OE response group, it is not possible to determine a response rate, however 74 completed the survey. All of those approached at trade shows completed the questionnaire.

The length of experience of the response groups was high, with at least 50% in all response groups having greater than 10 years' experience (Figure 37). One OE having less than 1 years' experience was included. This was due to the fact their driving hours per day was high, and they had much experience of the kind of tasks being investigated. It was therefore thought they could still contribute to the questionnaire.

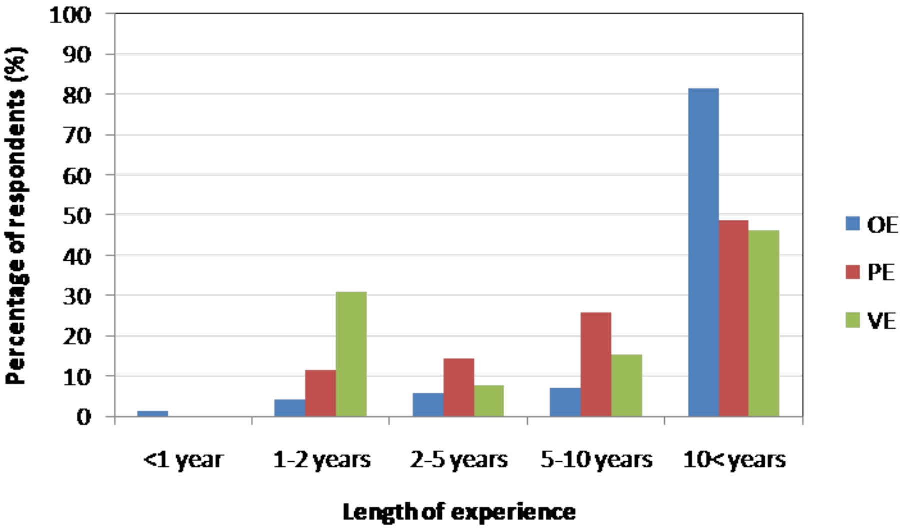


Figure 37 Length of experience for the three response groups OE, PE and VE.

The distribution between the various areas of expertise for PE and VE are illustrated in Figure 38, and OE in Figure 39.

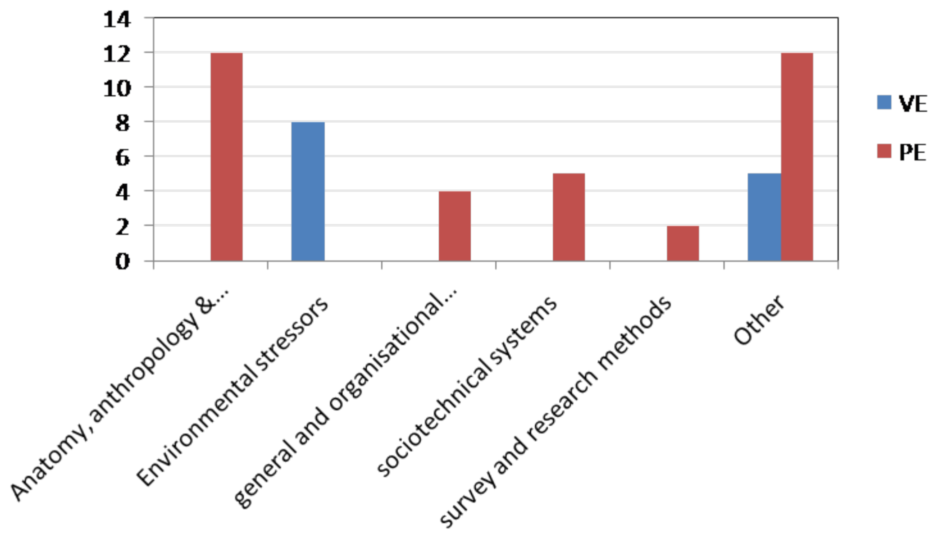


Figure 38 Distribution of expertise for PE and VE

The distribution of expertise for PEs is relatively even, with the exception of the environmental stressors section. The selection is biased towards those with greatest experience in anatomy, anthropology and physiology in human activities. This is as expected as a number of key ergonomists in this area were targeted for completion of the questionnaire.

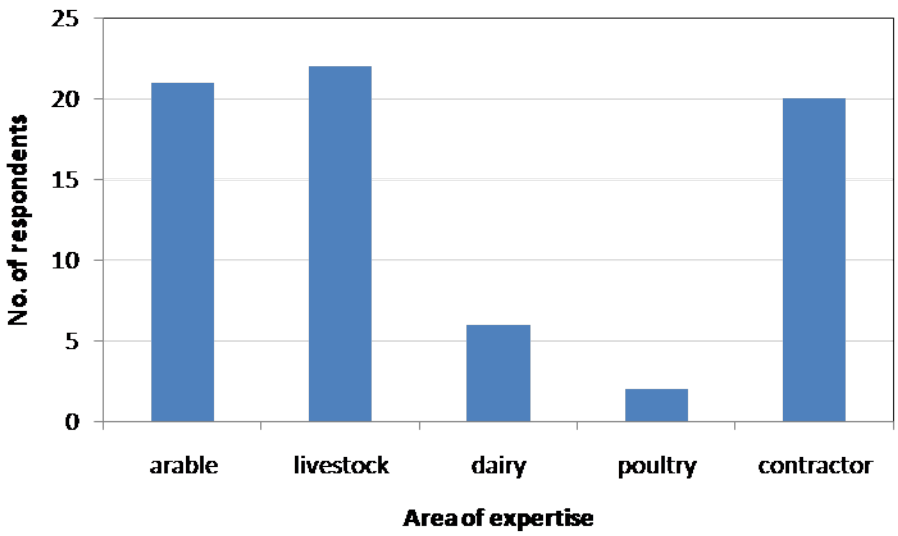


Figure 39 Distribution between the main areas of expertise for OE

The distribution between the main areas of expertise is replicable of the split in land use as specified by the Department for Farming and Rural Affairs (Figure 40). The relatively small contribution of poultry farmers is suggested to be due to the low requirement for tractors within poultry farming, and also due to the supplementary nature of this sector of farming. That is that most poultry farmers will have a main focus elsewhere, with livestock or arable for example.

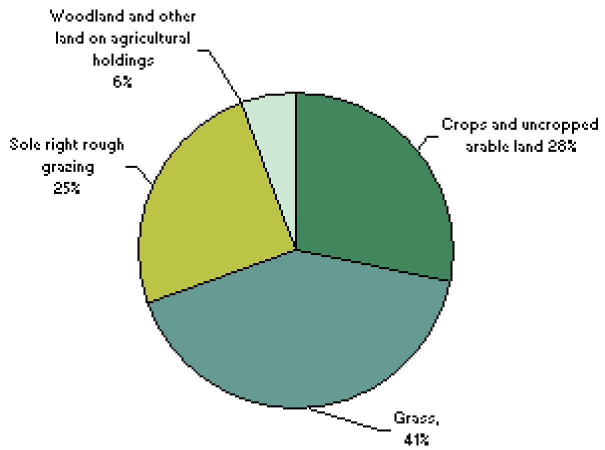


Figure 40 Agricultural land use, reproduced from DEFRA, June 2008

The OE were asked to detail their driving time per day, during busy periods, and also the number of breaks taken during these working times. A high proportion of the operators work in excess of 10 hours a day (Figure 41).

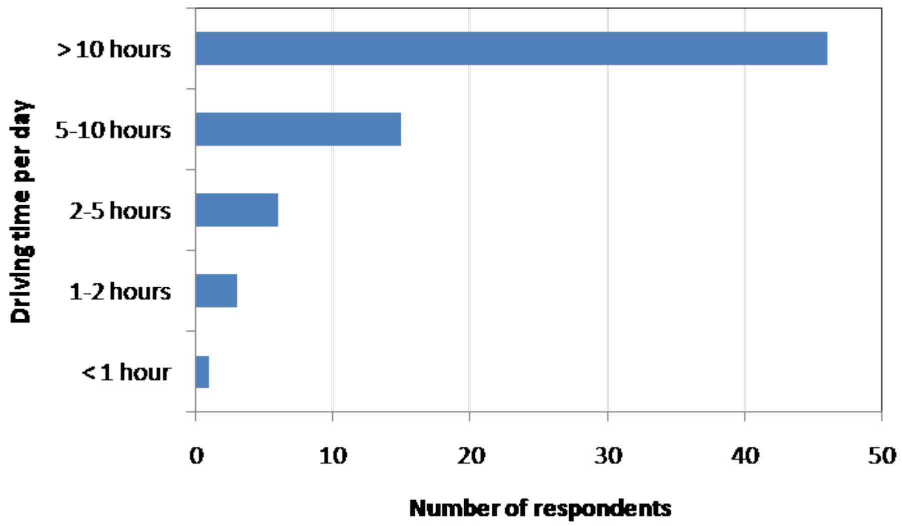


Figure 41 OE driving time per day (during busy periods)

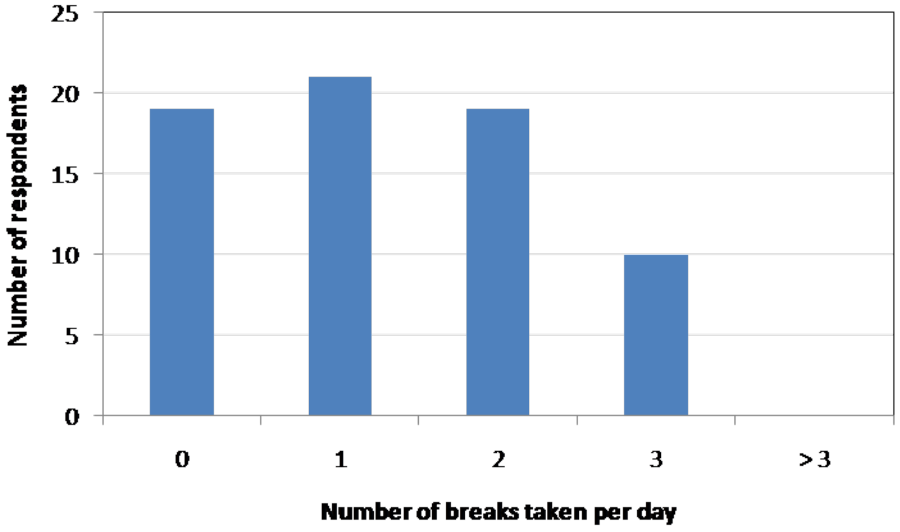
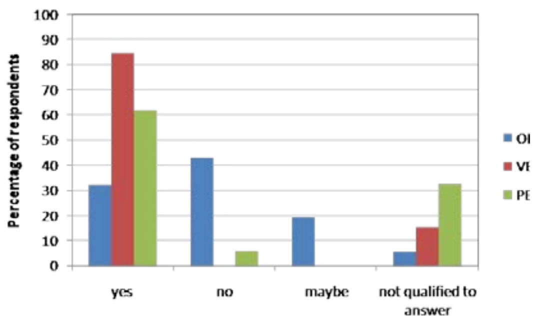


Figure 42 Number of breaks taken per working day (OE only)

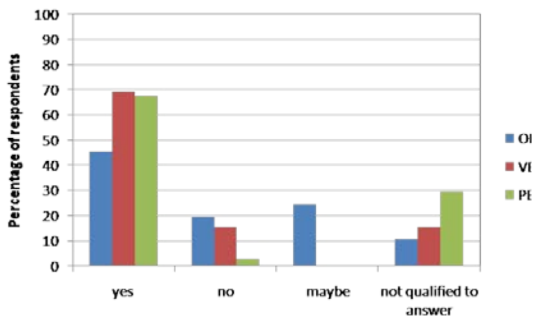
It is also clear from the data presented in Figure 42 that the long working durations are not combined with breaks from the tractor seat. Many operators commented that they ate lunch on their laps whilst driving, only leaving the cab to inspect faulty or broken implements, which they often classed as a break.

5.4.2 Low back risk assessment

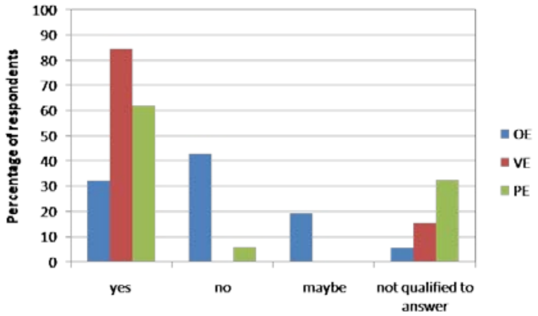
Subjects were asked to evaluate the risk for low back pain posed by exposure to WBV, trunk rotation and a combined exposure. A large consensus was present for the risks from trunk rotation and (apart from OE's) WBV was present. More VE rate WBV as a greater risk for LBP than trunk rotation, however nearly 90% are in agreement that the risks increase when the exposures are combined. Over 60% of PE are also in agreement that the risks increase when the exposures are combined, however this is not the same for the OE group, where a larger proportion felt there was no increased risk when the exposures were combined.



a)



b)



c)

Figure 43 The risk of low back pain from a) WBV, b) trunk rotation, c) risk increase from both. (OE n=33 ; PE n=37 ; VE n=13)

PE and VE groups were asked to assess the relative risk of nine predetermined exposure combinations, with trunk rotation and WBV as variables. Tables 16 and 17 display the PE and VE group responses respectively, giving the percentage of responses for each rating. The exposures were as follows:

Key to combination of risk factors represented in TablesTable **16** andTable **17**

1 no twist, low vib. (smooth driving ~0.25m/s^2)

2 no twist, medium vib. (rough driving ~0.5m/s^2)

3 no twist, high vib. (off road driving ~1m/s^2),

4 medium twist (70°), low vibration

5 medium twist, medium vibration

6 medium twist, high vibration

7 high twist (170°), low vibration

8 high twist, medium vibration

9 high twist, high vibration

Table 16 Level of risk associated with exposure to vibration (V) and trunk rotation (T), expressed as percentage of posture expert responses (mode highlighted; N=38)

Combination	Not at all	Slightly	Moderately	Very	Extremely
1	43%	**57%**	0%	0%	0%
2	5%	**62%**	29%	5%	0%
3	0%	23%	**50%**	18%	9%
4	0%	**50%**	45%	0%	5%
5	0%	5%	**65%**	25%	5%
6	0%	0%	26%	**53%**	21%
7	0%	0%	30%	**60%**	10%
8	0%	0%	5%	**60%**	35%
9	0%	0%	0%	16%	**84%**

Table 17 Level of risk associated with exposure to vibration (V) and trunk rotation (T), as

percentage of vibration expert responses (mode highlighted; N=13)

Combination	Not at all	Slightly	Moderately	Very	Extremely
1	**67%**	33%	0%	0%	0%
2	22%	**44%**	33%	0%	0%
3	0%	11%	**44%**	**44%**	0%
4	22%	**56%**	22%	0%	0%
5	11%	22%	**67%**	0%	0%
6	0%	11%	22%	**44%**	22%
7	11%	11%	**56%**	22%	0%
8	0%	0%	33%	**56%**	11%
9	0%	0%	22%	11%	**67%**

The pattern of risk assessment boundaries is similar for the two expert response groups. It is interesting to note that the majority of VE did not consider low vibration to be a risk factor for LBP, although the PE did. The majority of the VE also did not consider high twist with no vibration (category 7 in the tables above) to be as high risk as the PE. The conclusion from both response groups is that the risk for LBP increases as both exposure magnitudes (level of rotation and magnitude of vibration) are increased, with high magnitudes of vibration combined with high trunk rotation categorised as the highest risk for LBP by both expert groups.

5.4.3 Acceptable working durations

A measure often employed within risk control is the limiting of exposure durations, appropriate to the exposure magnitude. The three respondent groups were asked to specify time limits for exposures involving increasing levels of rotation with and without WBV. All experts were in agreement that exposure duration should be reduced when vibration exposure is combined with operator twist.

Table 18 Suggested exposure time limit for exposures across the three expert groups, for varying exposure combinations of trunk twist and WBV exposure (mean, with range specified in parenthesis)

	No twist, no WBV	Med. twist, no WBV.	High twist no WBV.	No twist, with WBV.	Med. twist, with WBV.	High twist, with WBV.
VE (N=13)	06:30 (02:00, 08:00)	01:45 (00:30, 02:00)	00:53 (00:20, 01:00)	03:00 (01:30, 03.45)	01:00 (00:50, 01:00)	00:30 (00:25, 00.30)
PE (N=20)	04:00 (02:00, 08:00)	01:00 (00:30, 01:20)	00:15 (00:10, 00.30)	02:00 (02:00, 03:00)	00:30 (00:20, 01:10)	00:10 (00.00, 00:25)
OE (N=26)	09:00 (08:00, 12:00)	08:00 (05:30, 09.30)	04:00 (01:00, 08:00)	06:00 (04:30, 10.00)	05:00 (04:00, 06.50)	03:30 (02:00, 04:00)

Although the respondent groups gave different duration responses, the relation between the accepted durations for each condition is the same for each group.

The level of twist appears to be more dominant than the presence of WBV when experts are asked to rate acceptable exposure durations (for the magnitudes of vibration and twist specified here). The relation between the experts' judged durations is shown in Figure 44. A large proportion of the OE group (45%) disputed the requirement for formalised exposure time limits, common stated answers included 'until the job is completed' 'if I can do it at my age, anyone can' and 'increase the number of breaks taken'.

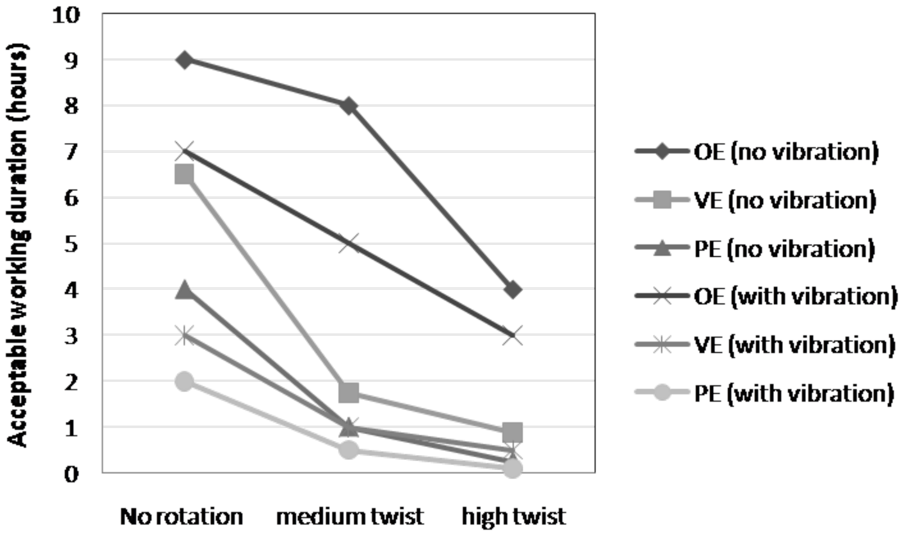


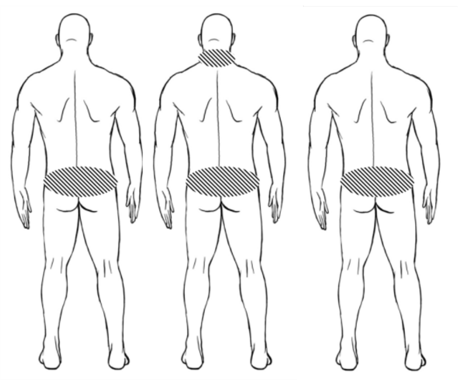
Figure 44 The mean acceptable working durations for the specified exposures

5.4.4 Risk assessment and guidance

Those with experience in WBV risk assessment (VE, N=9; PE, N=5) were asked to consider at what level of the evaluation operators' posture should be considered. All PE (100%) and the majority of VE (89%) agreed that there is a need for acknowledgement of additional risk at risk assessment level. A lower proportion (PE, 80%, VE, 67%) thought there should be an inclusion within standards, and fewer, although still a majority (PE, 80%, VE, 56%) concurred that a consideration of combined exposures should be recognised within legislation. Many felt that further investigation was required to quantify the nature of any interactions. Others pointed to the new technical standard that is under development.

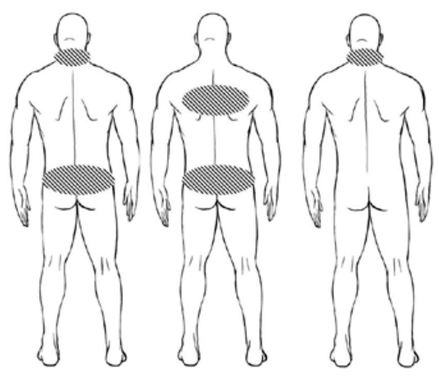
5.4.5 Body part discomfort

Experts marked on body outlines where they considered discomfort may develop under vibration and posture stress. The results were categorised by body segment and are shown below in Figure 45. All groups associated low back discomfort with WBV. OE only associated trunk rotation with neck discomfort, unlike PE and VE groups. When considering combined exposures, all experts judged an increase in discomfort.



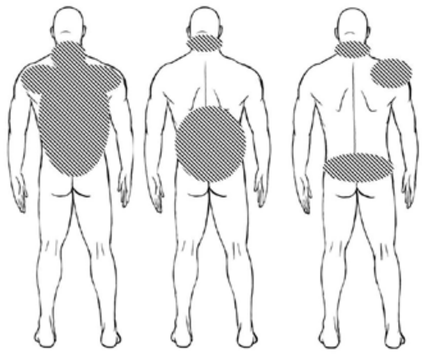
PE, N=35 VE, N=13 OE, N=22

a) whole-body vibration



PE, N=35 VE, N=13 OE, N=22

b) trunk rotation



PE, N=35 VE, N=13 OE, N=22

c) Whole-body vibration and trunk rotation

Figure 45 Areas where >40% of experts judged to be uncomfortable when exposed to either a) whole-body vibration or b) trunk rotation or c) combined

OE (N=32) provided details on which tasks caused them particular discomfort. Hedge cutting and ploughing were the most common responses, with 5 and 4 operators noting the discomfort caused by these tasks specifically. Rotation is clearly a factor with comments from OEs including “any jobs requiring rearward vision” “all jobs that require almost continuous rotation of the head”. However, WBV also appears to be an issue with “hit head on cab roof when going over rough ground”, “driving on road results in neck problems”, “very rough travel affects visibility of the implement”. OEs also comment on cab ergonomics, in addition to roof height, the placement of levers in the cab are a cause for concern. In particular, when operators are required to twist rearwards, controls placed low and forward on the side panel are difficult to reach. The operators comment that roof height is an issue as they may hit their heads when travelling over very rough ground. It is suggested that the seat suspension should be attenuating vibration at this level, so maybe roof height is not the real issue.

5.4.6 Evaluation of Previous Research

The suggestions made by Sjofløt (1980) and Bottoms and Barber (1978) were considered by the experts for their value in a typical agricultural driving task with twist and vibration components. 23 OE completed; 13 VE and 9 PE completed this question. The results are displayed in Figure 46

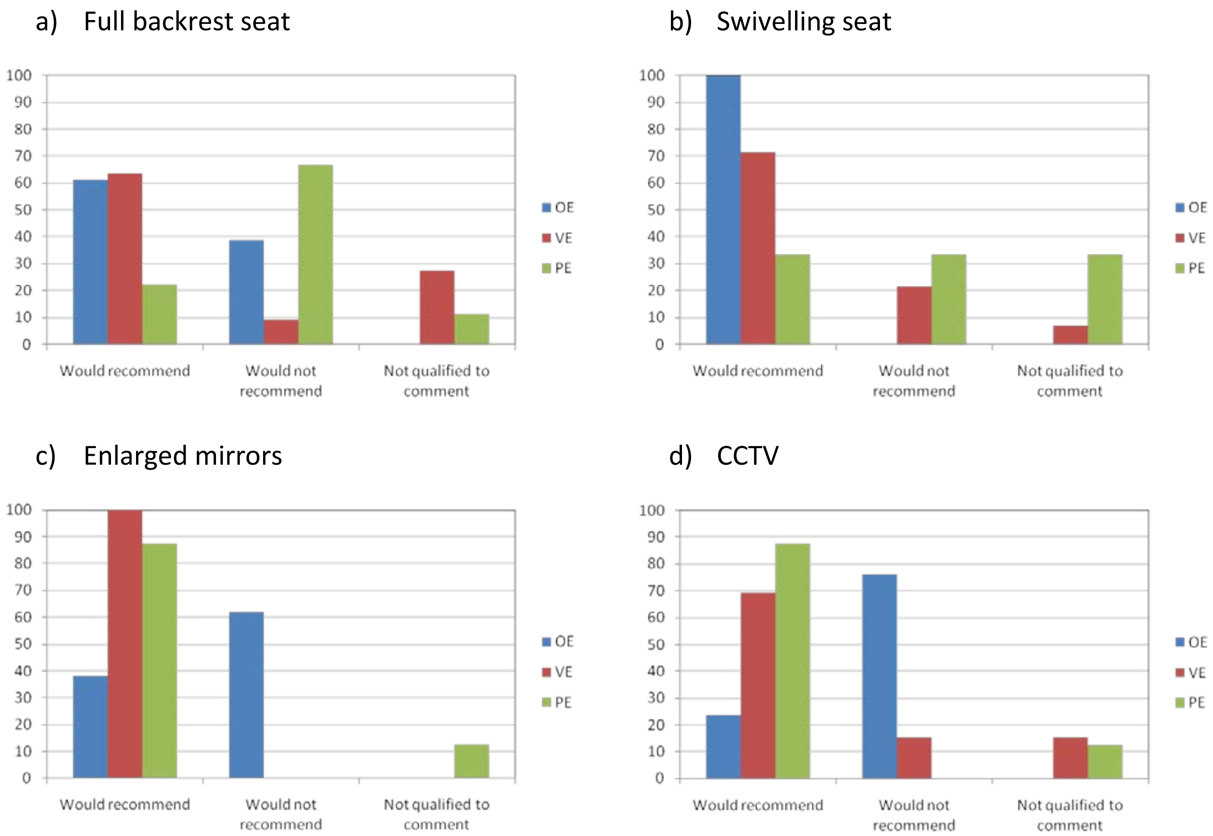


Figure 46 Consideration by experts of previous recommendations from the literature for reducing stress from WBV and twisted postures.

It is clear that no one addition to the tractor cab is comprehensively recommended by all expert groups. Of particular note are the opinions on the full backrest seat. There is considerable disparity both between and within the groups. It is also interesting to note that 100% of OE would recommend a swivel seat, but this is not matched in the other expert response groups. Of all the considerations, CCTV is least recommended by the OE, although would be recommended by the PE. This may be due to the perceived fragility of CCTV for it to be used in an off road driving environment. However, VE and PE may be aware of the successful use of CCTV in other industries and therefore would consider it a suitable solution.

A comment box was provided, and some experts gave particularly insightful comments. These are included below:

VE “[I would recommend] a tilting seat for when wheel is in furrow. Rotational deformation of the spine and twisting is a further evaluation problem. Have tried mirrors, they can reduce the time spent twisted and so would CCTV. Mounted outside the cab the mirrors get broken, inside the cab the space is limited. Have tried swivel seat - 2 problems, width available inside cab (between wheels) and feet offset from pedals - safety issue. Full backrest impedes rear vision unless combined with mirrors”

VE “In the task you have chosen (ploughing) the highest shock and vibration often occurs at the headland, at which point the driver reverts to a forward facing posture*. Whereas most of the time, he/she is monitoring the plough, the vibration is relatively low. When spraying, the need to check for blocked nozzles, it’s another matter!”

VE “Driver seat adjustment for some environments may intentionally deviate from manufacturer guidance. Drivers MAY adjust the seat toward the top stop to mitigate the downward (compressive) shock at the expense of more top-stop impacts. The backrest should not be too contoured to allow lateral movement. Too much lateral restraint may lead to discomfort and neck strain when the vehicle transverses obstacles at an angle.”

PE “I am not sure about the swivel seat, as the given circumstances could induce too much 'free motion' in the seat. There would then be an associated muscle loading in holding the seat in position. If it was a fixed position swivel seat that could then be moved, the likelihood is that the driver would just turn around rather than release the seat. Enlarged mirrors are also questionable, since they would be unlikely to give the specific required view for the ploughing task.”

The VE noting the shock vibration whilst facing forward is in direct contrast to what was observed in the field study. With reversible ploughs (where the whole plough turns over to return down the field) the turning of the plough, which causes a large shock, is often done whilst turning the tractor when the operator is facing rearward. This is an illustration of how the tasks and exposures are evolving along with the technical developments to protect the operator.

It is clear from the discussion provided by the experts that considerable evaluation of a suggested technical solution is required before its success can be determined. Its success is not only determined on task, but also operator preference and working style.

OE respondents were asked if there were any other ways they perceived the issues described above could be reduced. Cab and seat suspension were mentioned by a large number (n=15) of OE. Other recommendations could have been made by an ergonomics professional, such as better lever placement, arm support, shorter working periods and task rotation. The other issue mentioned included the placement of implements to the front of the tractor, although it was thought by those suggesting that this would affect visibility and affordability. A contractor, with high working hours and much experience suggested greater degree of seat base rotation (most seats only rotate to 20°), increasing to 75-90°, CCTV and automatic guidance systems to reduce requirement for observation.
Many OEs also commented how useful the addition of air conditioning within the tractor cabs was, and how much more comfortable this made their working environment. Other comments included height from the cab to the ground, and the requirement to 'jump down' from the cab gave problems with knees and lower back.

There was an open ended box for questions at the end of the questionnaire. OE comments in here largely echoed points that had been raised by others during the questionnaire. Additional feedback was largely on cab ergonomics, and appreciation of the research being completed. Aside from general comments, there were no comments that impact upon the research from the PE and VE respondents.

In addition to completing the questionnaire, a discussion was started among those on a forum on Farmers Weekly Interactive (n=44). These are not all UK based, and many of the posts were general conversations about tasks. However, some interesting issues were raised, these are summarised here.
"Is there any way the link arms and hitch can be further out so you can see where you are when hitching something up. I am not a giraffe! The other thing that bothers me while hitching stuff up is that I have to lie almost flat to reach the pedals and see what I'm doing out the back, adjustable pedals would help. I'm not a small person either at around 5ft 9. And don't mention the contortions I have to perform to lift the arms up once I've managed to get the tractor near the implement..."
"Foot pedals that don't ruin your knees!"
"Always amazes me that it doesn't seem that the designers don't consult the drivers

enough."

"Also, instead of bending over looking out the back window, a little camera to watch the linkage and back of tractor...great when hitching up trailers and feed wagons etc."

"A camera on the baler so I do not have to turn round to see the pick-up reel."

These comments mostly mention the requirement for difficult postures to facilitate task completion. The focus of the research was not specifically mentioned within the forum, although the sample of comments were selected in light of the research focus. However, these comments do confirm the issue of awkward postures for operators in agriculture.

5.5 Discussion

This survey utilised a mixed-mode method to collect expert opinion. This involved the use of both paper-based and web-based surveys. Gosling et al., (2004) concludes that internet based questionnaires field largely similar results to that of paper based questionnaires, and can contribute a great deal to many areas of experimental psychology. The value of both web and paper based surveys is limited by the willingness of people to complete them (Griffis et al., 2003). This is recorded via a non-response error, this arises through the factor that not all individuals included in the sample are willing or able to complete the survey. This is particularly difficult to define when the sample cannot be clearly defined i.e. where an open invitation is issued on a web portal such as is the case for part of the OE and PE response groups. Response rates are generally considered to be the most widely compared statistic for judging the quality of surveys and ironically one of the most controversial (Johnson and Owens, 2003). They concur that the main issue with response rates is to ensure that the responses are unbiased and typical of the target population. It is possible that collection bias may have affected the results from this survey, with the low numbers of vibration experts responding. However, there was little spread in the conclusions in each of the response groups, suggesting the sample was representative of the expert opinion. Although the number of VE completing the questionnaire is small is comparison to the other response groups (VE = 13). This is representative of the small numbers of experts working in this field in the UK. A number of those at the HRV conference would have been working with hand arm vibration, and therefore it may not have been appropriate for some of those to complete. For the other expert groups a large a varied response was present and it is believed that these responses are typical of the experiences and expertise of the target populations.

In the 'area of expertise' question, a large proportion of the PE did not consider their area of expertise to be within the areas specified by the Institute of Ergonomics and Human Factors (IEHF). The responses under 'other' included the following: design (n=3); transport ergonomics (n=2); crash testing (n=3); risk assessment (n=1); anthropometry (n=2). Although individuals working within these areas, with perhaps the exception of crash testing, would have the expertise required for completion of the survey. However this does raise an additional question about the categories of specialism dictated by the IEHF and whether these address the real areas of practice for working ergonomists. These findings have been fed back to the IEHF, who are coincidentally undertaking a review of these classifications and will use this data in their consultation. The daily working hours indicated by the OE responses suggest that assessing risks posed by equating risk over a 'normal' 8 hour day may not be appropriate.

The overall level of health risk posed by the exposures was judged to be similar by the PE and VE groups. The majority of OE did not equate WBV with LBP, which was in contrast with the other response groups. There is literature that links WBV to LBP (Bovenzi and Betta, 1994; Lings and Leboef-Yde, 2000), these results may tentatively suggest the focus could be directed at other body areas.

When controlling the risks posed by a hazard, reduction of the causal factor at source is often the preferred solution. However, when this is not an available option, reduction of exposure duration is utilised. For WBV exposure, the Physical Agents (Vibration) Directive provides guidance on current limit values. All groups reduced their recommended exposure duration with increasing twist and vibration levels. The greatest disparity was between the operator and academic experts, perhaps unsurprisingly. Only 55% of operators provided a duration recommendation, the remainder affirming that despite any associated risk, they would continue with the task until completion. This highlights the issue of risk prevention in agriculture and therefore the suggestion is made that risk reduction strategies employ any possible engineering solutions firstly, in an attempt to avoid the issue of non-compliance. If a rough estimation is made that most tasks are more severe than the starting point in the acceptable exposure duration recommendations, then in excess of 50% of the drivers questioned are driving for greater durations than recommended in this section.

Body maps are often used to evaluate self-reported and expert opinion of exposures (Robb and Mansfield, 2007; Kuorinka et al., 1987). In this study, the body map is utilised for comparison between operator first-hand experience of the exposures and academic experts' experience in judging risk scenarios. In general there was a consensus between the 3 response groups on where musculoskeletal discomfort symptoms would display. The low back area was represented in all but one occasion (trunk rotation only, OE). This is in agreement with the multifactorial nature of LBP development (Frymoyer et al., 1983). The right shoulder was indicated by OE as being likely to display discomfort symptoms. This may be indicative of the issues caused by control placement in the cab (controls are banked to the right of the operator in UK tractors) or the direction of twist (in general to the right). Donati et al. (1984) investigated the location of discomfort development under simulated agricultural driving tasks. The predominant areas of discomfort were the lumbar back and neck. However, under dynamic twisting conditions, in that study subjects also indicated discomfort in the right thigh, arm and shoulder therefore indicating that side-specific discomfort is a feature in other similar research. Operators in a driving task study (Wikstrom, 1993) marked the neck and shoulders, also similar to that illustrated here. This issue of control placement is also raised by Donati (2002) in his review of cab ergonomics. There is an increasing trend to mount controls on the armrest rather than banked on the side of the cab, the controls would then move with the seat. Further investigation would be required to determine if this reduces the discomfort felt by the operator. In the OE response group, the thigh backs were represented in 36% of responses for a combined exposure; this was not seen in either the PE or VE responses. Discomfort in this area has previously been linked to the anthropometry of the operator population investigated (Gyi and Porter, 1999) or from badly fitting, or improperly adjusted seats (Magnusson and Pope, 1998). Comments from the questionnaire suggest that leg pain stems from the requirement for pedal force to the front of the operator, when the seat pan is rotated (OE, n=3). This may suggest a requirement for training interventions for operators within agriculture of possible redesign of the seat. The effect of seat pan rotation will be investigated in Chapter 9.

Donati et al. (1984) suggest that although the use of big mirrors can improve the working posture (Sjøflot, 1980), these at best do not solve all the problems, in particular when the systems for controlling implements are located outside the cab. It was also suggested that the use of these mirrors require a degree of learning effort in contrast to the habit of directly viewing the implements.

Technical design recommendations from previous literature were not all well received. Whilst the benefit of a full backrest seat was recognised by the VE and PE, the requirement for unobstructed axial rotation for rearwards attention can be affected by backrest height. Recently developed seats may provide an acceptable compromise (Figure 47) as the backrest height can be adjusted during use, so that full backrest support may be provided when required. The backrest can then be lowered when required to reduce obstruction in tasks with high twist components.

a) Grammer Universo M

b) Grammer Compacto XM

Figure 47 Examples of static (a) and adjustable (b) seat backs available

Initial concerns include the effect of the lowered backrest on the distribution of pressure across the back of the operator. The adjustable seat is used in a latter laboratory study within this thesis (Chapter 9), and therefore consideration will be made of this subsequently.

100% of OEs would recommend a swivel seat, some with experience of certain tasks would welcome a greater degree of rotation, although it seems space for movement within the cab is a limiting factor. It has previously been suggested that the alleviation of the rotation requirement by improving the visibility conditions, a better location of the controls by adopting seat profiles and taking into account internal dimensions of cabs would reduce the stress placed upon the operator (Donati et al., 1984). It seems from some of the OE body maps that there is a prevalence of thigh discomfort. In addition to the effect of poorly fitting seats (Magnusson and Pope, 1998), it may also be the case that the stress of the rotation will shift from the neck to other body parts, namely the thighs as different parts of the body take the strain in the new posture dictated by the rotated seat. The PE did not recommend the use of swivelling seats; many noted that an increased muscular effort is often required to maintain the seat base rotation at the required level.

The operator group were asked to consider which tasks caused the greatest discomfort, those requiring twist with a force requirement and high levels of vibration, particularly shock vibration were well represented. Control placement, armrest length, insufficient head room and requirement for foot pedal force were all issues that operators raised as causing particular discomfort. It is suggested many of these could be solved with relatively simple ergonomics interventions. These conclusions have been reached in previous research (Donati, 2002) and therefore it seems more advice or maybe pressure may be required to compel the industry to consider.

5.5.1 Limitations of the study

In this study three groups with knowledge and expertise in the exposures commonly experienced by agricultural tractor drivers were chosen as representative of the key stakeholders in the area. However, it is conceded that it may have been beneficial to include a response group from a medical and biomechanics backgrounds to allow for completeness. The desire to attain responses and opinions from both operators and academic experts on the same issues meant that the investigation in each subject area had to remain simple enough for others to understand. The benefits being that a clear comparison between response groups is easily available, however, the information gleaned from the experts could have been greater if separate questionnaires were developed for each area of expertise.

There were no female responses to the operator questionnaire, however it is known that females do operate the machinery, and their opinion on their specific difficulties with operation may have been particularly insightful.

Some of the responses from the experts suggested that their familiarity with the types of exposures was low. This may have affected their responses, although it is suggested that this would have been of greatest effect in the technical recommendations section, where the responses were more varied among the groups. In the risk assessment and discomfort mapping, there was generally a majority consensus, suggesting agreement among the groups

5.6 Conclusions

The results from the expert opinion survey illustrate that all expert groups consider and increased risk for musculoskeletal discomfort in operators exposed to both axial rotation and WBV. Operators reported discomfort in the right shoulder and thigh backs when exposed to both risk factors. This was not highlighted in the academic responses. Those with experience in risk assessment were in agreement that the issue of postural stress should be considered when assessing the risk from vibration exposure. Interventions aimed at reducing the requirement for twist and improving seat discomfort should therefore be prioritised as a risk reduction strategy for off road drivers. The hypotheses are accepted or rejected in the following section.

H_1 The risks of musculoskeletal discomfort from WBV and trunk rotation, judged by the experts, will be greater when exposures are combined

All expert groups judged the risks from simultaneous exposure to WBV and trunk rotation to be greater than when exposed to either WBV or trunk rotation separately. The hypothesis can therefore be accepted.

H_2 The areas of perceived discomfort as judged by the experts will match subjective results gained in laboratory studies (Chapters 6, 7 and 8).

When exposed to the test WBV conditions (Chapter 7) discomfort was greatest in the low back, all expert groups marked this as the area of predicted discomfort development. When exposed to the test trunk rotation conditions (Chapter 6), discomfort was greatest in the neck and right shoulder. All expert groups agreed with the risk for neck discomfort, but less than 40% of respondents in each group predicted the right shoulder would feel uncomfortable. The combined exposure conditions (Chapter 8) caused discomfort in the neck and low back, with medium levels of discomfort across the other body regions. The operator experts predicted areas of discomfort were the closest match. At least one expert group, particularly the operator experts, matched predicted discomfort with that experienced in the experiments in Chapters 6, 7 and 8.

H_3 Those with experience of posture and vibration assessment will recommend recognition of combined exposure risk in risk assessment techniques

100% of PE and 89% of VE conclude there is a need for greater acknowledgement of combined exposures at risk assessment level.

H_4 Recommended technological developments in agricultural tractor design from the literature (Bottoms and Barber, 1978; Sjoflot, 1980) will be considered apposite for reducing the risks from trunk rotation and WBV.

There was a mixed response among the expert groups regarding the use of the recommendations. Overall, enlarged mirrors would not be recommended, and swivel seats would be. A full backrest seat was not recommended by PE, but was by the other groups. CCTV was recommended by all bar the OE. The knowledge of the specific, and sometimes unique operating environments in UK agriculture is a clear requirement when specifying recommendations. The hypothesis is rejected.

CHAPTER 6: Subjective discomfort and muscular response to trunk rotation

This Chapter presents the first experimental laboratory study of the thesis. In this, the effect of trunk rotation upon subjectively rated discomfort and muscular fatigue response is investigated. Research was carried out in the environmental ergonomics laboratory. The study aimed to categorise the response to set trunk rotations. This enabled a baseline of discomfort for exposure to trunk rotation singularly to be established, in addition to the muscular response.

6.1 Introduction

The literature review, Chapter 2 discussed a range of previous studies that have considered the effects of trunk rotation. In summary, the conclusions of these studies include increased injury statistics (Kumar et al., 2001; Frymoyer et al., 1980), increased spine disorders (Occipinti et al., 1986) and increased discomfort (Wikström, 1993) for those exposed to trunk rotation. However, in a review of the literature on the causes of back pain Seidel (1993) acknowledged the need for further research in the specific area of postural effects, among others.

Whyte and Barber (1985) investigated numerous driving tasks within agriculture and found many require a substantial period of the working time facing rearwards. It was noted that the degree of twist varied considerably depending upon the task being completed. The twisted postures in agriculture may have to be maintained for long periods of time, with only short pauses in the neutral posture (Torén and Öberg, 2001). Many previous studies have only investigated short duration, intermittent or low magnitude twists (Wikström, 1994).

Passively loading of the cervical spine in extreme positions has been shown to cause sensations of discomfort and pain (Harms-Ringdahl and Ekholm, 1986). Toren (2001) suggests that considerable muscle effort may be required to keep the back strengthened particularly when seated postures in which the trunk is deviated or twisted more than 20° are adopted. Generated muscle tension is known to increase spinal loading (Corlett, 1989). Twisting the trunk to face rearwards involves overcoming the passive resistance of the tissues of the trunk. This passive resistance is low at the neutral position, and increases progressively as the trunk is twisted (McGill et al., 1994; Bodén and Oberg, 1998).

Bottoms and Barber (1978) investigated muscle activity in the shoulder and neck under trunk rotation and found muscular activity was reduced when seat base rotation was employed. In addition, Taoda et al. (2002) evaluated the physical reduction in load on forklift drivers with the use of a 45° swivelling seat. The amplitude of surface EMG on the trapezius, erector spinae and latissimus dorsi was reduced in a rearward facing posture when the swivelling seat was employed. EMG studies of axial rotation have focussed on the pattern of spinal loading (Marras et al., 1998; Kumar et al., 2001; Lavender et al., 1994). Many of these studies have demonstrated coactivation among the muscles of the trunk and back when twisting, some with the suggestion that coactivating muscles are not orientated so they contribute to twisting torque (Carlsoo, 1961). However, although numerous studies have investigated the muscles involved in creating the motion, these do not necessarily match the areas of discomfort development.

Few studies have focused on the specific location of discomfort manifestation whilst maintaining trunk rotation (Wikström, 1992), although this is common in the usual investigation of seating discomfort whilst driving (Gyi and Porter, 1999). Discomfort could be the first indication of more serious problems for drivers exposed to twisted postures. Schmidtke (cited in Mehta and Tiwari, 2000) suggests that task-specific physiological disturbances, such as muscle activity (electromyograms), generally appear prior to cognition. Following this the disturbances reach a level at which the operator perceives them. This is suggested to be a reaction of arousal and activation (i.e. heart rate, arrhythmia, and EMG of trunk muscles not specifically related to task). Wikström (1992) found that EMG activity and subjective discomfort (Borg's CR-10) correlated well with the degree of twist, with discomfort exclusively localised to the lumbar and neck-shoulder regions. This is the only known study investigating both subjective discomfort and muscular response to trunk rotation.

6.2 Aims & Hypothesis

In order to fully understand possible interaction effects between trunk rotation and WBV, it is important to fully understand the effect of each individual factor. Most studies have presented the effects of the individual factors, or combined effects, without the comparison between single and combined exposures. The aim of this study is to understand the effects of long duration static twists on the body, how this affects the muscle response and subjective discomfort.

The hypotheses for this study are therefore:

H_1 Discomfort, assessed subjectively, correlates positively with the magnitude and duration of the axial rotation

H_2 Measures of spectral shift (MPF) indicate fatigue when subjects are exposed to axial rotation

H_3 Measures of muscle activity (EA) indicate fatigue when subjects are exposed to axial rotation

H_4 The areas with the greatest subjectively assessed discomfort will be the neck and shoulders

H_5 The muscles exhibiting fatigue will mirror that of the areas of discomfort hypothesized in H_4

6.3 Methodology

The effect of trunk rotation was determined with the use of EMG fatigue analysis and subjective ratings of discomfort. These methods have been described in greater detail in Chapter 3, Experimental Methodologies.

The postures for investigations were developed with prior knowledge of agricultural cab layouts and consultation of the literature (see Chapters 2 and 4). The rotations for investigation were:

0° - control condition (P0), to establish a baseline for comparison with other studies

110° axial rotation - exposure condition (P1), aimed to replicate monitoring out of the rear-side window

170° axial rotation - exposure condition (P2), aimed to replicate monitoring out of the rear window and stimulate maximum voluntary rotation

For each subject, EMG data was collected, from 8 electrodes on the cervical, thoracic and lumbar spinal musculature. To establish the muscular response, the EMG was analysed for 2 fatigue parameters, change in electrical activity (EA) and a change in the Mean Power Frequency (MPF) signifying a spectral shift. Porter's body map was used to investigate subjective ratings of discomfort at 60s intervals. A schematic of the experimental method is illustrated in Figure 48.

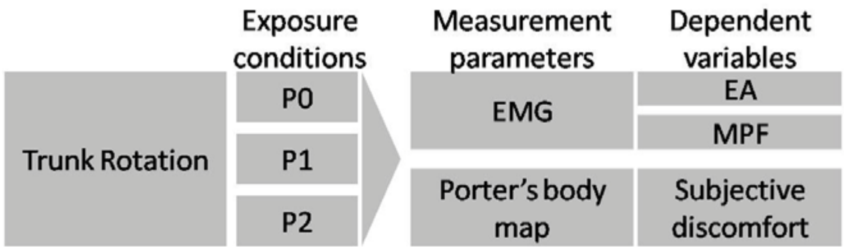


Figure 48 Schematic of experiment method

The duration for exposure was 10 minutes, this was chosen as a reasonable exposure time to elicit a muscular and discomfort response, if one is to be seen. Also this would allow the recovery time between conditions to be limited to <10 minutes (Lariviere et al., 2003) and therefore allowing a same-day repeated measures design to be employed increasing the reliability of the EMG results. Subjects were seated throughout the study on a full-backrest air suspension Grammer seat with armrests and material cushions. The seat was mounted on a rig in the laboratory in addition to a mock steering wheel and pedals (see Section 3.4.5), the suspension was not activated during this study. The level of rotation was defined by placement of a visual target at the three magnitudes of rotation (0°, 110° and 170° to the forward facing subject). The visual target used was a print out of the Porter's body map from which they were required to rate their discomfort. Participants were required to remain focus upon the print out at all times during their 10 minute exposure to encourage a static posture. Participants were also required not to speak other than to verbally rate their discomfort when prompted, therefore reducing unnecessary contamination of the EMG.

Participants were free to determine how they achieved the rotation (wholly trunk, neck or both) although feet and a hand were required to be placed on the pedals and steering wheel at all times, to simulate a driving scenario. The instruction was given that they must be seated as if they were in control of the vehicle at all times. The relative position of the body segments was recorded digitally on camera. Reflective markers indicated specified anatomical landmarks for comparison. Markers were placed on the acromion process, vertebra prominens (C7), external occipital protruberance, and squamosal sutre superior to the ear. Photos of the participant in each condition were taken during the experiment and subsequently analysed for the relative contribution of the neck and trunk to attaining the posture. Figure 49 illustrates the 3 posture conditions.

Figure 49 Typical postures during investigation, P0, P1 and P2 (displayed left – right)

The EMG and subjective data for each participant was analysed as outlined in the methodology (Section 3.). This involves time domain analysis of both the electrical and spectral parameters of the EMG, and also the subjective ratings of discomfort, provided every 60s. The study followed approved ethical protocols (see Section 3.4.7.1).

6.4 Results

6.4.1 Subjects

Subjects were recruited from the staff and student cohort at Loughborough University. Participants comprised healthy males and females (Table 19) who were screened for a history of back problems, those with a history were excluded. Volunteers completed informed consent forms before commencement of experiment. Subjects were not paid for their participation.

Table 19 Characteristics of experimental sample

(Values are presented as mean ± one standard deviation (range))

	N	Age (yr)	BMI
Male	2	20 ± 1.4 (19-21)	23 ± 0.9 (23)
Female	13	19 ± 0.5 (18-20)	22.2 ± 2.3 (16-25)
Total	15	19.1 ± 2.2 (18-21)	22.3 ± 2.2 (16-25)

6.4.2 Posture manifestation

Although participants were free to determine how they attained the required level of rotation, in reality little difference was seen between the relative contribution of neck and trunk twist among participants. When attempting 110° rotation, participants rotated mainly with their neck, mean 85° (± s.d 14) rather than the trunk, mean 25° (± s.d. 14), illustrated by Figure 50.

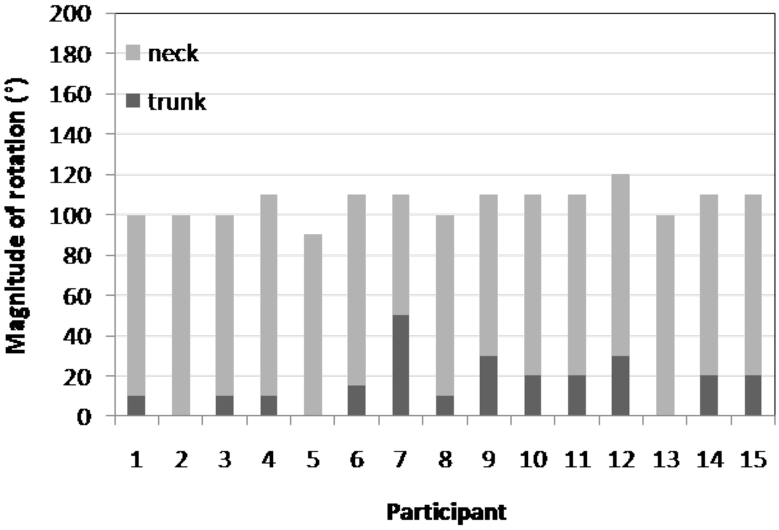


Figure 50. Measured rotation of participants, P1 condition (target 110°). Rotation of the neck and trunk are stacked bars, the total rotation is shown as the final bar height.

The mean attained rotation of 106° is very close to the target rotation (110°) set for the P1 condition. The neck contributed most to attain the required rotation, (mean 90°). The trunk played a more varying role, with minimal rotation in most cases, and with no rotation in some cases. In the case of participant 7, it is clear that trunk rotation compensated for reduced neck rotation. In the 170° rotation condition (Figure 51), the relative contribution of the neck was similar and the trunk much higher, mean rotation 85° (s.d. 7) and mean rotation 74° (s.d. 8) respectively.

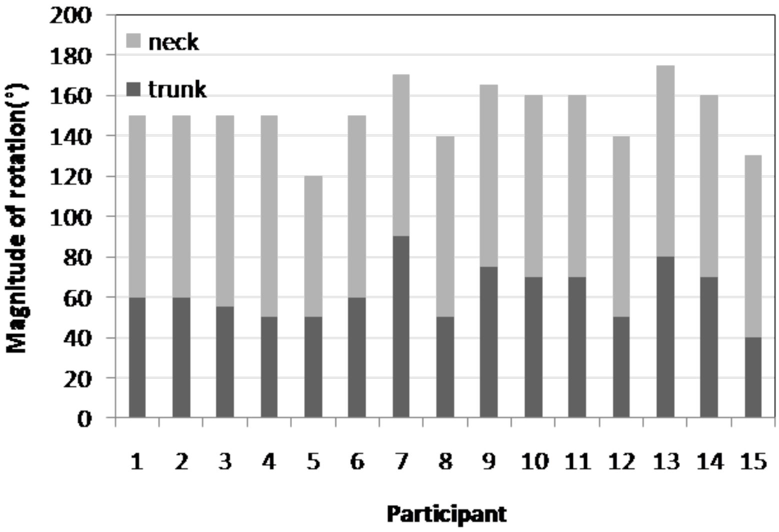


Figure 51 Measured rotation of participants, P2 condition (target 170°). Rotation of the neck and trunk are stacked bars, the total rotation is shown as the final bar height.

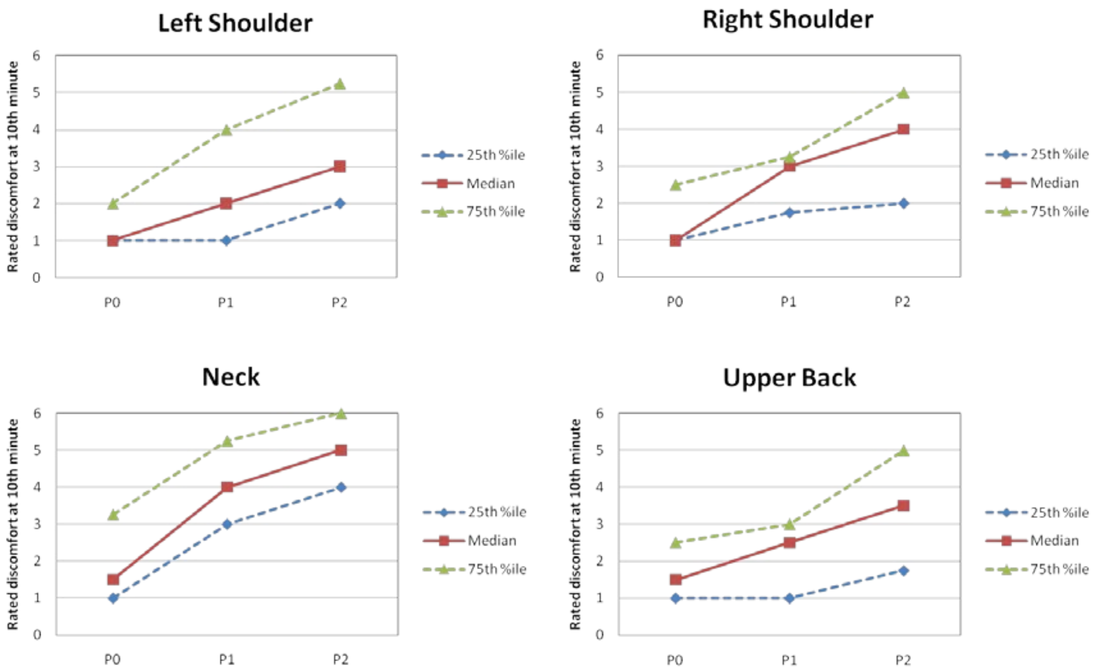
For the P2 condition, it is clear that the total rotation was somewhat less than the target rotation for many cases. The neck played a similar role in attaining the rotation, being at the maximum rotation for most cases. The trunk rotated significantly more in this condition. However, the relative contribution of neck and trunk to total rotation was similar for all participants. In comparison to 110° rotation, the trunk contributes more to the total rotation achieved. Although the target of 170° rotation (P2 condition) was not achieved by all participants, the participants were rotating to what appeared to be their maximum displacement without shifting in the seat.

6.5 Subjective Results

Subjective discomfort is considered in 3 main ways to address the original hypothesis; these are to consider the influence of posture on discomfort, to consider the pattern of discomfort development across the body, and also to assess the effect of time on discomfort development. Parametric assumptions cannot be met for the subjective data, and therefore where statistical analysis is required, a Wilcoxon test will be adopted, significance will be accepted at $p < 0.05$.

6.5.1 Influence of posture on discomfort

The influence of the posture on discomfort was investigated by looking at 10th minute discomfort between the three posture conditions for each body part (Figure 52)



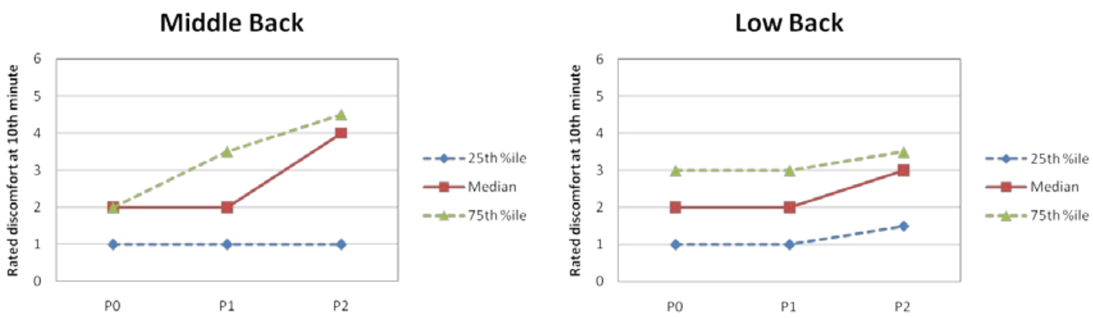


Figure 52 Influence of the increasing rotation 0° (P0), 110° (P1), and 170° (P2) on subjective discomfort after 10 minutes exposure

With increasing rotation, an increase in discomfort was seen in the two test conditions for all body regions. For the left shoulder and upper back, the increase in discomfort was equal between posture conditions. For the right shoulder and neck, the increase was greater between P0 and P1 than between P1 and P2. In the middle and low back areas, those resulting in the lowest overall discomfort of the three conditions, the discomfort increase were only prevalent between P1 and P2. Discomfort levels in the P0 condition were low in all body parts, although were slightly more in the low back than in any other area.

A Wilcoxon paired comparison of discomfort at the end of the first minute between conditions showed statistically significant differences between perceived discomfort ratings between rotation and no rotation, but not between the 2 rotation conditions, P0, T1 to P1, T1 ($p<0.005$, Wilcoxon), P0, T1 to P2, T1 ($p<0.001$), P1, T1 to P2, T1 ($p>0.05$). At the tenth minute, statistical analysis showed a significant increase in the discomfort ratings across the 3 conditions P0, T10 to P1, T10 ($p<0.001$), P0, T10 to P2, T10 ($p<0.001$) and P1, T10 to P2, T10 ($p<0.005$).

6.5.2 Influence of duration on discomfort

In the no rotation condition (P0) discomfort remained constant and did not increase beyond 'a little uncomfortable' for any participant during the 10 minute study duration (Figure 53). In the P1 rotation condition, discomfort increased systematically over time. In the P2 condition, discomfort increased rapidly in the neck and shoulders. Discomfort also developed in the middle back. The number of participants expressing higher levels of discomfort increased over time in the test conditions (Figure 54 and 55). In the P2 condition, 4 out of the 15 participants rated the maximum level of discomfort in at least one body zone during the tenth minute of investigation.

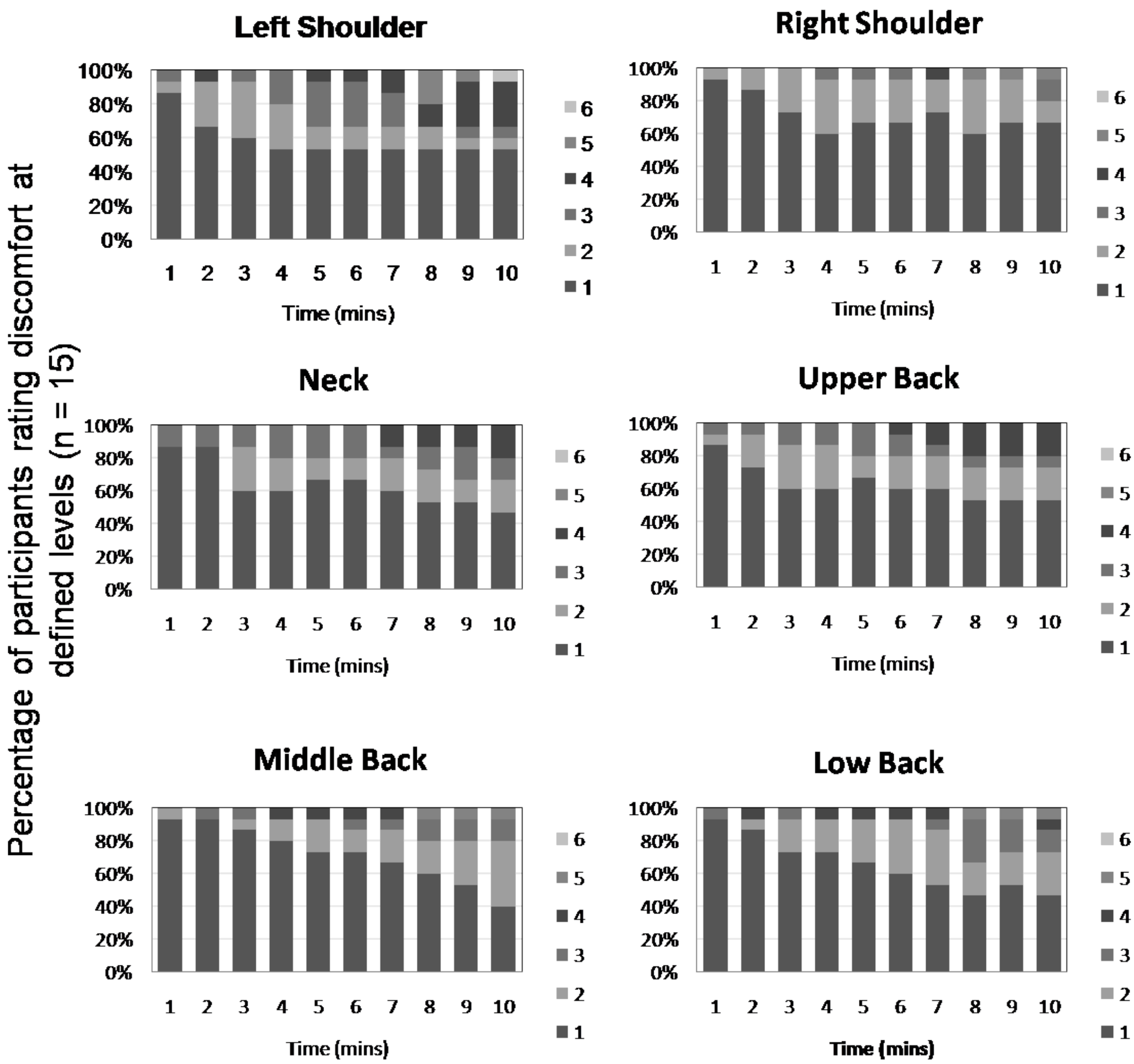


Figure 53 Discomfort development over time for all body parts, P0 rotation

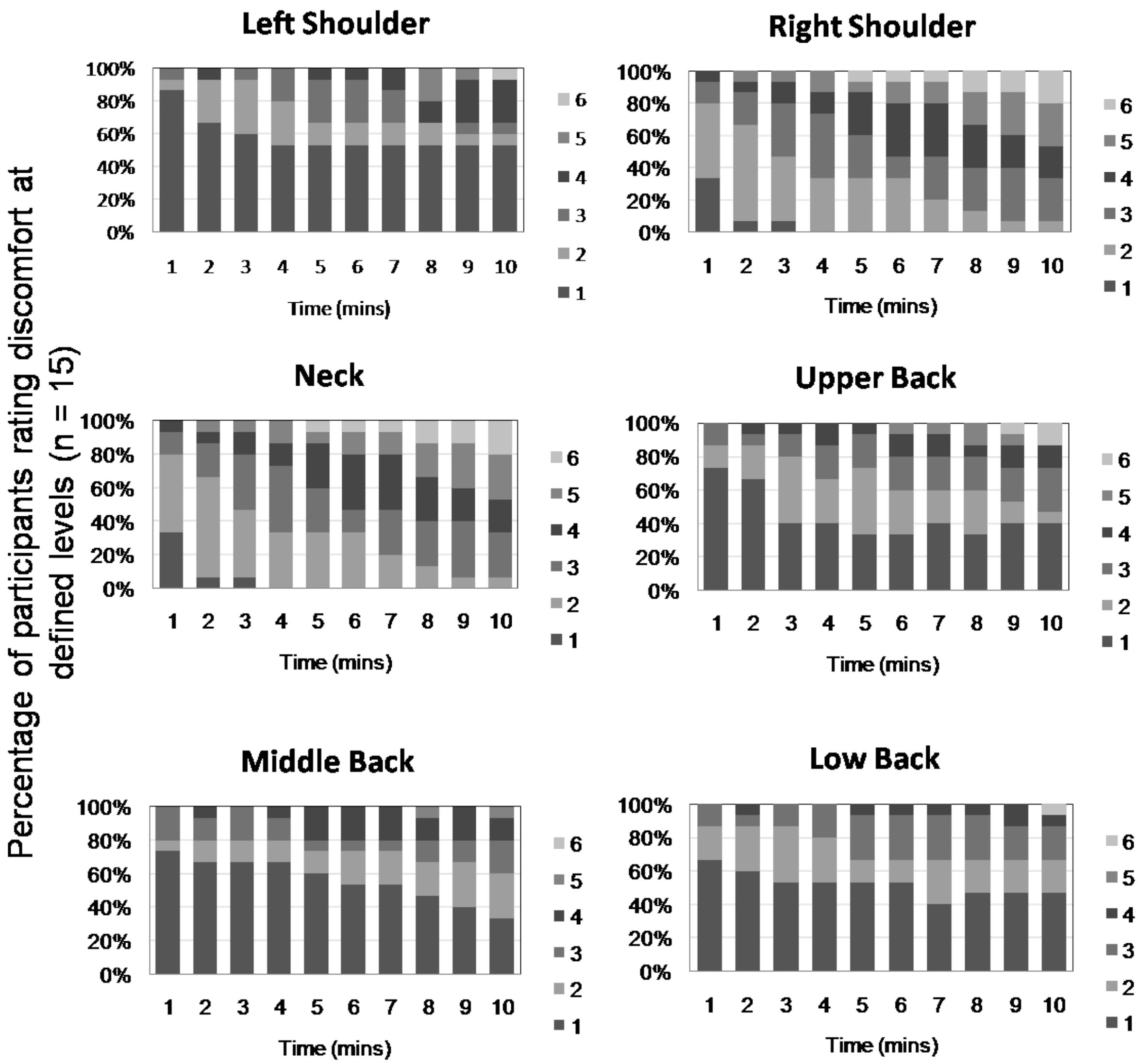


Figure 54 Discomfort development over time for all body parts, P1 rotation

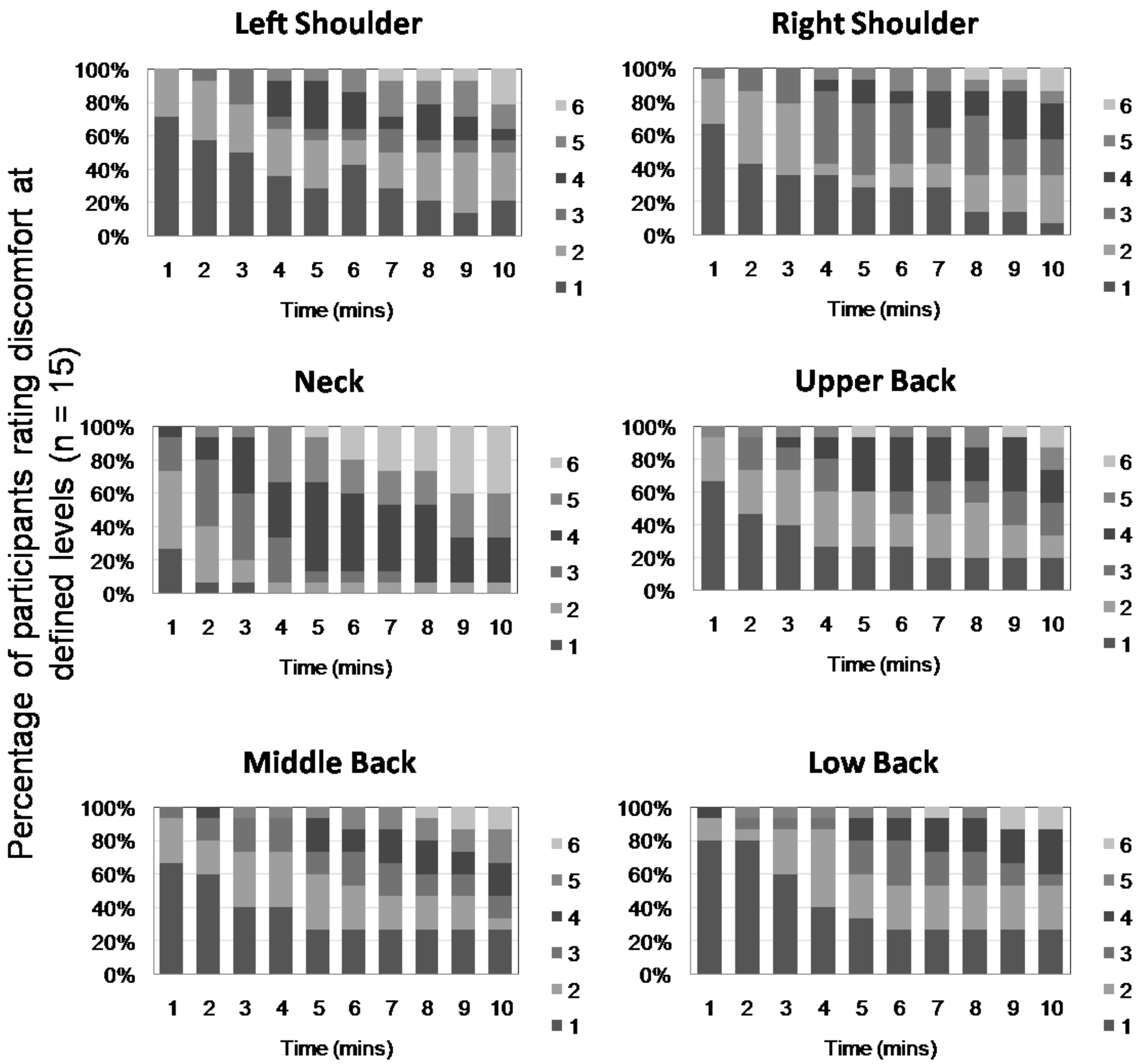


Figure 55 Discomfort development over time for all body parts, P2 rotation

The introduction of higher levels of discomfort comes sooner and to a greater extent in the experimental conditions, particularly the P2 condition. As can be seen from the neck graph in Figure 55, nearly 40% of participants are rating the highest level of discomfort in the 10th minute. In addition, in the same condition and body part, no subject is rating the lowest level of discomfort after the 3rd minute.

6.5.3 Influence of body part on discomfort ratings

The influences of specific body regions on the discomfort ratings were investigated. In the control conditions, overall discomfort remained low, although slight discomfort was seen in the middle and low back. However, in the cases of P1 and P2, the neck and right shoulder and upper back dominated the discomfort distribution over the body. It is also notable that in the P2 condition, more than a baseline, numerical value 1, discomfort was experienced in all body regions.

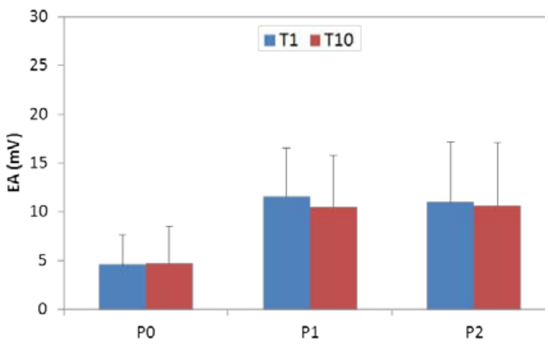
6.6 Electromyography Results

Participant 13 was removed from P1 and P2, due to the loss of contact of the electrodes during the study. Changes in both the spectrum and the amplitude of the EMG signal were seen over time in both of the experimental conditions. No significant changes over time were seen in the control condition.

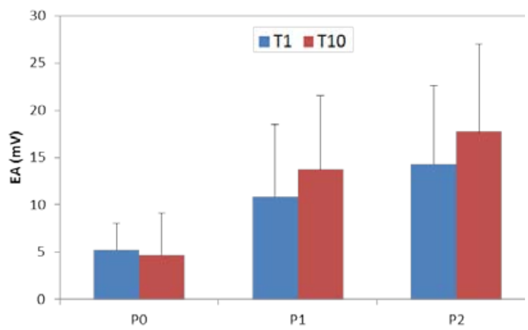
6.6.1 Muscle activity response

Increases in the activity over time are considered indicative of the presence of muscular fatigue. This can be illustrated as the gradient of the regression line through the data points over the time series. Graphs of individual participant gradient data is shown in the Appendix d). Illustration of the change in activity can also be considered by comparing activity at the start (1^{st} minute) and end (10^{th} minute) of the experimental condition. The results of this are provided in Figure 56. As can be seen, there are changes over time illustrated in some muscles in some conditions, and statistical analysis between the two data points, at 1^{st} and 10^{th} minutes can add significance to the changes. In particular the right trapezius descendens (TD R) shows increases over time in both the experimental conditions.

Trapezius decendens L



Trapezius decendens R



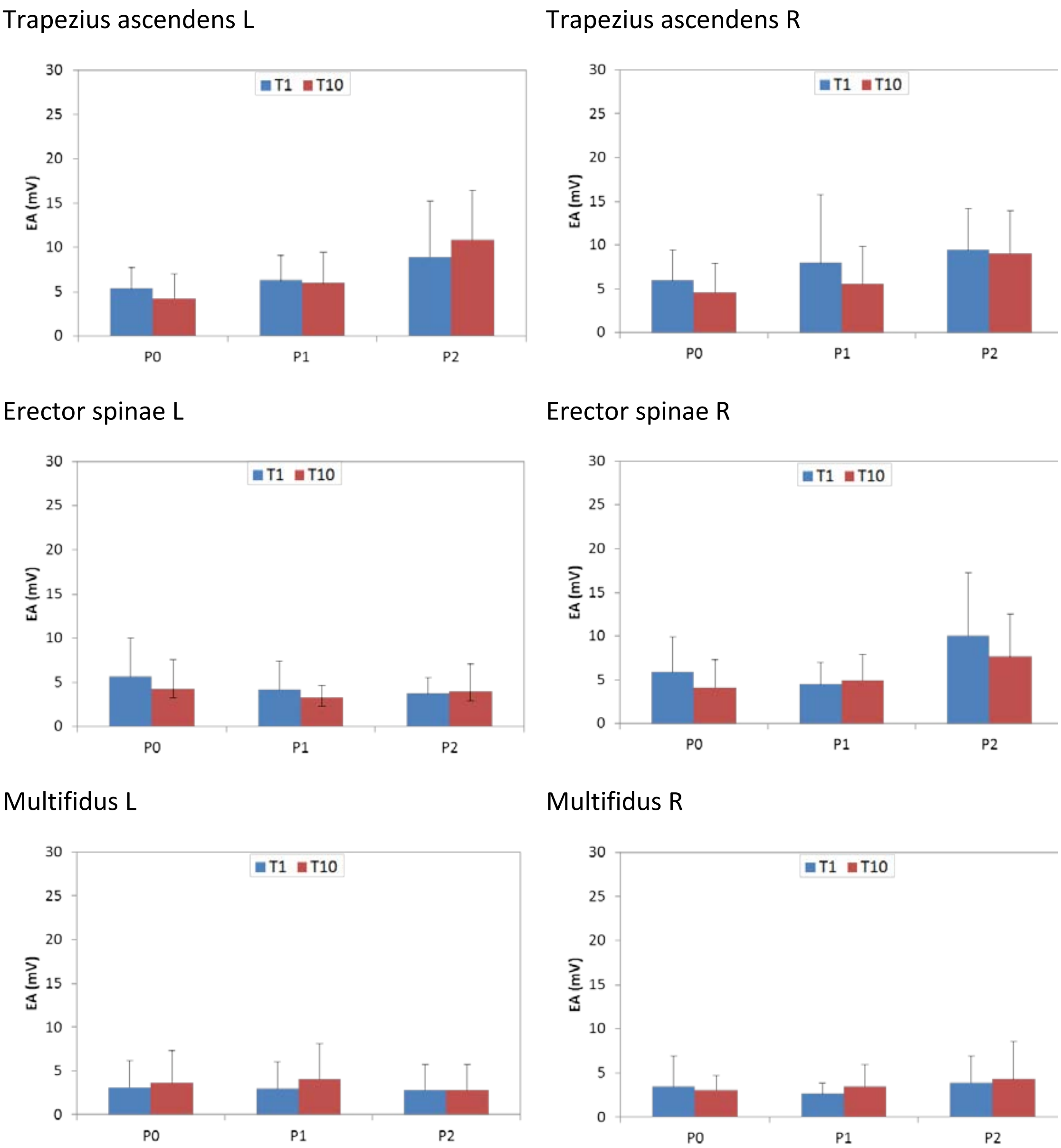


Figure 56 Comparison between activity at 1st minute and 10th minute, error bars designate 1 standard deviation

Statistical comparison of the results revealed an increase in muscle activity was present in the TD R in the P1 condition ($p<0.05$). In the P2 condition, both the TD R and TA L exhibited an increased activity over time ($p<0.05$). A repeated measures ANOVA revealed a linear increase in the indicators of fatigue between the three conditions for the TD R ($p<0.05$).

Comparison of the mean EA across the conditions has been previously used to demonstrate differences across the conditions. These are shown in Figures 57 and 58. As can be seen the general trend is for increased activity from the P0 to the P2 condition. Although levels of activity are cannot be used for indication of muscular fatigue, increased activity in a muscle is an indication of increased workload, and therefore it may be assumed that the TD and ES in particular have increased workloads in the P2 condition.

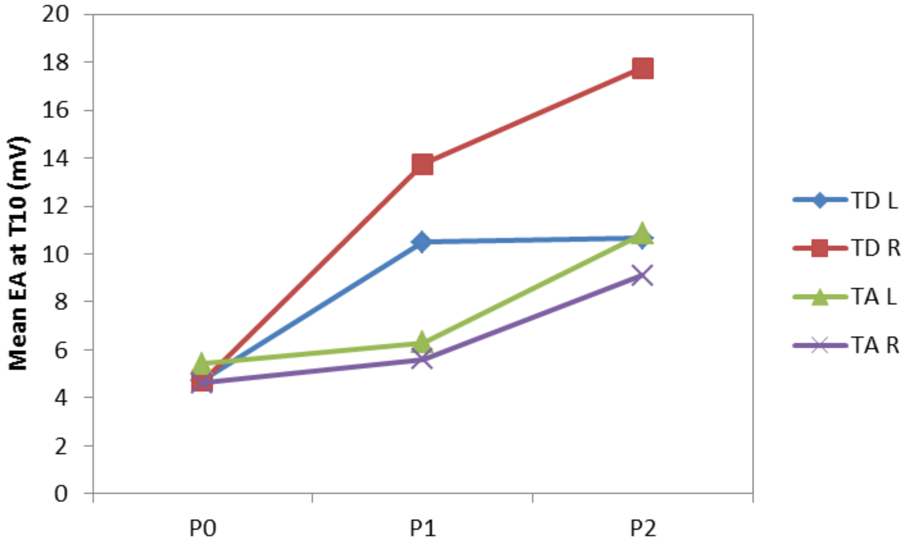


Figure 57 Mean EA at 10th minute

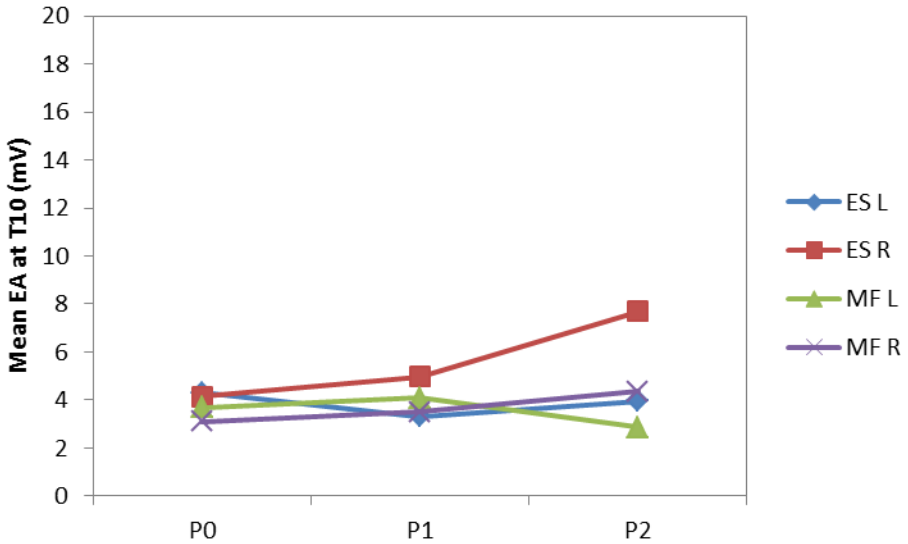


Figure 58 Mean EA at 10th minute (ES and MF)

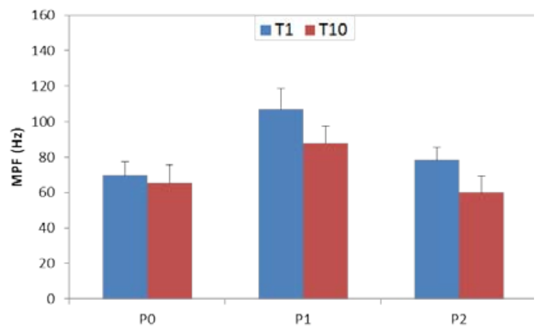
The EMG amplitudes in the thoracic and lumbar muscles (ES and MF) appear to be different on the left and right sides, although these differences are not statistically significant.

6.6.2 Spectral response

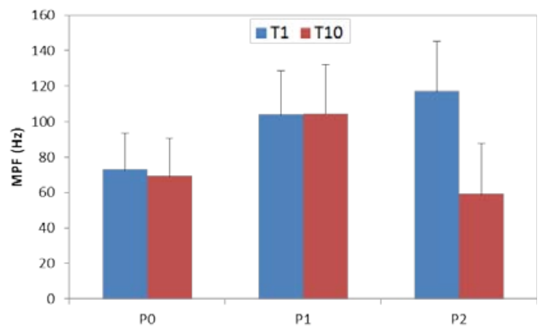
6.6.2.1 Time related changes in EMG spectrum

Comparison of the change in frequency over time indicates a similar response across the shoulder muscle groups, with a lesser response from the ES and MF. In the shoulder muscle groups, the TD and TA, the initial firing rate increase can be seen across the conditions as the level of rotation increases, shown as an increased MPF at T1 in the experimental conditions in comparison to the control. However, the slowing of firing rate, indicative of fatigue can be seen over the time, shown as a lower MPF at 10th minute in the experimental conditions, in comparison to the initial MPF for that condition. An illustration of the changes over time is provided in Figure 59.

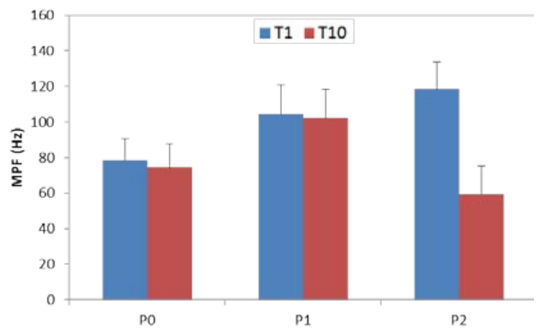
TD L



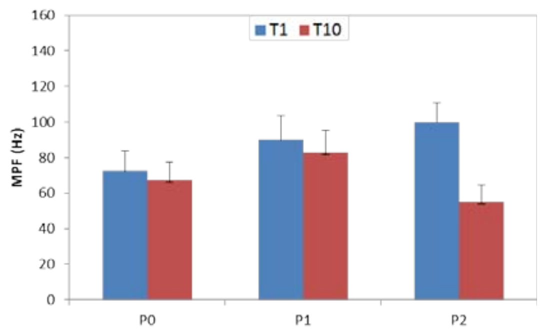
TD R



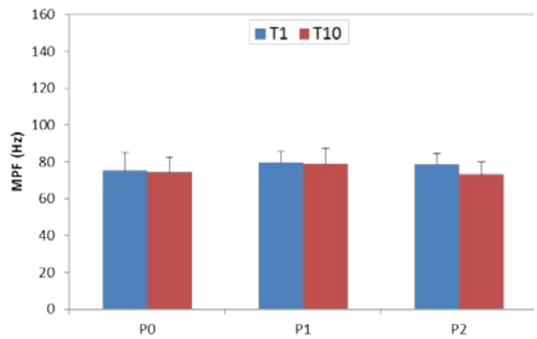
TA L



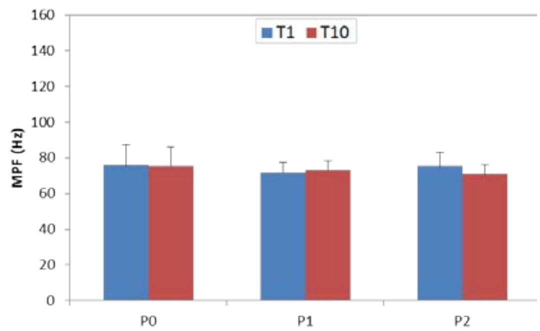
TA R



ES L



ES R



MF L

MF R

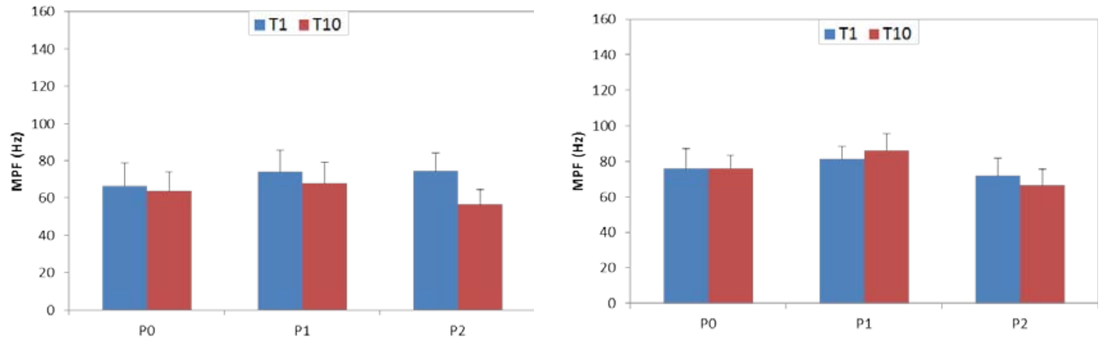


Figure 59 Mean MPF at 1st and 10th minute of investigation, error bars designate 1 standard deviation

A spectral shift to lower frequencies was seen for the TD L and TA R in the P1 condition ($p<0.05$). In the P2 condition, significant spectral changes were present in the TD L and TA L ($p<0.05$). A repeated measures analysis of variance (ANOVA) revealed no significant relationships between the conditions for any muscle.

6.6.2.2 Comparison of MPF across conditions

Figures 60 and 61 illustrate the mean MPF per condition for each of the muscles investigated. There appears to be a peak in the P1 condition and then a lowering in the P2 condition in comparison to the control.

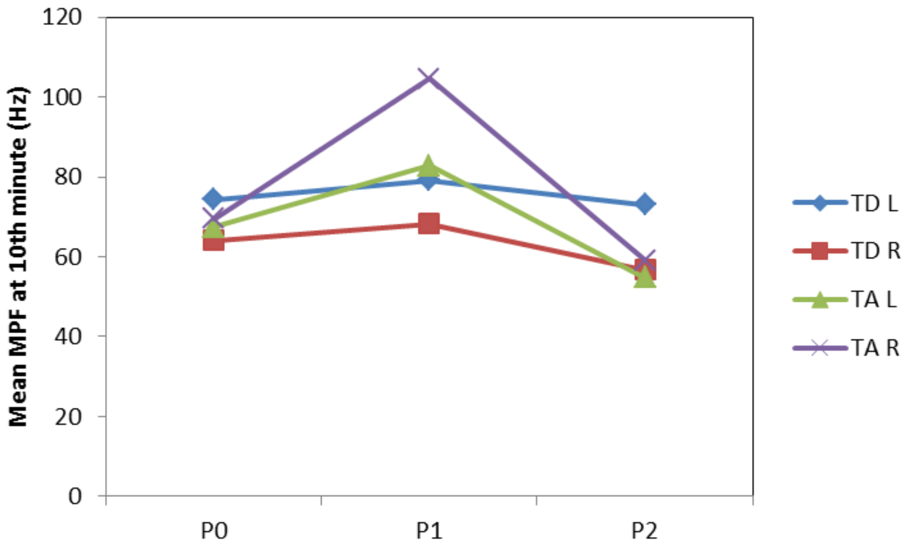


Figure 60 Mean MPF across conditions (TD and TA)

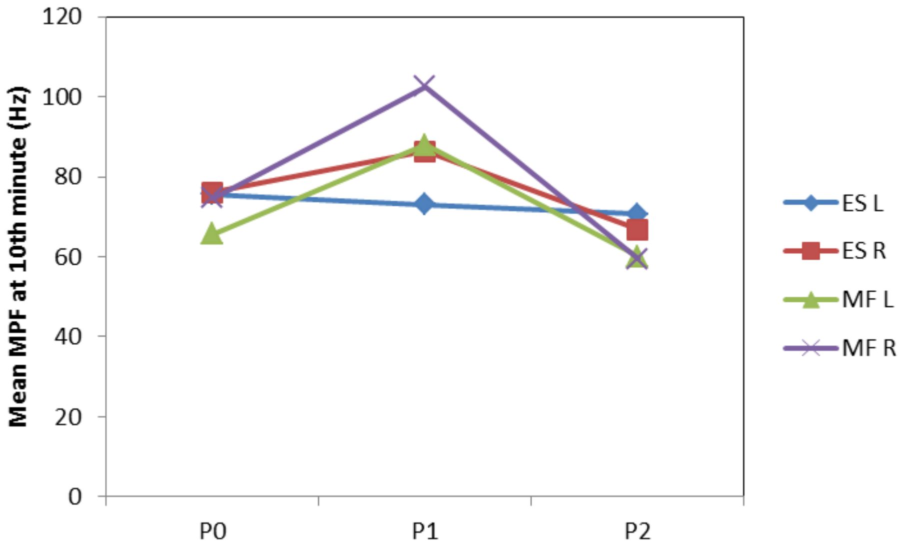


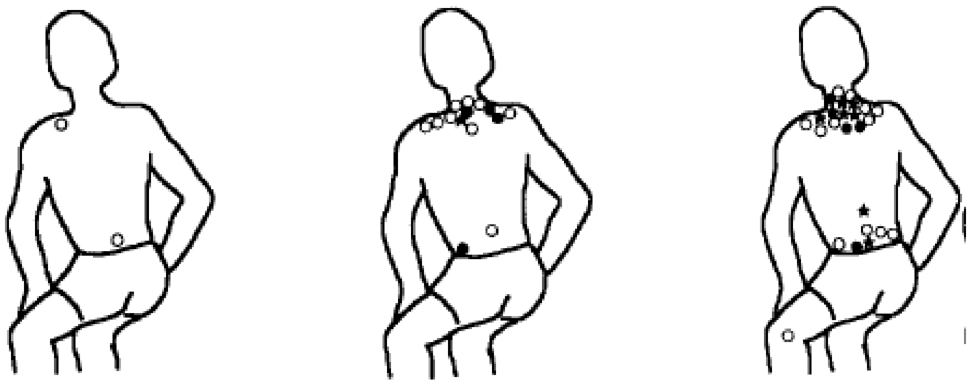
Figure 61 Mean MPF across conditions (ES and MF)

This could be explained by the increased firing of the muscles seen in the P1 condition, and then as the stress increases, the muscles start to fire synchronously therefore reducing the frequency measured at the skin surface.

6.7 Discussion

6.7.1 Subjective discomfort

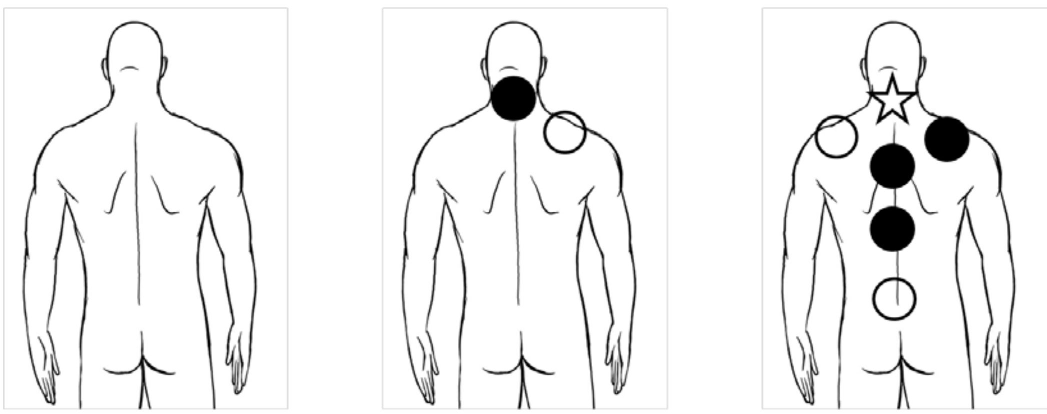
It is clear from the subjective results that both the duration and level of rotation had an effect of discomfort development. In the control condition, no subject experienced more than a level 2 discomfort in any body region. In the posture conditions, discomfort increased considerably in the neck and shoulders. Wikström (1993) investigated subjective discomfort in three postures; his results are shown in Figure 62.



No rotation | 90° rotation at head only | Rotation of neck and trunk rearwards

Figure 62 Localisation of discomfort under differing posture stresses (unfilled ring – weak discomfort; filled ring – discomfort; filled star – severe discomfort) from Wikstrom (1993)

It is clear that the areas of most discomfort were the neck, shoulders and low back. It is also clear that when rotating with the head only, the neck and shoulders are the only areas rated very uncomfortable and above. A similar method of analysis applied to the data in this study, the resulting in the images in Figure 63. For clarity, the areas of 'no discomfort' and 'a little discomfort' are not included. These may equate to the unfilled ring in the diagram above.



No rotation | 110° rotation | 170° rotation

Figure 63 Localisation of discomfort across the three posture conditions (unfilled ring - fairly uncomfortable; filled ring – uncomfortable; unfilled star – very uncomfortable

In the P1 condition, subjects attained the rotation mainly with their neck, which is similar to the study by Wikstrom (1993), although the target rotation here was 20° greater. The discomfort development in this case is very similar being focused on the neck, and if the cases of weak discomfort are excluded from Wikstrom's image, it is also possible to see that the direction of rotation is clearly marked by discomfort development in the right shoulder. In the P2 condition, there is greater disparity as the middle back is clearly represented from this study, but not in the previous experiment by Wikstrom (1993). This may be due to the longer experimentation time in this experiment, or due to the greater amount of trunk twist seen in the P2 condition, compared to his full body twist condition. The main areas for discomfort development, being the neck shoulders and low back is in agreement with the literature on injuries from twisted postures (Kittusamy and Bucholz, 2004).

Harms-Ringdahl et al. (1983) found when investigating extreme loading of the joints that discomfort increases linearly over 45 minutes, but this linear increase in discomfort was not replicated in the current study. Using Figures 53, 54 and 55 for consideration, it can be seen that there is an increase in the rated discomfort over time, as more participants rate higher levels of discomfort. However, this increase is not specifically linear.

It is possible that a ceiling effect was exhibited for some participants for some body parts. However, the greatest level of discomfort was only reached in one body part across the conditions, and therefore it is considered that the pattern of discomfort amongst the conditions and body regions investigated can still be exhibited in the presence of any possible ceiling effects.

6.7.2 Electromyography results

The EMG analysis illustrated variable results. The muscles illustrating fatigue characteristics are in particular the TD L and R, TA R and ES R (P1) and TD L and R, TA L and ES L (P2). The MF did not demonstrate statistical significance for any of the measured parameters. Many studies investigating trunk rotation have not considered the effect on the trapezius. Several authors noted that the ES was active during twisting and suggested that such contractions were for torque production and/or to provide a stabilizing component to the spine (Morris et al., 1962; McGill, 1991, Thelen et al., 1995). The EMG results in this study were not analogous with the other studies discussed here. The ES did show increased activity in 7 and 5 cases for P1 and P2 respectively. A spectral shift was seen in at least 8 cases for both the P1 and P2 conditions. Statistical significance was seen in analysis of the gradients from zero of the ES R (P1) and ES L (P2). McGill (1991) suggests that the low levels of activity indicate the presence of some form of inhibitory mechanism that serves a protective function to the spinal tissues under stresses that are generated during axial torsion efforts.

It is also suggested that these trunk muscles are required to balance flexion-extension and lateral bending moments and thus are limited in their contributions to axial torque. Although the trapezius is not specifically investigated in many studies, it has been shown that muscles with a coactivating role do exhibit increased activation under axial rotation (Pope et al. 1986; Carlsoo, 1961).

Schultz et al. (1983) suggest that some muscles function to counterbalance flexion and lateral bending moments that are produced by the primary axial torque generators such that maximum activation would not be expected from these stabilizing muscles. McGill (2001) demonstrate that the thoracic ES have very minor potential to generate axial torque, but nonetheless demonstrate a strong link with axial torque, they may be a prime candidate to function in a stabilizing role. It is also suggested that the stabilized lumbar joints, from the ES, from a more rigid structure upon which the primary twisting muscles can produce greater amounts of torque. It is suggested that this description may also be applied to other muscles in the area such as the trapezius. Kong et al. (1996) suggest at higher loads or larger flexed postures, muscles were found to pay a more crucial role in stabilising the spine compared with the passive structures, which may explain the low activity increase in the ES and MF seen in this study.

Gregerson and Lucas (1967) investigated lateral bending found a degree of rotation between C7 and the sacrum between 5 and 13 degrees. It is not unreasonable to suggest that the same conversely occurs, that is with twisting, a degree of lateral bending will occur. This cannot be clearly investigated from these results, however, with the employment of the CUELA posture measurement system in later studies, this will be investigated.

In the interpretation of the both the EMG and subjective results, no gender differentiation was made. Although is it generally accepted that females exhibit weaker muscle forces under test, previous studies investigating muscular fatigue have found no gender differences in the median frequencies, or the change over time in back muscle fatigue tests (Mannion et al., 1997). Additionally it was found that males and females employ similar strategies for recruitment of muscles in executing axial rotation.

Spectral changes in the EMG identified fatigue in equivalent muscle groups to the regions of perceived discomfort. These findings are analogous with previous research (Dedering et al.,

1995) in which Borg ratings of exertion correlated with spectral changes on the low back. If the exposure duration was extended to reflect those seen in agriculture, the discomfort and muscular fatigue may have been extended to other muscle groups investigated. Previous studies have demonstrated a link between trunk rotation and low back disorders (Troup, 1978; Frymoyer et al., 1983), however for the durations investigated here, neither discomfort nor changes in the EMG were observed in the low back/MF.

6.7.3 Posture

In both postures, the neck contributed the most to attain the required rotation, rotating at the maximum amount in most cases. In the P1 condition, participant 13 leant their head back to attain the rotation; participant 15 leant forward with their trunk. In the P2 condition, participants 9 and 15 both leant forward. This study was always designed to maintain maximum fidelity with the actual exposures it is designed to investigate. The participants were free to determine how they achieved the required rotation, and therefore the individual way the participants attained the rotation may contribute to the variability in the results.

6.8 Conclusions

Both subjective and objective measures of discomfort and fatigue increased when exposed to postural rotation. The area of the both most affected was the neck and shoulders, with least effect seen in the low back. The findings are discussed with reference to the original hypothesis below:

H_1 Discomfort, assessed subjectively, correlates positively with the magnitude and duration of the axial rotation

The discomfort experienced by the subjects did correlate positively with both the magnitude and duration of the rotation with discomfort remaining low in the control condition and increasing in P1 and P2.

H_2 Measures of spectral shift (MPF) indicate fatigue when subjects are exposed to axial rotation

Decreases in the MPF are indicated in the TD L, TA R and ES R in P1. Decreases are also seen in the TA L and TD L in the P2 condition.

H_3 Measures of muscle activity (EA) indicate fatigue when subjects are exposed to axial rotation

Increases in EA were indicated in the TD R in P1 condition and ES L, TD R and TA L in P2 condition.

H_4 The areas with the greatest subjectively assessed discomfort will be the neck and shoulders

The areas with the greatest discomfort were the neck, right shoulder and upper back

H_5 The muscles exhibiting fatigue will mirror that of the areas of discomfort hypothesized in H_4

In the P1 condition, areas of greatest discomfort were the neck and right shoulder, with fatigue exhibited in the TD L and R, TA R and ES R. In the P2 condition, the areas with the greatest discomfort were the neck and right shoulder, with fatigue exhibited in the TD L and R, TA L and ES L. Although the greatest discomfort between the 2 conditions is seen in the neck, the EMG and subjective results both illustrate the risk to the right shoulder.

CHAPTER 7: Subjective discomfort and muscular response to whole-body vibration

This Chapter presents the second experimental laboratory study of the thesis. The effect of whole-body vibration (WBV) upon subjectively rated discomfort and muscular fatigue response is investigated. This allows for baseline comparisons to be constructed between these results and those in Chapter 6 to form the basis for investigations into the possible effect of interactions.

7.1 Introduction

The vibration magnitudes experience by operators in agriculture is known to be in excess of EU regulations for many tasks (Sorainen et al., 1998). Studies concerning agricultural tractor drivers have shown that the magnitude and duration of vibration exposure in agriculture are associated with lifetime, transient and chronic LBP (Mayton et al., 2007; Bovenzi and Betta, 1994; Boshuizen et al., 1990). Many more studies have demonstrated the negative health effects of vibration exposure in other industries (Wikstrom et al., 1994; Lings and Leboeuf-Yde, 2000). Mounting epidemiologic evidence demonstrating this association between LBP and vibration environments has led to the increasing focus on the biomechanical effect of occupational vibrations (Pope et al., 2002; Bovenzi et al., 2006). An increased predicted odds ratios from 1.1 (Boshuizen et al., 1989) to 2.3 (Bovenzi and Hulshof, 1999) has been predicted for LBP as a function of lifetime cumulative WBV from agricultural driving tasks.

The study of subjective response to vibration is well established, with many of the original discomfort contours for exposure to vibration based rating scales for subjective discomfort (Fothergill 1972; Jones and Saunders 1974; Oborne and Clarke 1974). However, the location of such discomfort is rarely examined. Investigations of rated discomfort from operators in vibration exposed environments have shown that operators report pain in the cervical spine (Dupuis and Zerlett 1987) shoulders (Miyashita et al. 1992) in the legs (Bovenzi and Zadini 1992) and most frequently the low back (Bovenzi and Zadini, 1992; Boshuizen and Bongers, 1992; Dupuis and Zerlett, 1987; Miyashita et al., 1992). In laboratory studies where the frequency range can be isolated, maximum sensitivity and the main discomfort is experienced in the upper torso and head when exposed to 4-16Hz vertical vibration (Whitham and Griffin 1978). At frequencies outside this range, discomfort is experienced in the lower body, abdomen and buttocks (Whitham and Griffin, 1978). In the same study, frequency was found to have a greater effect on discomfort than magnitude. Griffin and colleagues (Whitham and Griffin, 1978, 1977; Fairley and Griffin, 1988) have significantly increased the understanding of the discomfort arising from vibration exposure. However, much of this work was conducted with sinusoidal or single axis vibration on flat seats with no backrest or armrest support. It is also considered important to consider the discomfort effect when standard vehicle seating is used.

In investigations of the muscular fatigue response to WBV, the erector spinae (ES) is almost solely considered. Measures of thoracic and lumbar ES showed a left frequency shift when exposed to 5Hz sinusoid vibration of 0.2g r.m.s. (Hansson et al., 1991). Shifts in frequency were greatest at 5Hz in comparison to other frequency responses (Pope et al., 1998). In addition, higher average activity levels were found in the vibration conditions (Pope et al., 1998). Although there is a focus on the low back and neck in the epidemiological literature, studies investigating the EMG response have not investigated these muscles groups under exposure. The previous studies investigating muscular responses to WBV have rarely considered the fatigue response of the muscles analogous to the areas of musculoskeletal symptom display. The studies of discomfort have not been conducted in a normal seating environment.

7.2 Aims & Hypothesis

In order to fully understand possible interaction effects between trunk rotation and WBV, it is important to fully understand the effect of each individual factor. The previous study considered the effect of trunk rotation singularly. The aim of this study is to understand the effects of multi-axis vibration on the body, how this affects the muscle response and subjective discomfort.

The hypotheses for this study are therefore:

H_1 Discomfort, assessed subjectively, increases with the magnitude and duration of the vibration

H_2 Measures of spectral shift (MPF) will indicate fatigue when subjects are exposed to vibration

H_3 Measures of electrical activity (EA) will indicate fatigue when subjects are exposed to vibration

H_4 The areas with the greatest subjectively assessed discomfort will be the low back

H_5 The muscles most likely to exhibit fatigue will mirror that of the areas of discomfort hypothesized in **H_4** including the erector spinae

7.3 Methodology

The effect of WBV was determined with the use of EMG fatigue analysis and subjective ratings of discomfort. These methods have been described in greater detail in Chapter 3, Methodologies.

A discussion of the vibration exposures in agriculture (Chapter 5) suggests that there is great variation in both the magnitude, and the frequency component of WBV exposures, from the many vehicles and tasks commonly completed. It was therefore considered preferable not to favor any one frequency in the typical operating range, as this may be unrepresentative of some tasks and vehicles. The vibration for investigation was therefore based on a nominally flat 1-20Hz spectrum (Figure 64). Two magnitudes of vibration for the experimental conditions were used along with a control (no vibration). The vibration magnitudes for investigation were:

V0: 0m/s^2 r.m.s – control condition to establish baseline

V1: 0.5m/s^2 r.m.s – lower vibration condition

V2: 1.0m/s^2 r.m.s – higher vibration condition

The lower vibration magnitude was chosen to reflect the 0.5m/s^2 r.m.s action level specified in PA(V)D. The higher vibration level was chosen to allow a linear comparison to be made between the three exposures. This experiment was intended as a comparison to the twist study detailed in Chapter 6. The methods followed were therefore a direct repeat of those described in the previous Chapter, with the addition of the use of the multi-axis vibration simulator (Chapter 3, Section 3.4.5). For that reason, the methodology involved in the collection of the subjective and EMG data is not repeated here.

The duration for exposure was 10 minutes. Subjects were seated throughout the study on a full-backrest air suspension Grammer seat with armrests and material cushions. The seat, along with the steering wheel and pedals, was mounted on the multi-axis vibration simulator in the Environmental Ergonomics laboratories at Loughborough University. Participants were again asked to keep feet and hands placed on the pedals and steering wheel to simulate a driving scenario, the instruction was given that they must be seated as if they were in control of the mock-vehicle at all times. The study followed approved ethical protocols.

7.4 Results

17 participants completed all conditions. One participant was excluded from the remainder of the analysis due to vibration magnitude being outside the 10% tolerance.

7.4.1 Subjects

Subjects were recruited from the staff and student cohort at Loughborough University. Participants comprised healthy males and females (Table 20) who were screened for a history of back problems; those with a history were excluded. Volunteers completed informed consent forms before commencement of experiment. Subjects were not paid for their participation.

Table 20 Demographic data of experimental sample

(Values are presented as mean ±standard deviation (range))

	N	Age (yr)	BMI
Male	5	19 ± 3.3 (19-26)	22.7 ± 2.5 (19-27)
Female	11	20 ± 1.0 (18-21)	22.5 ± 2.6 (20-26)
Total	16	19.3 ± 1.9 (18-26)	22.64 2.5 (19-27)

7.4.2 Vibration

The PSD of a typical vibration exposure measured on the seat surface is shown below in Figure 64.

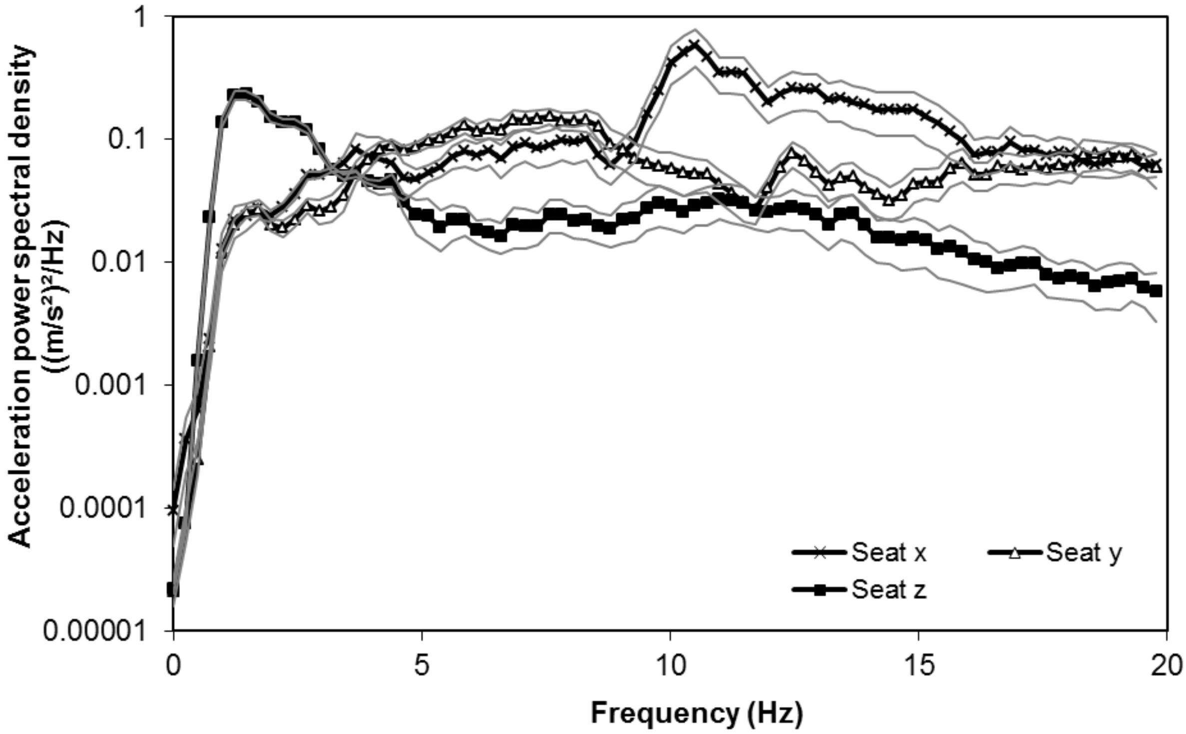


Figure 64 Power spectral densities at the surface of the seat in x- y- and z-axis, with standard deviations, taken from the P1 condition

Vibration magnitudes measured at the seat were within a 10% tolerance of V0 (no vibration), V1 (0.32 x; 0.23 y; and 0.39m/s² z-axis, weighted r.m.s.) and V2 (0.73 x; 0.60 y; and 0.82m/s² z-axis, weighted r.m.s.).

7.4.3 Subjective Discomfort

As with the previous Chapter, the subjective discomfort is considered in 3 ways to answer the hypothesis.

7.4.3.1 Influence of vibration magnitude on discomfort

The influence of the vibration magnitude on the discomfort experienced by the subjects was investigated by comparing the median discomfort scores at the 10th minute for each vibration condition (Figure 65)

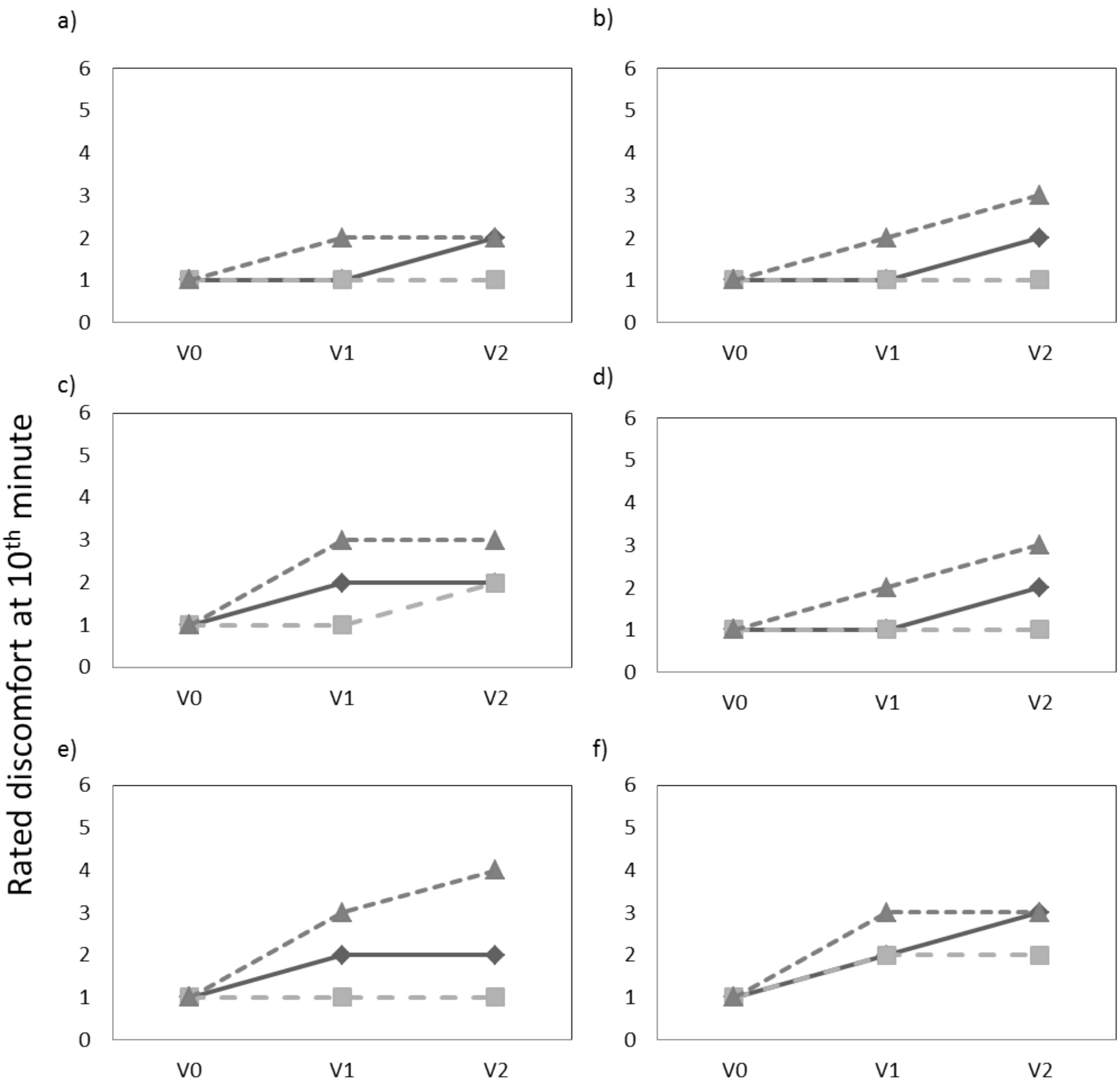


Figure 65 Influence of the 3 experimental conditions on subjective discomfort, median scores are shown as unbroken lines, 25th and 75th percentiles are shown by broken lines. The graphs show the results for the a) left shoulder, b) right shoulder, c) neck, d) upper, e) middle and f) low back

Discomfort in the V2 condition either equalled or exceeded the discomfort experienced in the V0 or V1 conditions for all body parts. There was little difference in the discomfort across the investigated body regions, with no body region clearly more uncomfortable than any other. The 25th percentile remained at the lowest level in all conditions with the exception of the neck and low back. The greatest median discomfort score was 3, fairly uncomfortable, in the low back V2 condition. There are significant differences ($P<0.05$, Wilcoxon) between V1 to V2 for all the body parts. The same applies for V0 to V1 with the exception of the right shoulder and upper back, where no significant differences were found.

7.4.3.2 Influence of duration on discomfort

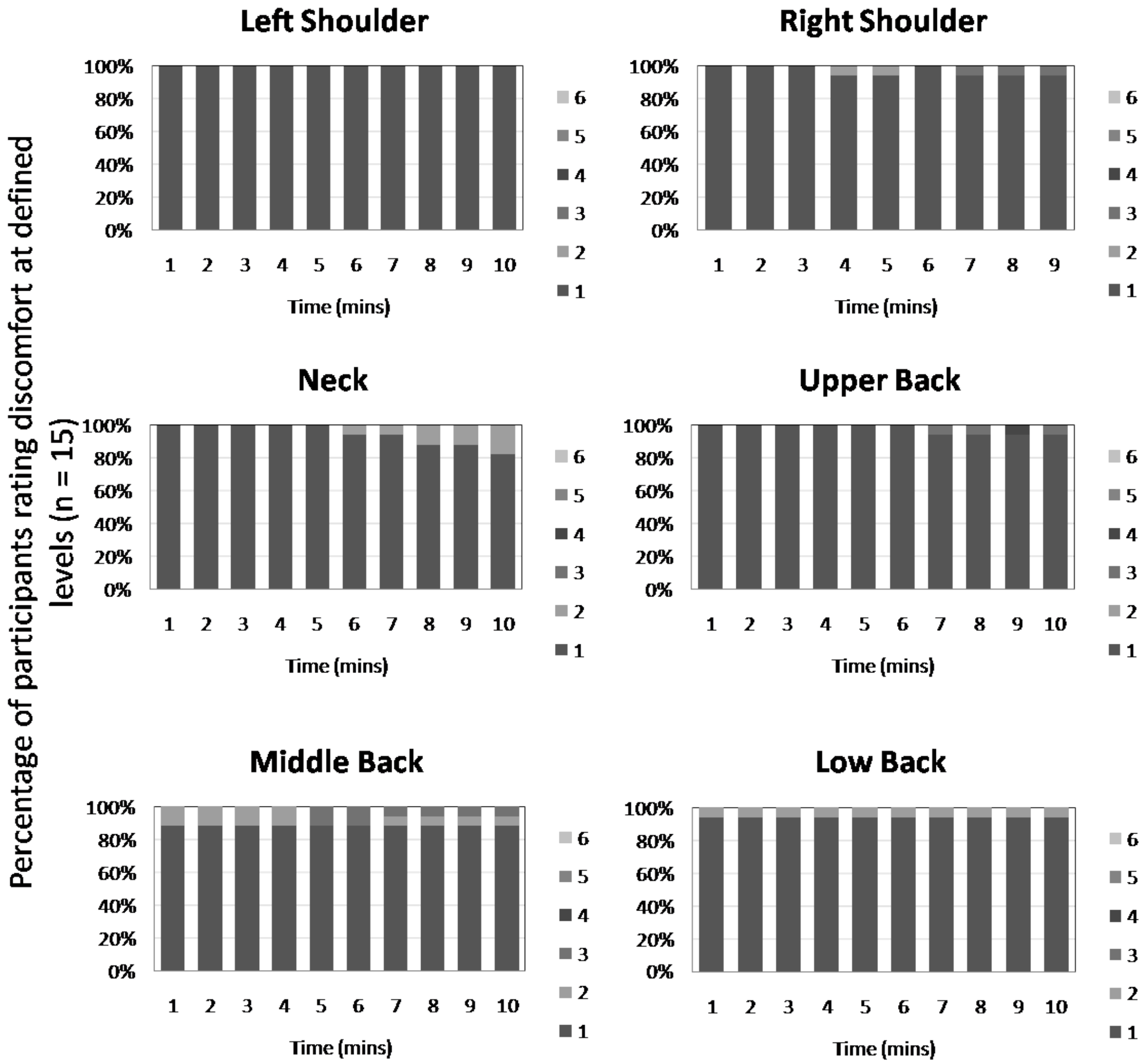


Figure 66 Discomfort development for all body parts over 10 minutes, V0

Figure 66 demonstrates the low percentage of participants increasing their discomfort rating over the 10 minute duration. This is as expected. The changes over time in the discomfort are not significant ($p>0.05$, Wilcoxon) for any body part.

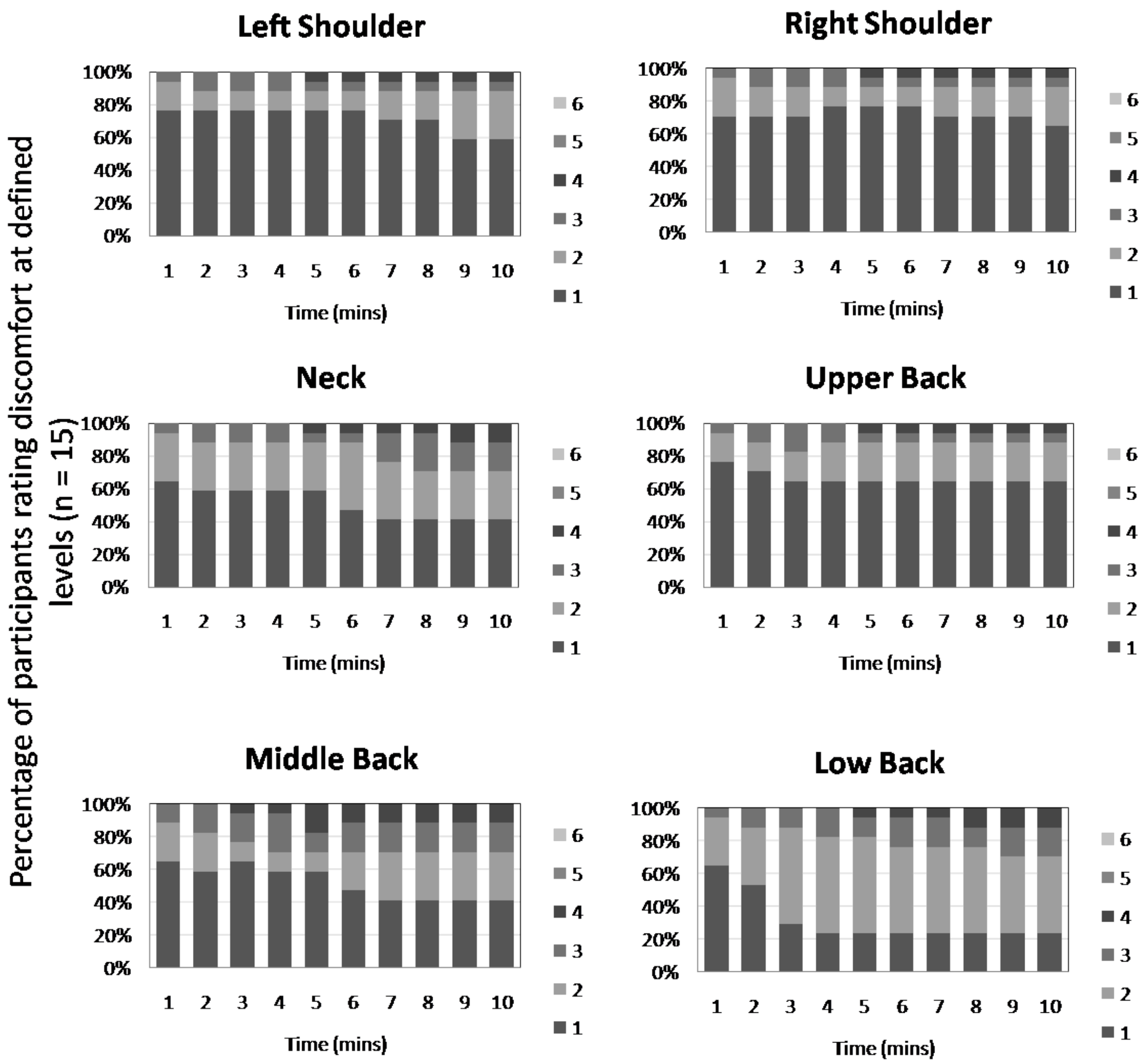


Figure 67 Discomfort development for all body parts over 10 minutes, V1

In the V1 condition (Figure 67) the number of participants remaining at the baseline discomfort is lowest in the low back. The proportion of participants increasing their discomfort over the experiment duration is similar in the other body regions. The change (increase) in discomfort over time is significant ($p<0.05$, Wilcoxon) in the neck, middle and lower back.

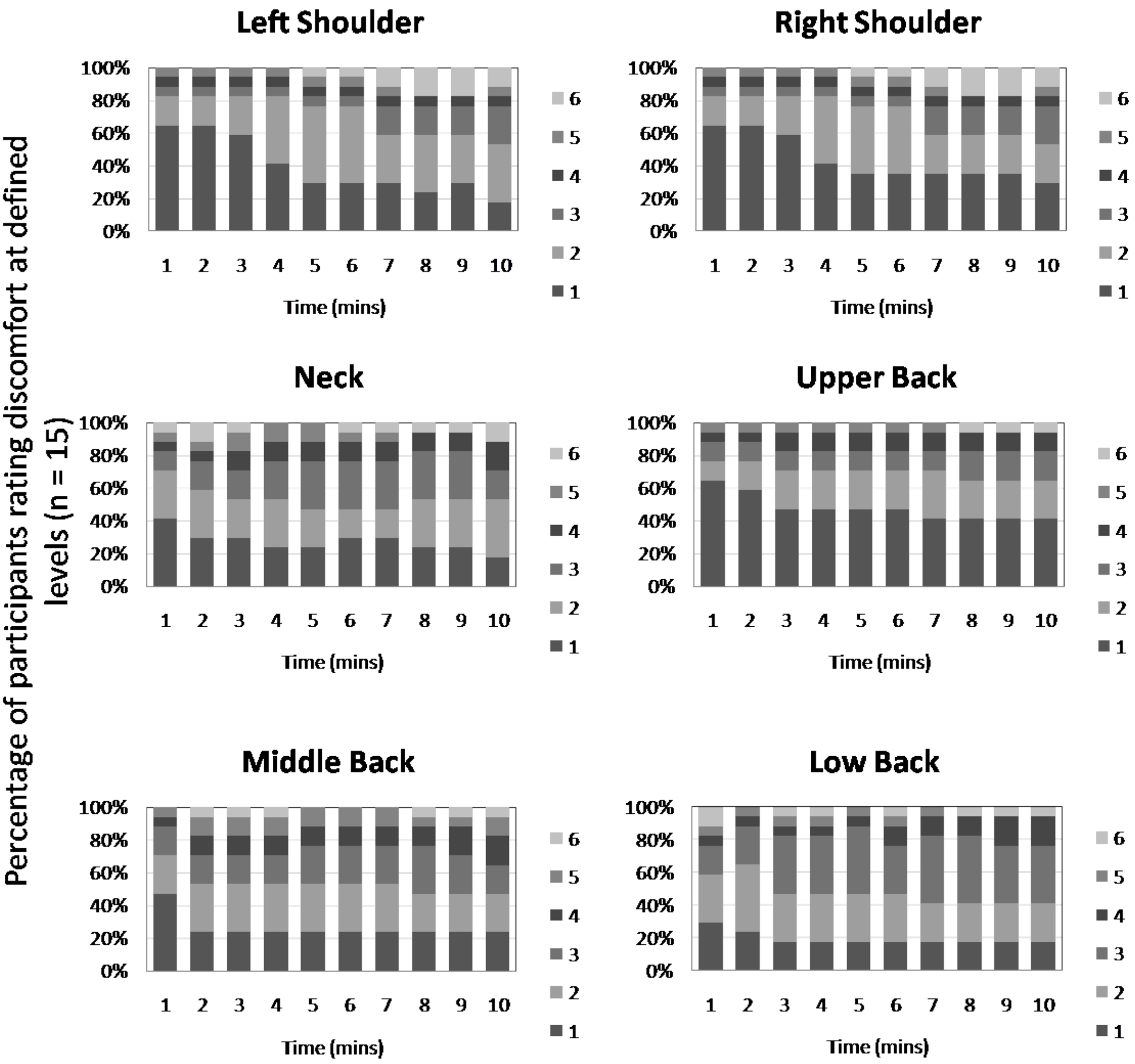


Figure 68 Discomfort development for all body parts over 10 minutes, V2

It is clear from Figure 68 that more participants are rating greater discomfort earlier in this condition in comparison to both V0 and V1. The changes in rated discomfort over time are statistically significant in all investigated body regions.

7.4.4 EMG

Individual EMG data is presented in the appendix, e).

7.4.4.1 Muscle activity response

The gradient of the activity response was used in the previous Chapter to display individual responses to the vibration exposure. There were no significant trends amongst the individual participants gradients, there is greater disparity amongst the gradients in the V2 condition than in the other conditions, with some muscles exhibiting both larger increases and decreases over the investigation period. Comparison of the activity levels at start of investigation and end of investigation revealed significant decreases in EMG activity (not indicative of fatigue) are seen in many muscles in the control condition. The levels of muscular activity are similar across the muscles investigated, indicating an even response of the back muscles to the vibration stimuli.

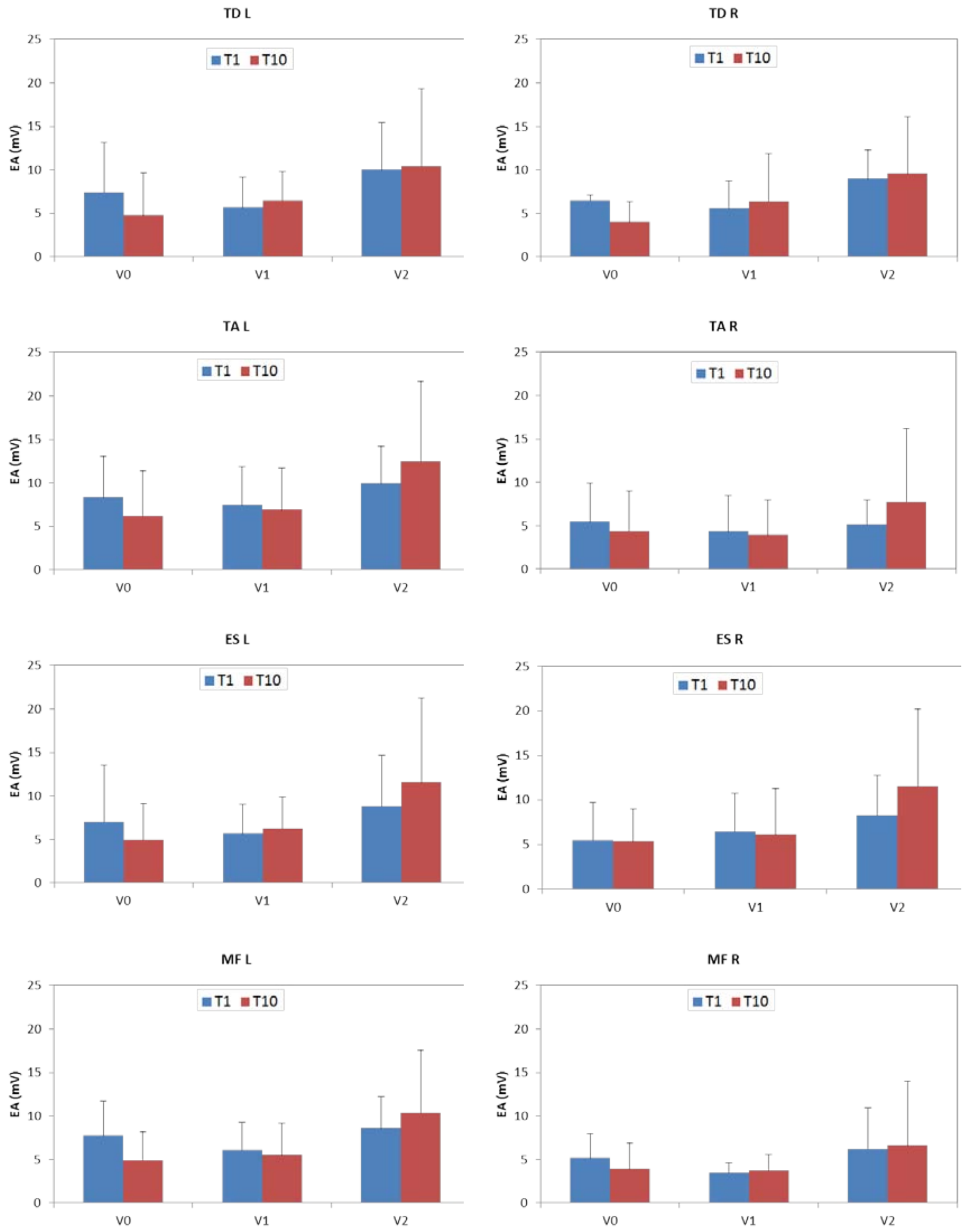


Figure 69 Mean electrical activity at 1st and 10th minute, error bars designate 1 standard deviation

In the V1 condition, only one muscle, ES R illustrates elevated activity over time. In the V2 condition however, only the ES L and MF L do not show significant increases in activity over the 10 minute experimental duration. In addition, it is clear from Figure 69 that there is elevated activity at the start of the experiment in the V2 condition.

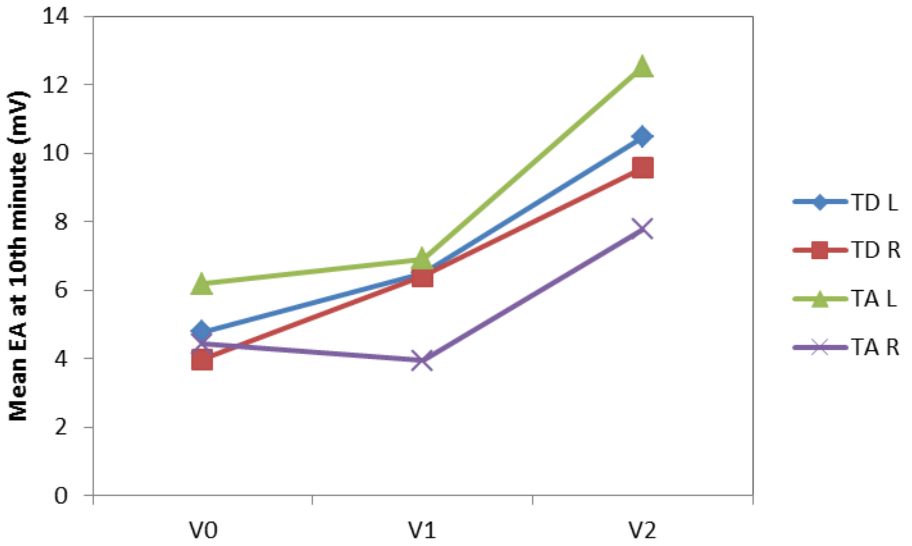


Figure 70 Mean EA at 10th minute across conditions (TD and TA)

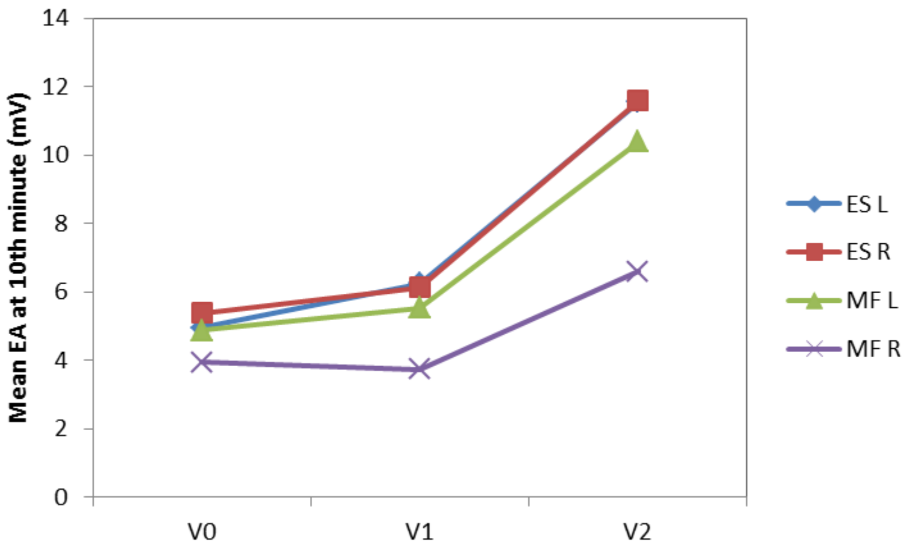
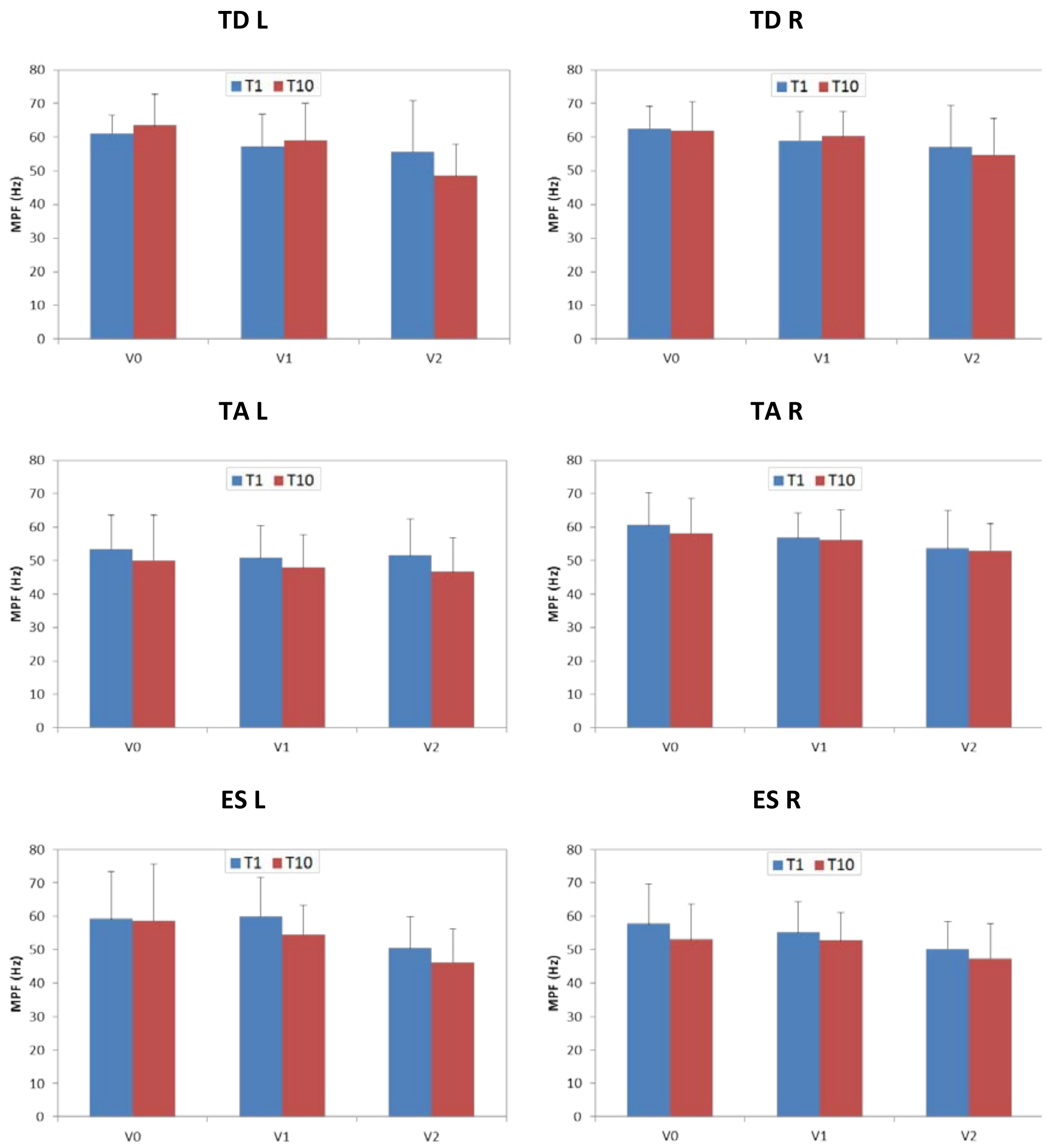


Figure 71 Mean EA at 10th minute across conditions (ES and MF)

There is a clear trend in the Figures above, with an increase in EA in the V2 condition. This was also indicated in the previous Figure 69) where the increase in activity in the V2 condition is clear. A paired samples t-test reveals that the differences in 10th minute activity is significantly different between the 3 conditions (V0-V1 $p<0.05$; V1-V2 $p<0.001$; V0-V2 $p<0.001$).

7.4.4.2 Muscle frequency response

Evaluation of the frequency shift over the experimental duration can be completed by considering the frequency at the initial period of investigation and the latter period of investigation. Completing this provides the data shown in Figure 72 where it can be seen that particularly in the multifidus, the decrease in frequency over the 10 minutes is apparent.



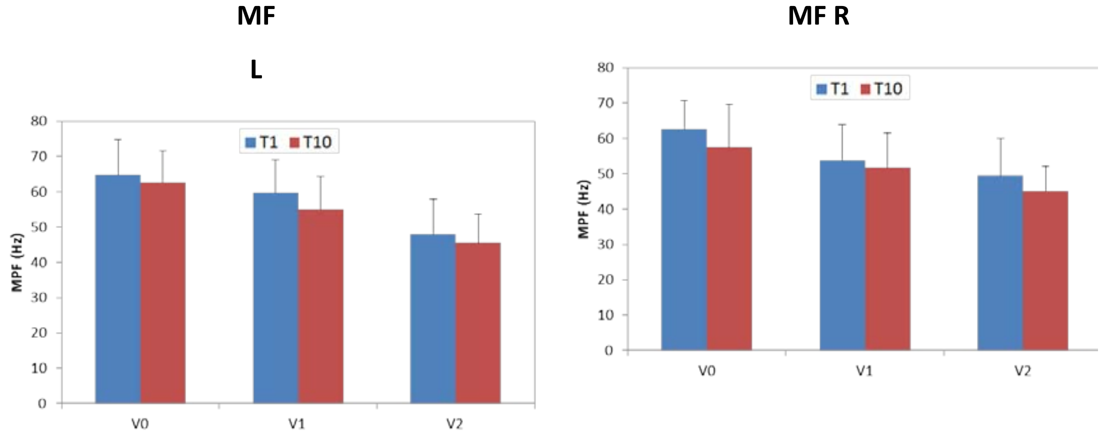


Figure 72 Mean power frequency at 1st and 10th minute, error bars designate 1 standard deviation

Comparisons of the MPF at the start of investigation and the end (Figure 72) revealed there are no significant ($p<0.05$, t-test) decreases in MPF over time in the V0 control condition for any muscle. When exposed to vibration in the V1 condition, a significant decrease in MPF is seen in the TA L and R, ES R and MF L. The TA L also shows a significant left shift in the V2 condition with the addition of the MF L and TD L. However, the ES L and ES R do show significant increases over time in the V1 and V2 conditions respectively. Elevated electrical activities were seen in the muscles when first exposed to vibration, which further increased over time in some muscles. This is in agreement to previous studies investigating the activity response (Pope, 1993). Both significant increases in activity *and* decreases in MPF were seen in the ES R in the V1 condition and in the TD L, TA L and MF R in the V2 condition.

The data illustrated in Figures 73 and 74 are the mean MPF across the conditions to allow for direct comparison. As can be seen from the graphs, there is little variation both between the muscles and the conditions, in general there does appear to be a decrease in the frequency at the vibration magnitude increases. This is what would be expected if the vibration had caused a frequency shift in the muscle.

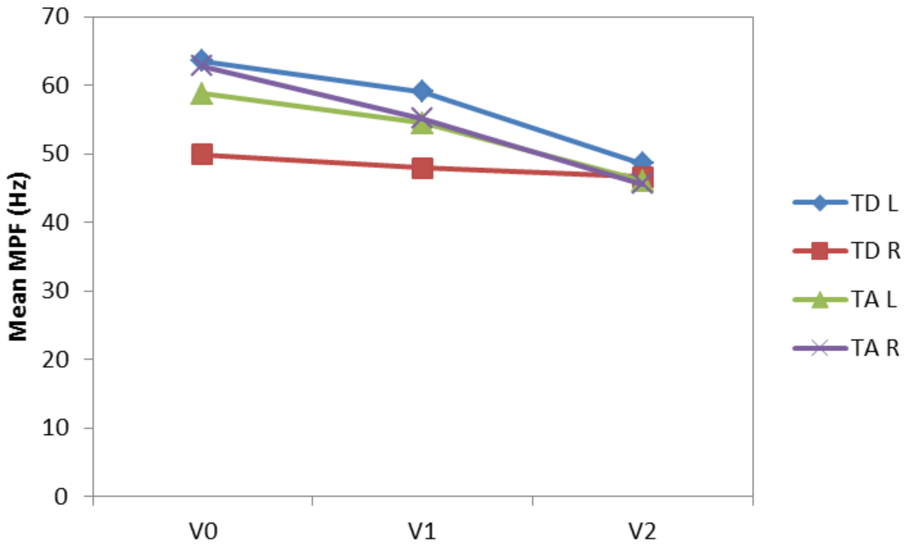


Figure 73 Mean MPF across conditions (TD and TA)

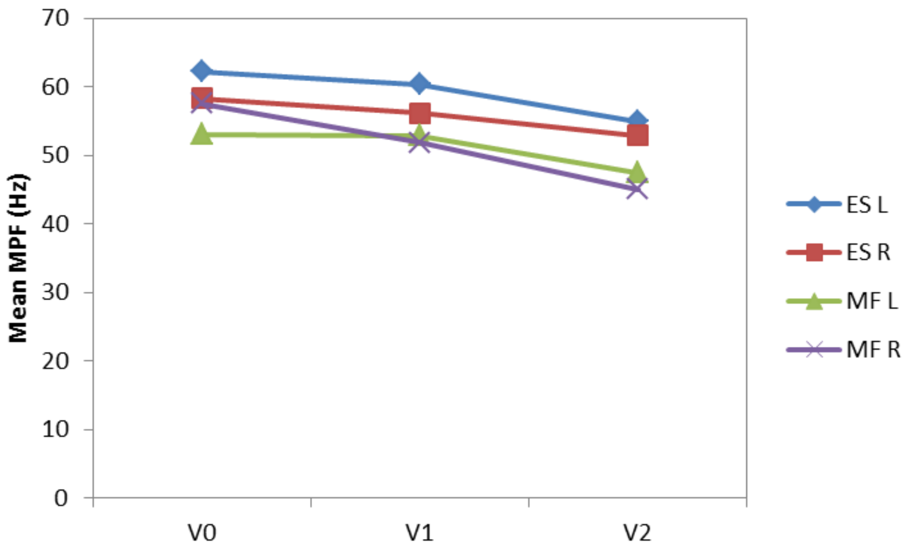


Figure 74 Mean MPF across conditions (ES and MF)

7.5 Discussion

7.5.1 Subjective discomfort

It is clear from the subjective results that both the duration and magnitude of vibration had an effect on discomfort development. Discomfort was lowest in the V0 condition, not exceeding 'no discomfort' in any body part. Discomfort increased through the experimental conditions, the discomfort increase was equal between the two vibration conditions in the low back, but not in the other body parts.

In the discomfort studies discussed in the introduction, the body regions where operators had self-reported discomfort were the neck, shoulders and low back. This in agreement with the discomfort reported in this study, in addition to the other areas of reported discomfort. Table 21 reports the results to this and other comparable studies. It can be seen that the subjective ratings are comparable between the current study and others in the table.

Table 21 Comparison of current study results with previous results on subjective discomfort when exposed to vibration

Author	Scale range	Vibration	Subjective score	Relative score
Fothergill and Griffin (1977)	4 point, very uncomfortable (4) – noticeable but not uncomfortable (1)	0.4m/s² r.m.s 10Hz Sinusoidal	Noticeable but not uncomfortable	1
Fothergill (1972)	5 point, very unpleasant (5) – noticeable (1)	0.7m/s² r.m.s, 8Hz sinusoid	Not unpleasant	2
Jones and Saunders (1974)	5 point, very unpleasant (5) – not uncomfortable (1)	0.7m/s² r.m.s, 10Hz sinusoid	Mean threshold of discomfort	2
Morgan (2011) Current study	6 point, not uncomfortable – extremely uncomfortable	0.5m/s² r.m.s 1-20Hz random	A little uncomfortable	2
Fothergill and Griffin (1977)	4 point, very uncomfortable (4) – noticeable but not uncomfortable (1)	1.1m/s² 10Hz Sinusoidal	Mildly uncomfortable	2
Fothergill (1972)	5 point, very unpleasant (5) –	1.1m/s² r.m.s, 8Hz sinusoid	Mildly unpleasant	3

	noticeable (1)			
Jones and Saunders (1974)	5 point, very unpleasant (5) – not uncomfortable (1)	1.2m/s^2 r.m.s, 10Hz sinusoid	Uncomfortable	3
Current study	6 point, not uncomfortable – extremely uncomfortable	1.0m/s^2 r.m.s 1-20Hz random	A little uncomfortable – uncomfortable	2-4

The vibration frequency range used in this study is similar to that investigated by Whitham and Griffin (1978) although they reported greatest sensitivity in the upper torso and head. The greatest sensitivity to discomfort in this study was in the low back. The vibration used in the Whitham and Griffin study (1978) was vertical vibration only and therefore this may explain the difference between their findings, and the findings presented here. In addition, a full backrest seat was used in the present study which through providing additional support to the upper back and neck may have reduced the effect of the vibration in these areas.

7.5.2 Muscular fatigue

No muscles showed a frequency decrease over time in the control condition. 4 muscles in the V1 condition and 3 muscles in the V2 condition did decrease the MPF over time. From this it could be concluded that the vibration exposure has an effect on the frequency response of the muscles, but there was not demonstrable difference between the effects of the 2 vibration magnitudes on the frequency. Muscle activity was seen to increase in the vibration conditions. Many more muscles had significant increases in activity in the higher vibration (V2) condition in comparison to the lower vibration (V1) condition. In contrast, many muscles showed a decrease in activity over the 10 minute experiment in the control condition. The thoracic ES has been shown to left shift when exposed to 0.2g m/s^2 r.m.s (Hansson et al., 1991). The ES examined in the present study demonstrated fatigue in the right side only in the V1 condition, and no significant changes in frequency were seen in the V2 condition. The magnitude of the vibration in the study by Hansson was very high, and therefore the greater muscular response in his study is as expected.

Previous studies have investigated the different responses between male and female subjects. This study was not powered to conduct such an analysis. Additionally, Griffin and Whitham (1977) showed no difference in vibration discomfort contours between men, women and children.

7.6 Conclusions

There was no clear distinction between the areas of discomfort, although marginally greater discomfort was rated in the low back in the V2 condition. The range of muscles exhibiting fatigue characteristics was also not confined to one area of the back. Together this suggests that when exposed to WBV, the whole back and neck are affected. The findings are discussed with reference to the original hypothesis below:

H_1 Discomfort, assessed subjectively, increases with the magnitude and duration of the vibration

The discomfort experienced by the subjects did increase with the magnitude and duration of the vibration exposure. Marginally greater discomfort was experience in the low back.

H_2 Measures of spectral shift (MPF) will indicate fatigue when subjects are exposed to vibration

Four and three muscles exhibited fatigue when assessed with spectral parameters in the V1 and V2 conditions respectively. Therefore, although the presence of vibration fatigued the muscles, there was no clear increase with vibration magnitude.

H_3 Measures of electrical activity (EA) will indicate fatigue when subjects are exposed to vibration

One muscle increased activity in the V1 condition, in comparison to 6 muscles with increased activity in the V2 condition. Therefore it can be assumed that an increasing vibration magnitude has an increased effect on the muscles assessed.

H_4 The areas with the greatest subjectively assessed discomfort will be the low back

The area with greatest subjectively assessed discomfort was the low back, although there was not a large distinction between the discomfort in this area and the others investigated. Therefore this hypothesis can be accepted but with reservations.

H_5 The muscles most likely to exhibit fatigue will mirror that of the areas of discomfort hypothesized in H_4 including the erector spinae

The multifidus (right side only) did exhibit fatigue, but in the V2 condition only. There was no clear pattern in either the discomfort on the muscular fatigue development. Therefore this hypothesis cannot be accepted or rejected.

CHAPTER 8: The effects of simultaneous exposures to trunk rotation and whole-body vibration

This Chapter details a laboratory study designed to combine the exposures investigated in Chapters 6 and 7. Both trunk rotation and WBV were found to instigate muscular fatigue and discomfort in the previous Chapters. This study aimed to establish how these effects would differ when experienced synchronously. The methodology is largely unchanged from the previous studies, with the addition of a supplementary posture measurement system.

8.1 Introduction

Operators of agricultural vehicles are often exposed to high magnitudes of vibration whilst seated in a twisted posture (Sorainen et al., 1998; Toren, 2001). This driving scenario is not exclusive to agriculture, and is seen in the use of forklift trucks (Hoy et al., 2005) and load-haul-dump mining machines (Eger et al., 2008). Various studies present in the literature have demonstrated both trunk rotation and WBV to be precipitating risk factors for musculoskeletal disorders of the low back (Bovenzi and Hulshof, 1999; Lings and Leboeuf-Yde, 2000; Pope et al., 2002). The effect of combining these stressors, however, has been investigated less extensively.

Wikström (1993) completed a comparative assessment of driving scenarios whilst exposed to whole-body vibration and differing levels of trunk rotation. With increased rotation, both the levels of discomfort and the areas affected increased. In addition, the spinal muscles were found to exhibit fatigue under the high magnitude twist condition. Epidemiological evidence links combined exposures to LBP in both tractor drivers (Boshuizen et al., 1990) and other exposed populations (Hoy et al., 2005). As a result of their exposure, operators have experienced an increase in discomfort symptoms in the low back, neck, shoulders and knees (Wikström, 1993; Zimmermann and Cook, 1997). Objective measures of trunk rotation are rarely conducted. Muscular response has been investigated (Bottoms and Barber 1978; Wikström, 1993; Wilder et al., 1982), however these studies have focussed on the activity response of the muscles perceived to be generating the rotation, the erector spinae and abdominal muscles. Investigation of the muscular fatigue analogous to the areas of reported discomfort symptoms has not been previously considered.

The operator working posture is affected by many factors including (but not exclusively) workstation layout, workers' anthropometric characteristics and the location/orientation of the work surface (Kittusamy and Buchholz, 2004). Ergonomic interventions such as seat re-design have been explored. Both Bottoms and Barber (1978) and Torén and Oberg (2001) have demonstrated that in an environment where both vibration and trunk rotation are present risk factors, reducing the required trunk rotation placed less stress upon the operator. In addition Newell and Mansfield (2007) demonstrated that there was a workload cost to the operator when exposed to both trunk rotation and WBV. This effect was exacerbated when the operator was not provided with armrest support.
The measurement of vibration is often well defined, and is guided by the relevant ISO standards (ISO 2631, 1997). However, guidance on how the posture of the operator should be taken into account is limited. Postural assessment methods are available, although not designed for use in a vehicle environment, and there are no specific guidelines on acceptable exposures other than those provided by the postural assessment tools themselves.

The majority of studies have utilised visual methodology for capturing the operators' posture (Bottoms & Barber, 1978; Eger et al., 2008; Toren, 2001). Goniometers are also used, but less frequently (Newell and Mansfield, 2008). In the investigation of trunk rotation only, axial rotation testers have been utilised, where the operator is held at the desired magnitude of rotation (Kumar, 1995, 1999, 2001). However, this methodology is impractical for use on a vibration platform. To date there have been no studies that have considered the combined fatigue and discomfort response from exposure to both trunk rotation and WBV.

8.2 Aims & Hypotheses

It is important to improve the understanding of the effects of interactions between the effects of WBV and trunk rotation. This will help guide both the effective reduction of exposures, and help provide guidance on prioritisation in such risk management. The aim of this study is to understand any possible interaction effects between static twists and WBV exposure on the body, how this affects the muscle fatigue response and subjective discomfort. The results can then be compared to the results from Chapters 6 and 7, to fully understand the effects of the interaction.

The hypotheses for this study are therefore:

H_1 Discomfort, assessed subjectively, will increase as both the trunk rotation and vibration exposure increase

H_2 More muscles will be affected by fatigue, assessed by muscle activity, when exposed to both stressors

H_3 More muscles will be affected by fatigue, assessed by spectral shift, when exposed to both stressors

H_4 The muscles with greater rated subjective discomfort, will be the neck, shoulders and low back based upon the combined results of Chapters 6 and 7

H_5 The muscles exhibiting muscular fatigue will be mostly TD and TA, based upon the combined results of Chapters 6 and 7

8.3 Experimental Method

The effect of simultaneous exposure to trunk rotation and WBV will be determined with the use of EMG fatigue analysis and subjective ratings of discomfort. These methods have been described in greater detail in Chapter 3 (Experimental Methodologies).

The conditions for exposure are a combination of those tested in isolation in Chapters 6 and 7. These are as follows, with the notation that will be used throughout this Chapter to denote these exposures. The notation follows that previously used in Chapters 6 (P0, P1 and P2) and 7 (V0, V1 and V2) for the single exposures.

- PV0 – control condition, no vibration, no rotation
- P1V1 – 110° twist, 0.5m/s^2
- P1V2 – 110° twist, 1.0m/s^2
- P2V1 – 170° twist, 0.5m/s^2
- P2V2 – 170° twist, 1.0m/s^2

The order of the test conditions was balanced using a Latin-square design. For each subject, a range of data was collected, this included EMG, from 8 electrodes on the cervical, thoracic and lumbar spinal musculature, and subjective ratings of discomfort. The duration for exposure was 7 minutes. With the increased number of conditions, and the hypothesised increased risk, this allowed the same-day methodology to be maintained for this study, and therefore maintain coherence with the studies detailed in Chapters 6 and 7. The EMG and subjective data for each participant is analysed as outlined in the methodology Chapter 3, and unchanged from Chapters 6 and 7. This involves time domain analysis of both the electrical and spectral parameters of the EMG, and also the subjective ratings of discomfort, provided every 60s. The same experimental procedure was followed as with Chapters 6 and 7, although the posture was measured separately.

8.3.1 Posture assessment

A posture measuring system, CUELA (Computer-assisted recording and long-term analysis of musculoskeletal loads) (Ellegast and Kupfer, 2000) was utilised for measurement of the subjects posture. This system was developed by the German Institute for Industrial Health (IFA, previously BGIA). The CUELA system used (v.2, Hermanns et al., 2007) allows for the measurement of seated postures, the parameters measured are noted in Table 22.
This person-centred measuring system consists of accelerometers (Analog Devices ADXL 103/203) and gyroscopes (muRata ENC-03R), as well as a miniature data storage unit with a flash memory card, which can be attached to the subject's clothing. The system is battery operated; therefore the subject is able to move freely. The sampling rate is 50 Hz.

Table 22 Degrees of freedom measured by the CUELA measurement system

Joint or body region	Degree of freedom
Cervical spine	Torsion; flexion/extension; abduction/adduction
Thoracic spine	Torsion; flexion/extension; abduction/adduction
Hip joint	Flexion/extension; abduction/adduction

All body angles are 'zeroed' at the beginning of a measurement. The participant is required to stand upright, with head in the Frankfort plane. The sensors are all initialised at this moment and then the measurement can begin. Individual angle offsets depending on the subject and errors caused by sensor attachment are eliminated at this juncture. This setup means movement artefacts are less than ±1° in low vibrational environments, and may increase up to ±4° during shocks or rough, high amplitude, low frequency vibrations (Hermanns et al., 2007). The provision of a synchronised video file allows for elimination of major motion artefacts, or false posture readings. Figure 75 illustrates a subject with the CUELA measurement system attached. When seated with the CUELA system applied, the sensors at the back of the subject were found to interfere with the seat, therefore a 'u-shaped' section of foam was applied to the backrest to isolate that sensor and avoid interference.

The posture data is logged on a data logger (IFA, 2009) for analysis within Widaan, custom software developed by Ingo Hermanns at IFA. A computerised model of the subject is developed within Widaan and displayed alongside the synchronised video and timeline graph of posture degree of freedom selected. Once the details of the postures are within Widaan, statistical analysis of those postures can be completed. Therefore it is possible to determine how the participants rotated, the angle of rotation for each segment, and also distributions amongst the subject population.

Figure 75 Subject with CUELA posture measurement system applied

8.3.2 Procedure

The procedure followed in the experiments is identical to that followed in Chapters 6 and 7, until after the electrodes are applied. At that point the CUELA system is fitted. The system is plugged into the evaluation software (Widaan); this allows all sensors to be zeroed to the initial posture. The participant is then disconnected from the Widaan software, and connected to the battery powered datalogger. Once the participant is seated in the chair, the CUELA measurement is synced with the video recording by the participant making a series of repeated joint movements (e.g. a nod of the head). The EMG start is synced with the start of the vibration exposure and the subjective ratings. Participants completed 5 experimental conditions, balanced using a Latin square to minimise possible order effects.

8.3.3 Ethics

The ethics for all the studies are discussed in more detail in Chapter 3. All participants volunteered informed consent forms and were screened for a history of back problems. Those with a history were excluded. Subjects were not paid for their participation

8.3.4 Subjects

Subjects were recruited from the staff and student cohort at Loughborough University. Participants comprised healthy males and female Table 23.

Table 23 Demographic data of experimental sample (Values are presented as mean ±standard deviation (range))

Subjects	N	Age (yr)	BMI
Male	5	19 ± 1.5 (17-21)	22.7 ± 1.3 (20-24)
Female	10	19 ± 0.6 (19-20)	23.0 ± 3.7 (16-30)
Total	15	19 ± 0.9 (17-21)	22.9 ± 3.1 (16-30)

8.4 Results

This section presents the findings for the EMG and subjective discomfort results for the five experimental conditions. The results of the CUELA posture assessment are also presented. Subjective results are analysed using non-parametric Wilcoxon (statistical significance accepted at $p<0.05$). EMG results are analysed with a parametric t-test (statistical significance accepted at $p<0.05$).

8.4.1 Vibration

The vibration was measured at the seat for all participants. Those with exposure outside the 10% tolerance set were excluded from analysis. The PSD of vibration exposure at the seat surface for all subjects in the lower vibration condition is shown in Figure 76 and in the higher vibration condition, Figure 77.

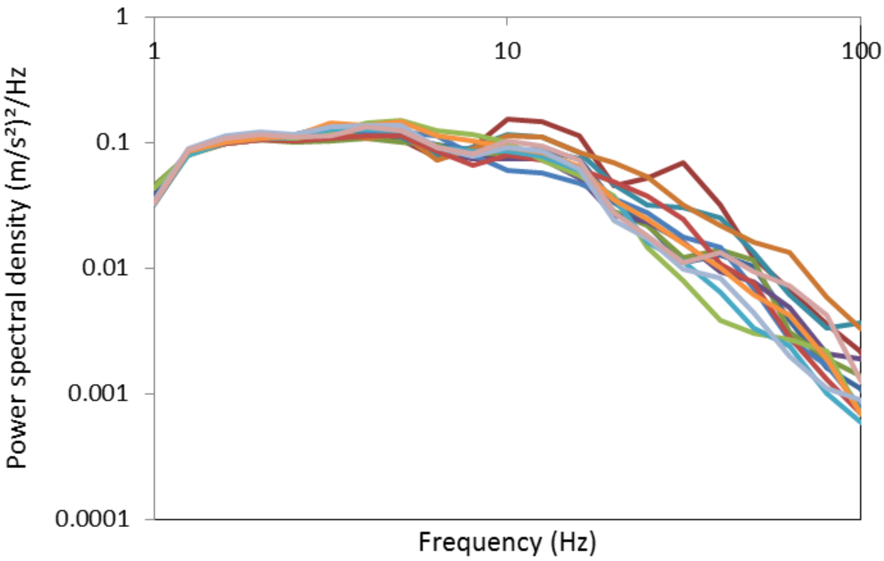


Figure 76 Weighted PSD of 0.5m/s² vibration, all subjects, z-axis

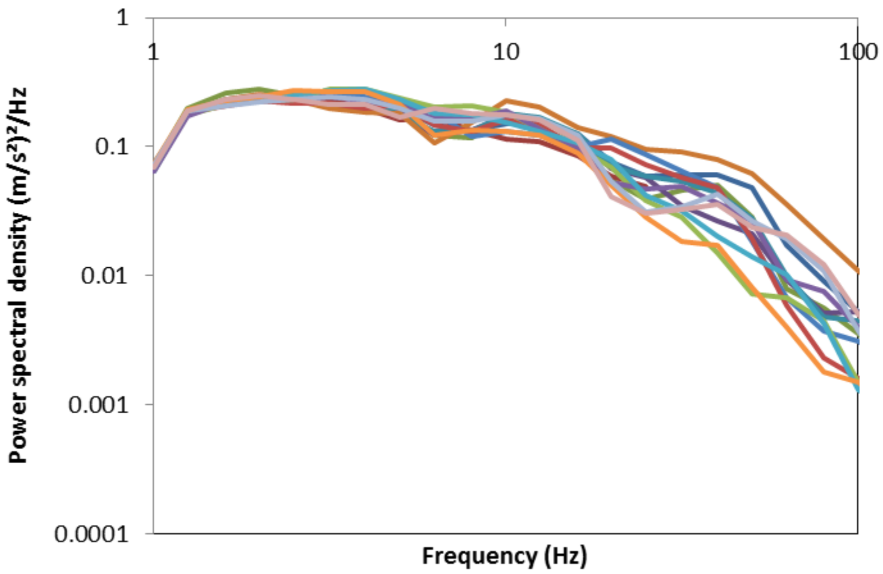
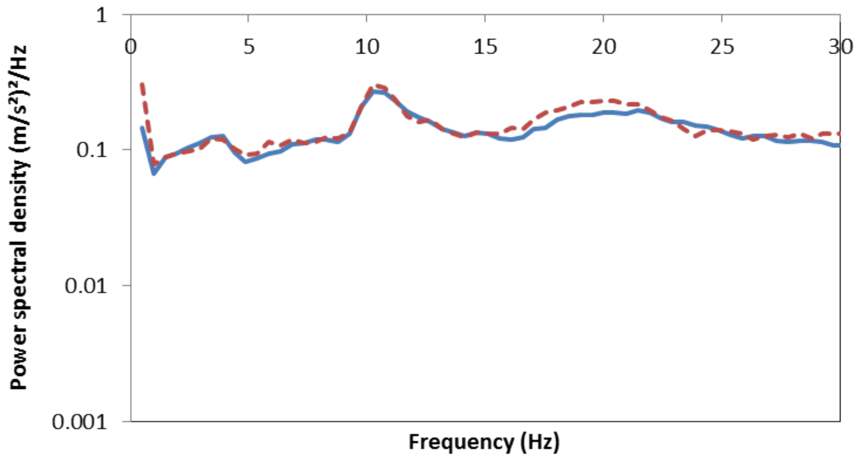


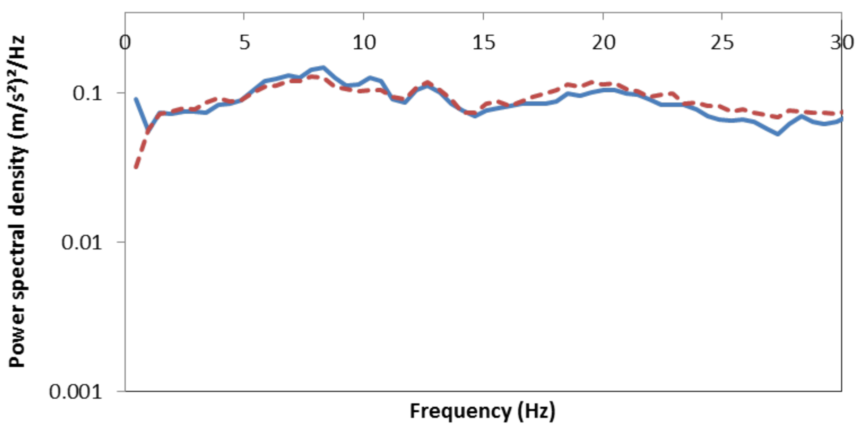
Figure 77 weighted PSD 1.0m/s² vibration, all subjects, z-axis

The vibration measured at the seat was reasonably unaffected by the posture of the subject, as illustrated in Figure 78 for the V1 vibration magnitude and Figure 79 for the V2 vibration magnitude. A typical PSD of the weighted vibration at the seat surface for the 2 posture conditions and the 2 vibration conditions is provided.

a)


1
0.1
0.01
0.001
0
5
10
15
20
25
30
Power spectral density (m/s²)²/Hz
Frequency (Hz)

b)


0.1
0.01
0.001
0
5
10
15
20
25
30
Power spectral density (m/s²)²/Hz
Frequency (Hz)

c)

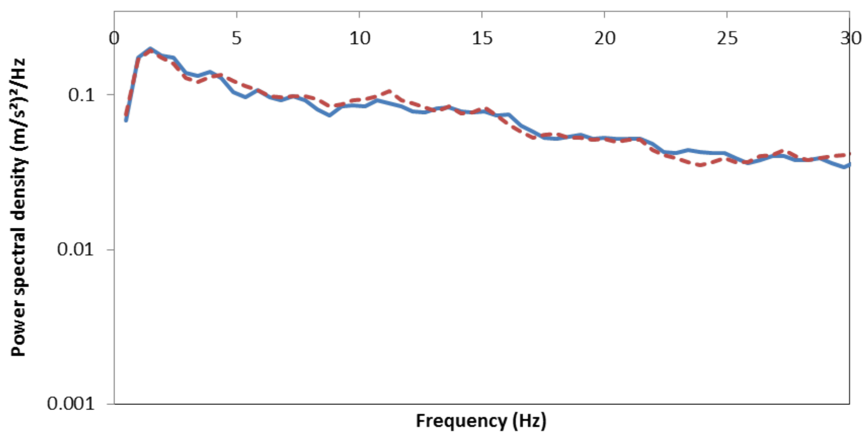
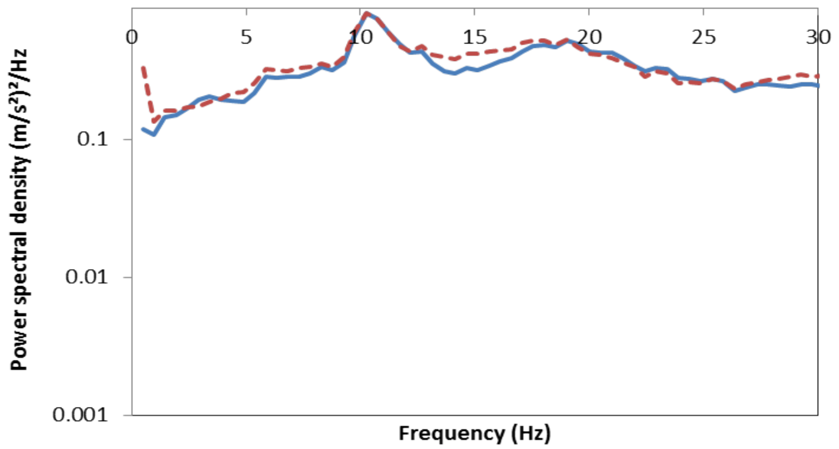
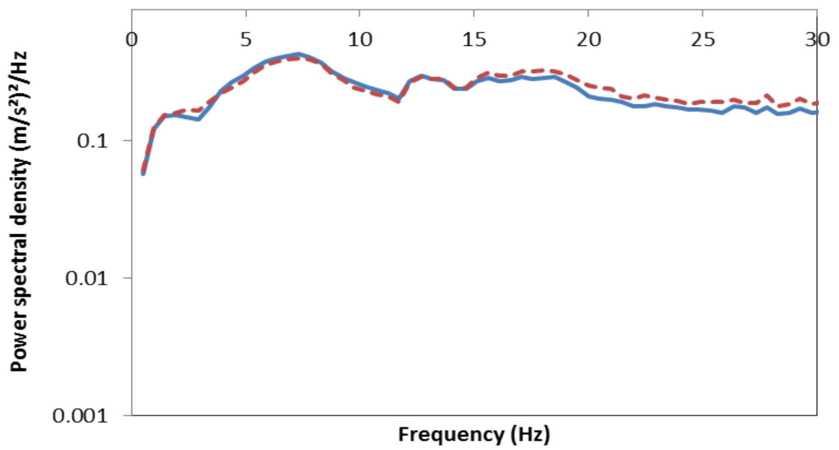

0.1
0.01
0.001
0
5
10
15
20
25
30
Power spectral density (m/s²)²/Hz
Frequency (Hz)

Figure 78 Typical weighted PSD of the P1V1 (unbroken line) and P2V1 (broken line) conditions in the a) x-, b) y-, and c) z-axis

a)



b)



c)

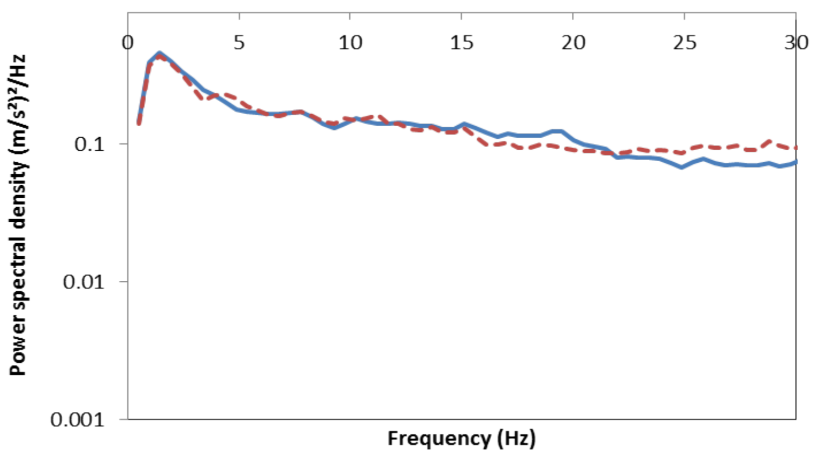


Figure 79 Typical un-weighted PSD of the P1V2 (unbroken line) and P2V2 (broken line)

conditions in the a) x-, b) y-, and c) z- axis

8.4.2 Subjective discomfort

The influence of condition on subjective discomfort are considered in the same way as within previous Chapters. Figure 80 below illustrates the median and the 25th and 75th percentile discomfort scores for the 5 test conditions.

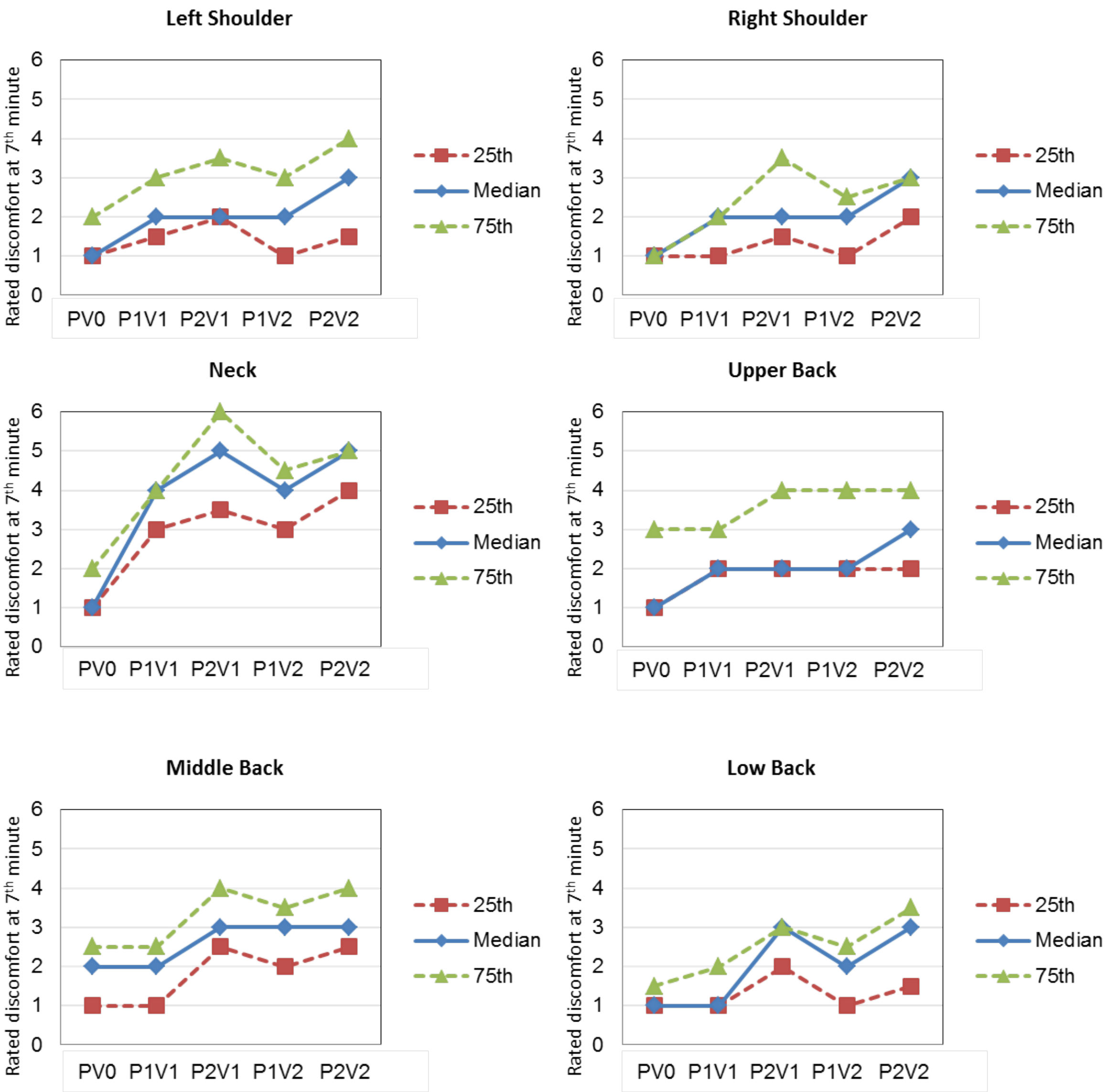


Figure 80 Influence of the 5 conditions on subjective discomfort after 7 minutes exposure

The neck is the region where the greatest amount of discomfort is felt across all body regions, with the 170° twist conditions causing the greatest levels of discomfort. The pattern of discomfort in the left and right shoulder are very similar with the greatest amount of median discomfort occurring in the P2V2 condition. The discomfort felt across the P1V1, P2V1 and P1V2 conditions are similar, with slightly more subjects increasing their rated discomfort in the P2V1 condition. The discomfort in the 7th minute in the upper back is similar in magnitude at each condition as the shoulders. The extra stress created by the P2 rotation level is represented in increased discomfort in the P2V1 and P2V2 conditions in the low back. Statistical analysis of the results was completed with a Wilcoxon paired comparison. This revealed significant differences between the rated discomfort between T1 (end of 1st minute) and T2 (end of 7th minute) were seen in all experimental conditions in all body parts aside from the right shoulder in the P1V1 condition.

Wikström (1993) considered the interaction between the two exposures (vibration and twist) and showed a greater difference between the conditions than is seen here in Figure 80. In general, the 170° twist posture has a greater discomfort effect, as does the higher vibration levels. In the low back, there is a notable distinction in the discomfort experienced whilst seated in the two postures and exposed to the lower vibration level.

8.4.3 Electromyography Results

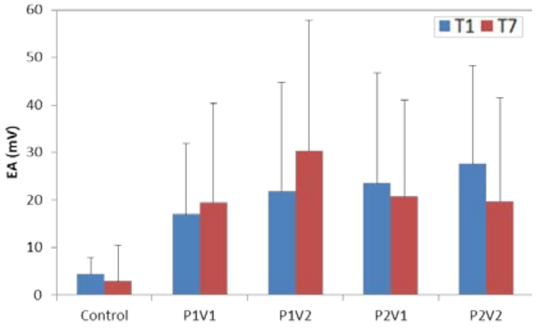
As before, the individual participant responses to the conditions are illustrated via the gradient of any parameter change over time. These are illustrated in the Appendix f).

8.4.3.1 Electrical Activity Analysis

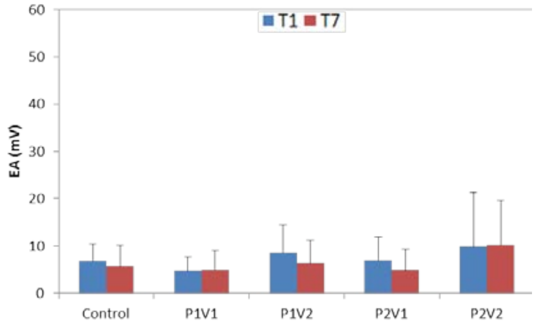
Again, considerable variation is seen in the data. There appears to be less variation in the muscles of the lower back in comparison to the shoulder and upper back muscles. In particular, the MF R appears to have very little variation from 0 in many of the experimental conditions.

Comparing the activity over the experimental durations also allows for a comparison between the muscle groups. Overall, the activity on the left musculature appears much greater than the right, with the exception of the TD. The muscle illustrating the greatest activity over the experimental conditions is the ES L. In all muscles, the control condition activity is low, and activity reduces over time (change not statistically significant). The results of comparison of 1st and 7th minute activity across the experimental conditions is provided in Figure 81.

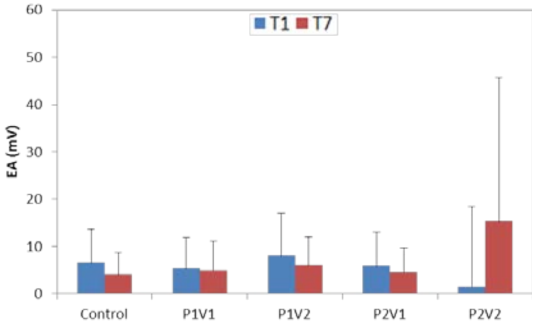
TD L



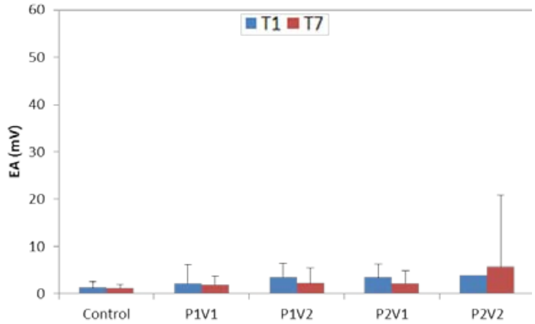
TD R



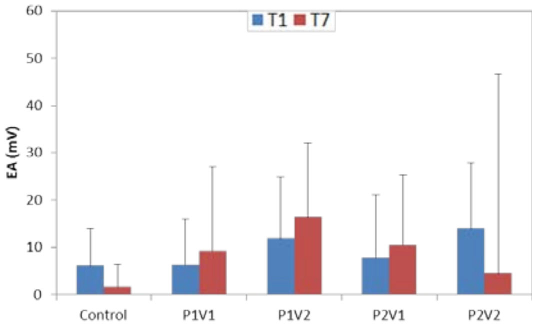
TA L



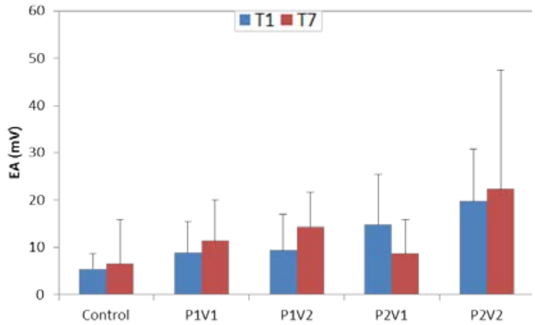
TA R



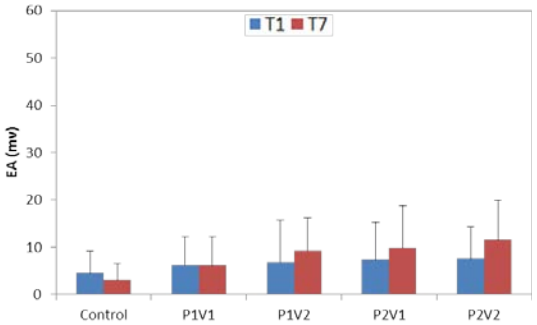
ES L



ES R



MF L



MF R

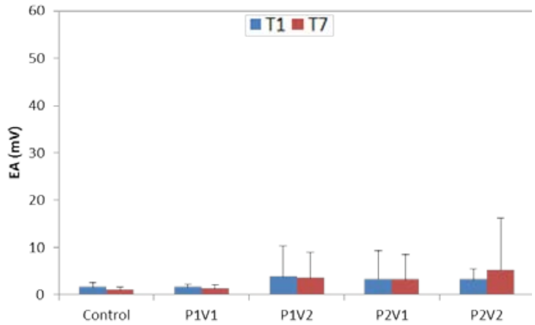


Figure 81 Mean EA at 1st and 7th minutes, error bars designate 1 standard deviation

A paired samples t-test was used to test for significance between the measured activities in the first (T1) and last (T2) minutes of investigation. The results are shown below in Table 24.

Table 24 Muscles exhibiting significant increases in activity from T1 to T2 (P<0.05)

Condition	Muscles exhibiting significant increases in EA
Control	None
P1V1	None
P1V2	ES R, MF L
P2V1	ES L, MF L
P2V2	TA L, MF L, MF R

The number of muscles, and therefore areas of the back, affected by increasing activity increases with increasing twist and WBV. It is interesting to note the addition of the TA L in the P2V2 condition, as only the ES and MF had been affected in the other conditions. There appears to be more of an effect on the left side, which is ipsilateral to the direction of rotation. Other authors have reported similar findings (McGill, 2001).

Considering the mean activity across the conditions can be helpful in indicating the final response of the muscles, not affected by the time-related changes. Presented below in Figures 82 and 83 are the results of that analysis for the muscles investigated here.

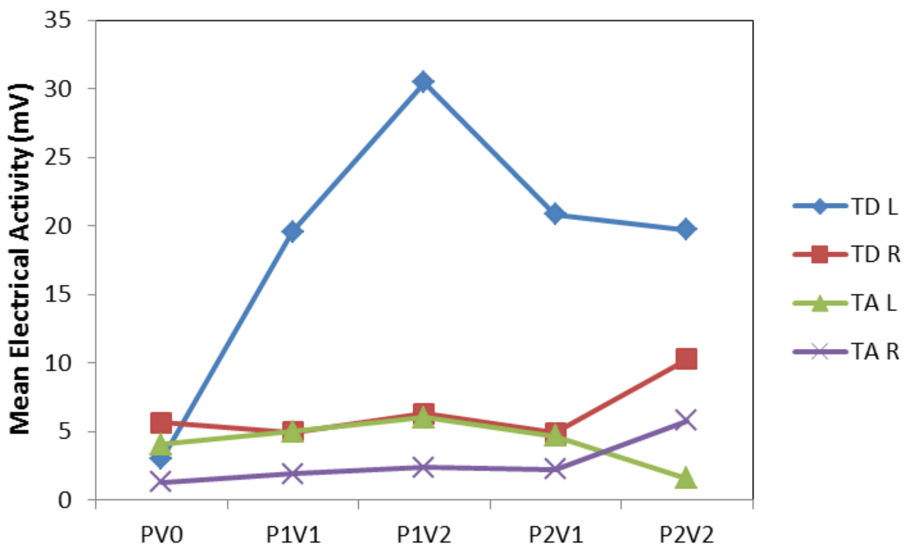


Figure 82 Mean EA across conditions (TD and TA)

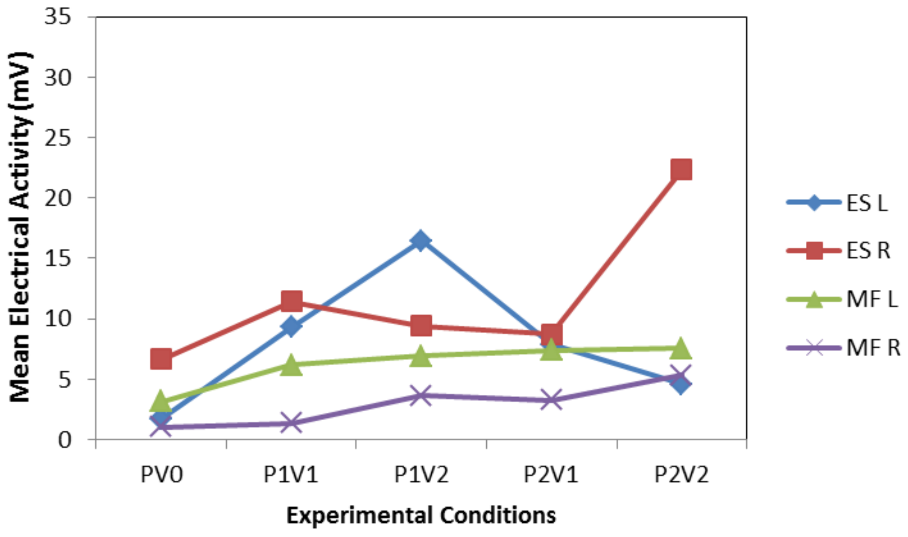


Figure 83 Mean EA across conditions (ES and MF)

The TD L has increased activity in comparison to the other muscles investigated, particularly in the case of the P1V2 condition. We can see though from the fatigue indications that although there was this increased activity, this did not manifest in muscular fatigue. The MF L and R show increasing levels of activity across the conditions, and do exhibit fatigue in the three latter conditions. The peak in the ES L activity in the P1V2 condition correlates to the indications of muscular fatigue with the statistical analysis of changes over time.

8.4.3.2 Mean Power Frequency Analysis

There are clearly a number of muscles with a negative gradient in the experimental conditions. This indicates that their muscles shifted to the lower frequency firing rates during the conditions, therefore signifying fatigue. However, the data also illustrates there are also a number of subjects whose muscles did not respond in this way.

Analysing for changes over time illustrates that there is little difference between T1 and T7 in each of the muscles investigates. It is clear that the muscles responding at the higher frequencies are the TA L and R.

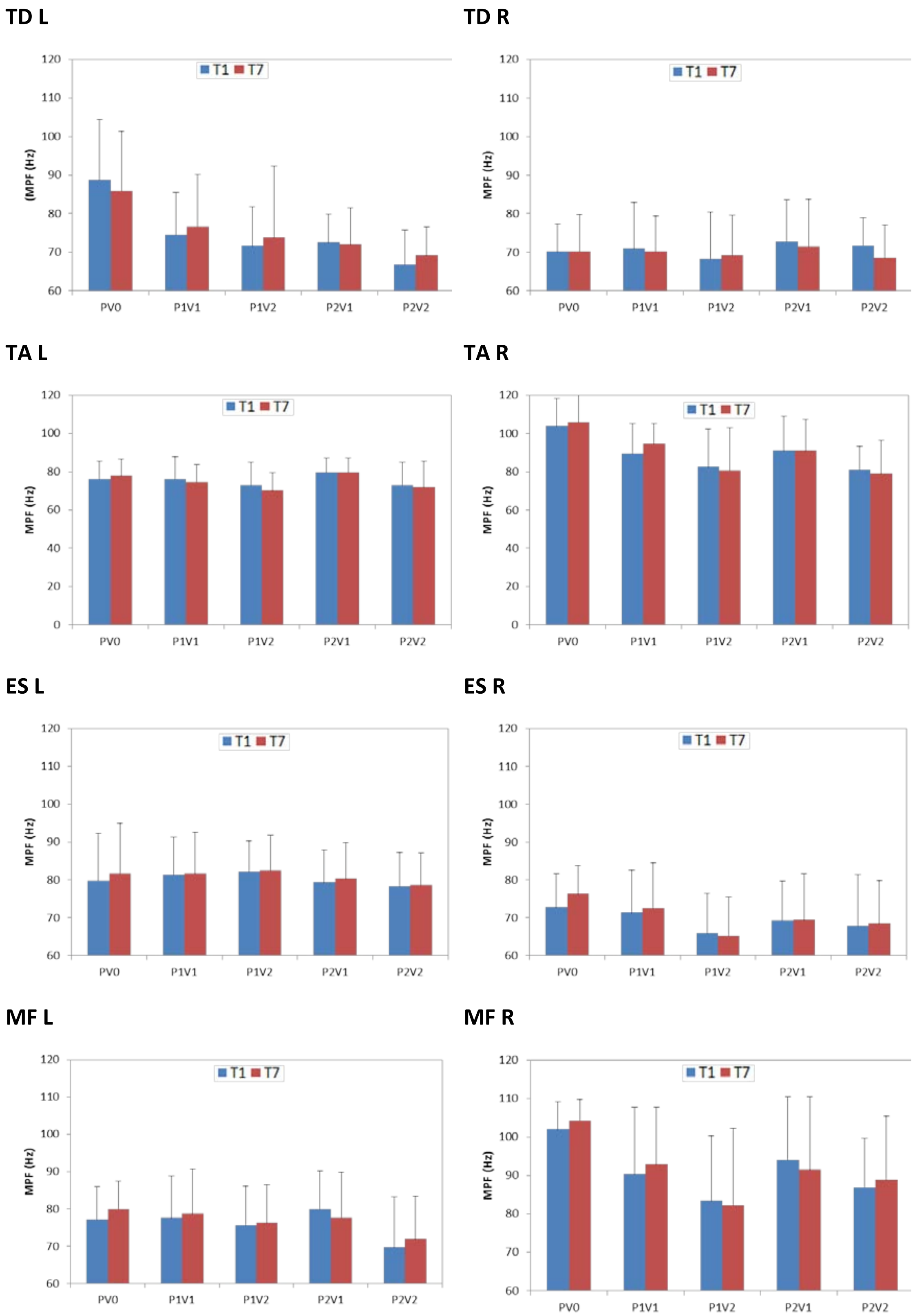


Figure 84 Mean MPF at 1st minute and 7th minute, error bars designate 1 standard deviation

Analysing for changes over time revealed there were no significant changes in the MPF over the 7 minutes in any of the experimental conditions.

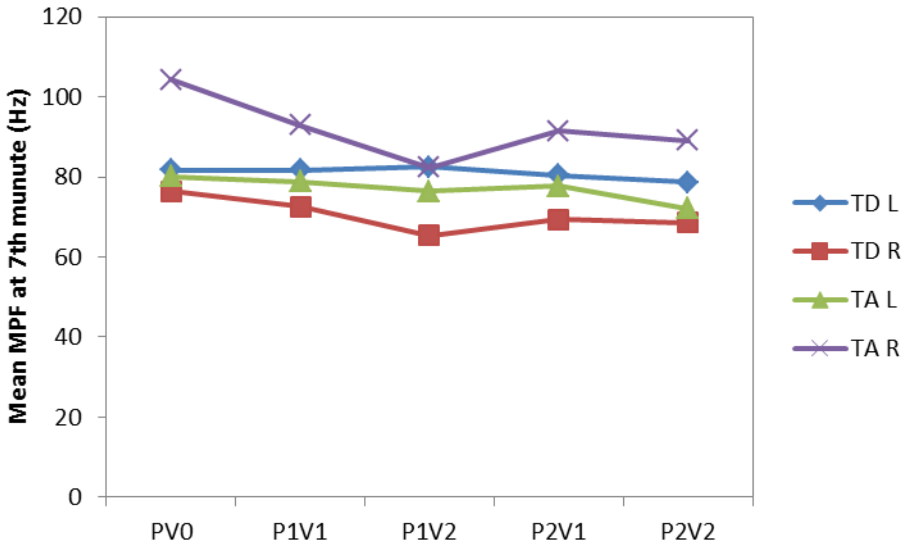


Figure 85 Mean MPF across conditions (TD and TA)

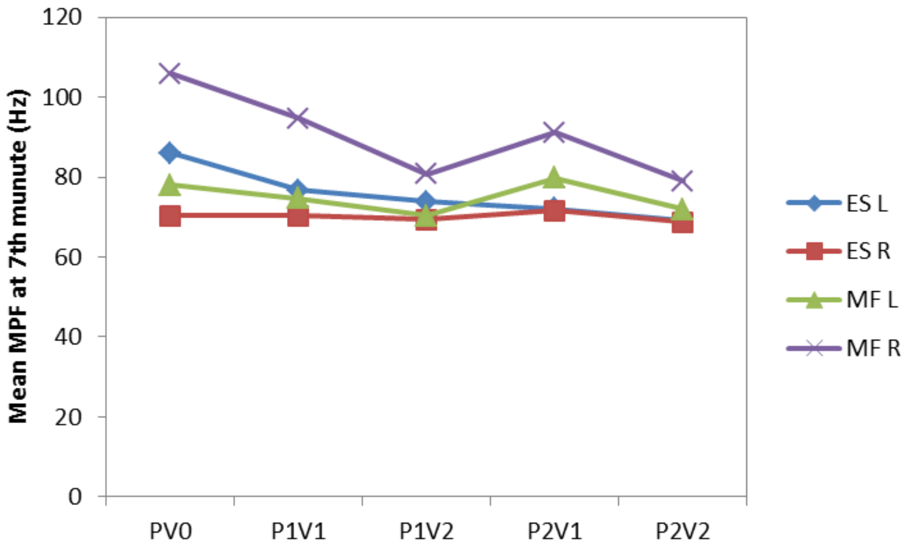


Figure 86 Mean MPF across conditions (ES and MF)

Figures 85 and 86 illustrate that although there were no significant differences over time, the overall responses of the individual muscles was quite similar. The decline in frequency over the conditions illustrates the different effects of the conditions, despite the conditions themselves not causing a shift during the time investigated.

8.4.4 Posture

The postures of the subjects were recorded with the CUELA measurement system. Between the P1 conditions, there were no significant differences between the attained rotation in either the cervical or trunk region. However, there was a significant difference between the trunk rotation between the P2 conditions. This did not result in a significant difference between the total attained conditions however.

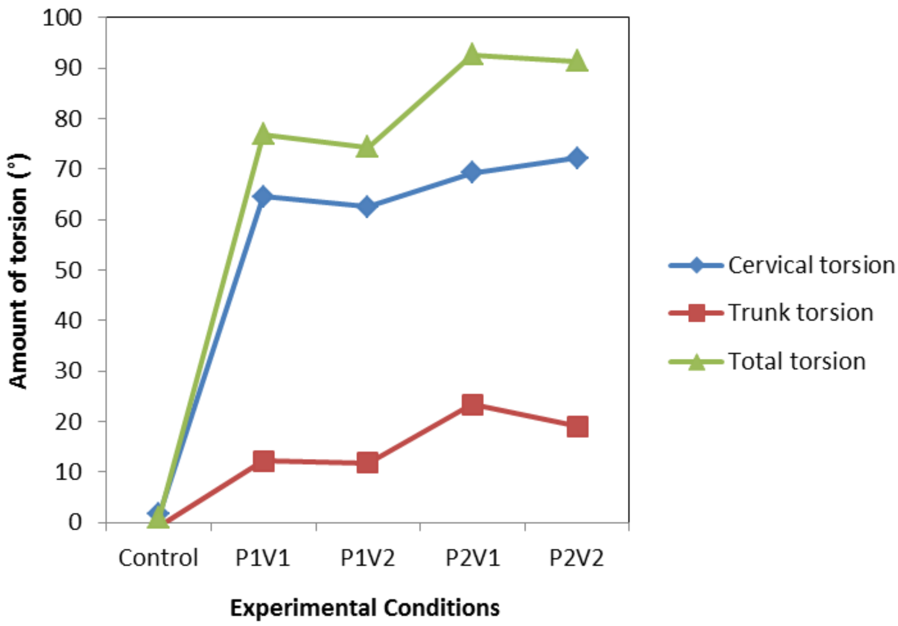


Figure 87 Mean rotation magnitudes across the 5 conditions, from CUELA measurement system

The majority of the torsion was achieved through the cervical portion of the spine. The greater contribution of the trunk torsion to the total torsion in the 170° twist conditions is similar to that found in the previous study (Chapter 6).

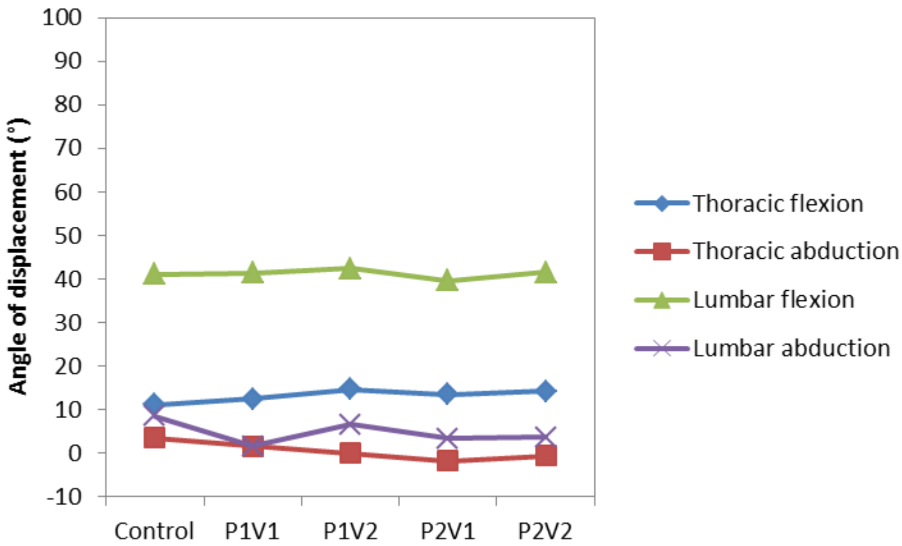


Figure 88 Lateral and forward flexion in the thoracic and lumbar spines

The data from the CUELA measurement system also allows the measurement of other factors in addition to the rotation. The results for each condition are illustrated in Figure 88. The high levels of lumbar flexion reflect the fact that the initial 'zeroing' of the sensors was completed whilst the subject was standing, and therefore although it appears that the subjects were flexing forwards, they were sitting upright. This was confirmed with inspection of the video of the subjects.

8.5 Discussion

As discussed in the introduction, evidence from epidemiologic studies suggests an increased risk for LBP when operators are simultaneously exposed WBV and trunk rotation (Kittusamy and Bucholz, 2004). Further to, an interaction of the variables may increase the risk (Okunribido et al., 2008). The biomechanical evidence base for the effects of dual exposures is less well defined (Seidel, 1993).

In general, increases in discomfort were seen in the experimental conditions in comparison to the control. In particular, as the level of trunk rotation increased, the increase in discomfort in the neck and low back were clear. The conditions requiring 170° twist caused the most discomfort, with the addition of the higher vibration magnitude further increasing discomfort in the cases of the shoulders, upper and lower back. Other researchers have also found that the level of rated discomfort increases when both stressors are experienced together (Wikström 1993; Zimmermann and Cook 1997). The levels of rated discomfort in this study are comparable to those reported in previous research (Wikstrom, 1993), in that the ratings were 50-75% of the maximum possible rating. The increased risk of LBP when exposed to both trunk rotation and WBV has been presented in the literature (Hoy et al., 2005; Pope et al., 1999). This study illustrates that the rated discomfort in the low back did increase when exposed to both stressors, however greater levels of rated discomfort were reported in the neck. The inter-subject variability was low, and subjects followed the same trend amongst conditions. The maximum discomfort was only reached by a few subjects in the P1V2 condition. It is interesting to note that this is less than the maximum discomfort reached in the investigations in Chapter 6, when subjects were rotated without vibration. This is in contrast to the findings reported by Wikstrom (1993), where there was less self-reported discomfort in the conditions without vibration in comparison. One possible explanation for this discrepancy is a potential difference in the discomfort threshold between the two groups of subjects. Alternatively, the exposure time was 7 minutes in this study in comparison to the 10 minutes exposure in Chapter 6. This may mean that the rated discomfort would have increased to exceed the levels seen in Chapter 6. More consideration will be given to this in the discussion section of the thesis, Chapter 9.

The number of muscles with a statistically significant increase in fatigue parameters increased when the magnitude of the exposures increased. When one of the exposures was at the higher level (P1V2 or P2V1), the fatigue was limited to the ES and MF. However, when both exposures were at the higher magnitudes (P2V2) then fatigue was also seen the TA. Other authors have also shown muscular fatigue in the ES when subjects are exposed to both rotation and vibration (Wikstrom, 1993). Both Kumar (1996) and Toren (2001) showed that the ES activity was reduced at the end of the range of motion. The rotation in the trunk in this study is comparable to those in the previous studies, however, increases over time in the ES were found in this study. The other muscles studied here are not normally considered in trunk rotation studies, as they are not classically thought to contribute to the rotation. However, as discussed earlier in the thesis, these muscles are considered for the investigation of vibration response, or are the areas of discomfort development. The MF and ES are both fatigued in the conditions where one, or both, of the stressors are at the higher level. This is indicative of the areas of risk increase for LBP reported in the literature. Although the neck is the area of greatest reported discomfort, the closest investigated muscles, the TD, do not exhibit fatigue in any of the conditions.

The vibration exposure did induce both discomfort and fatigue but overall discomfort was greater in the conditions with the higher twist component, irrespective of vibration magnitude. It is not suggested that the vibration magnitudes investigated here are comparable to the twist magnitudes, but both are representative of those experienced by operators in agriculture. The area affected by muscular fatigue was broadened when both stressors were at the highest values in this investigation. The upper limits of possible trunk rotation magnitude are explored in this thesis; however there are theoretically unlimited magnitudes of vibration exposure, of which a limited range are explored here.

The postures of the subjects measured by the CUELA measurement system did not reach either of the target rotations set in the methodology. However, it is considered that the true rotation of the subjects was much greater than what is depicted in Figure 87. The video recordings of the subjects during the experiment can be paused and postural analysis completed. When this is done, the levels of rotation attained by the subjects may not be at the full levels desired, however, from personal observations during the trials, they are similar to those attained in the Chapter 6. An illustration of this is provided in Figure 89, although the position the photographs are taken from are differing, it is possible to see that the levels of rotation are actually very similar.

Figure 89 Typical P2 axial rotations from Chapter 6 and Chapter 8

8.6 Conclusions

Two out of the three hypotheses were accepted. It can therefore be concluded that discomfort increases with an increase in exposure magnitudes. Subjects experienced muscular fatigue when exposed to either high vibration and low twist (P1V2); high twist and low vibration (P2V1); or both (P2V2). 170° trunk rotation has a greater effect on subjective discomfort ratings than 1.0m/s^2 r.m.s. However, differences are not seen in the number or location of fatigued muscles when exposed.

H_1 Discomfort, assessed subjectively, will increase as both the trunk rotation and vibration exposure increase

In general, increases in discomfort were seen in all experimental conditions from the control. Discomfort was greatest in the neck and low back in conditions including 170° rotation.

H_2 More muscles will be affected by fatigue, assessed by muscle activity, when exposed to both stressors

The number of muscles with a statistically significant increase in fatigue parameters increased when the magnitude of the exposures increased. When one of the exposures was at the higher level (P1V2 or P2V1), the fatigue was limited to the ES and MF. However, when both exposures were at the higher magnitudes (P2V2) then fatigue was also seen the

TA

H_3 More muscles will be affected by fatigue, assessed by spectral shift, when exposed to both stressors

There were no significant frequency changes in any muscle, in any condition.

H_4 Trunk rotation has a greater effect than vibration on the development of subjective discomfort, based upon the combined results of Chapters 6 and 7.

The conditions requiring 170° twist caused the most discomfort, with the addition of the higher vibration magnitude further increasing discomfort in the cases of the shoulders, upper and lower back.

H_5 Trunk rotation has a greater effect than vibration on the development of muscular fatigue, based upon the combined results of Chapters 6 and 7

Neither exposure appeared to have a greater effect, with the same number of muscles exhibiting fatigue when either exposure parameter was at the higher level.

CHAPTER 9: The effect of twisting motion on subjective discomfort and muscle fatigue: the use of a twisting seat base to reduce discomfort and muscular response

9.1 Introduction

Within the agricultural driving environment, the requirement for axial rotation is well acknowledged and has been investigated in the previous experimental Chapters. However, tasks often require both fore- and rearward attention which inevitably results in trunk motion. This is both motion between the extremes i.e. fore- to rearward, and stages in between. Some tasks are associated with greater frequency of rotations than others (see Chapter 4). With faster machines and greater output, there is increasing pressure on the operator to sustain this. Therefore, a greater understanding of how such exposures may affect the trunk biomechanics is required.

Traditionally, most biomechanical assessments of working postures have been limited to the static nature of the work (Marras et al., 1995). Some previous investigation of dynamic twisting been done mostly, but not exclusively by Marras and colleagues. In the later studies, Marras et al. (1993; 1995) reported odds ratios (comparing high to low risk) for trunk twisting velocity on the job between 1.09-1.66 respectively. These risk estimates are not truly representative of seated postures, as these are studies were completed with standing postures. High values of combined trunk velocities (e.g. simultaneous lateral flexion and twisting velocities) have been found to occur more frequently in jobs judged to be of high and medium risk than those of low risk (Fathallah et al., 1998). It not unreasonable to assume therefore that dynamic motion plays a role in the development of LBP. This role may be major when the motion occurs in multiple planes simultaneously (Davis and Marras, 2000). Trunk strength has been observed to be reduced by 15-80% during dynamic twisting in comparison to isometric twisting Marras et al. (1997).

EMG studies of dynamic twisting have found varied increases in agonist activity, from 56 to 157% (Marras and Granata, 1995; Marras et al., 1998). Conversely, other authors have found no increase in agonist activity, McGill (1992). Antagonist activity appears to follow similar trends in that varied increases (6-252%) were found by Marras and colleagues

(1995, 1998) and yet no increase was found by McGill (1992). In the study by Marras (1995) the mean twist was only 15° to the right, and 2° to the left, which are less than those commonly seen in agricultural driving tasks (Chapter 4) and therefore proposed for investigation here. The study also focused on manual handling tasks, which, although not specifically stated in the paper, it is assumed are completed whilst standing.

Trunk motion impacts the musculoskeletal system by altering the recruiting patterns of the trunk muscles (Davis and Marras, 2000). The total range of motion has been investigated, it was found that trunk activity levels are low up 20° rotation either side of the forward facing neutral (Toren, 2001). Decreases in strength capacity during dynamic exertions suggest that more muscle force would be required to respond to the external load demands. In most cases, the activity of the agonistic muscles as well as the antagonistic muscles increased during dynamic motions. This gives the indication that there is not only more activity in the primary force generating muscles, but also more overall coactivity of the trunk musculature in general.

The literature discussed here, focusing specifically on dynamic rotations do not include details of subjective discomfort. However, it is known that dynamic rotations make up a large component of many of the tasks investigated in the previous studies of this thesis. It is fair to consider the conclusions of these studies on discomfort in comparison to those under investigation here.

Many of the studies focusing on dynamic trunk rotation have been developed for analysis of lifting, and therefore look at trunk rotation in association with flexion, and also with a load applied. Discomfort development in these instances cannot be applied to the very different circumstance of dynamic twisting whilst seated and exposed to vibration. In fact, very few studies have solely considered the effect of dynamic twisting (Davis and Marras, 2000), and to the authors knowledge, none have considered these with the addition of WBV.

A high incidence of back injuries, sprains and strains of the musculature are known to occur in both professional and amateur golfers (Hosea et al., 1990; Gluck et al., 2008), this is often put down to the golf swing, where the trunk is rotated rapidly. Although this is suggested to be greater velocity of rotation and completed in a standing posture, it is worth considering that the results of such repeated movements may be similar to the results of the exposures proposed for study here.

It is apparent from the literature, the survey of expert opinion and the field study that a rotating seat base has become common place in many tractor cabs. It was felt important to consider the effect of this development on the conclusions of the current study. Bottoms and Barber (1978) investigated the use of a rotating seat to reduce the operator discomfort when completing tasks with a high twist component. The seat under investigation rotated 20° from the neutral, the main conclusions from the study were positive, with a reduction in the overall twist, decrease in neck and shoulder muscle activity in comparison to a static seat. In the other study investigating seat base rotation (Bottoms and Barber, 1978), the postures held by the operators were static, although contrary to this study the authors tilted the vibration platform by 10° to simulate a ploughing task (where two of the tractor wheels will be in the furrow, two resting on the unploughed ground). In addition, long duration studies (6-12 months) with 3 farms revealed favourable subjective judgments of discomfort reduction.

9.2 Aims and Hypothesis

The literature suggests a need for the investigation of dynamic trunk rotations, particularly whilst exposed to WBV. Therefore, this study will use EMG and subjective discomfort scoring to assess subject's responses to such rotations. In addition, the seat base will be rotated to set positions to evaluate the value of such an addition.

H_1 Discomfort, assessed subjectively, will be greater when the subject is rotating than when they are seated in a neutral forward facing posture.

H_2 Fatigue will be exhibited in the dynamic rotation conditions (Marras et al., 1995, 1998)

H_3 Evidence of muscular fatigue and discomfort will show a decrease in conditions where the seat base is rotated, so that the maximum required trunk rotation is reduced (Bottoms and Barber, 1978)

9.3 Methods

The dependent variables for this laboratory experiment remain the same as for the previous laboratory study (Chapter 8). The effect of the exposures described below will be determined with the use of EMG fatigue analysis and subjective ratings of discomfort. These methods have been described in greater detail in Chapter 3, Experimental Methodologies. However, the independent variables have changed, and are described in detail below.

9.3.1 Trunk motion

The dynamic rotation exposure was developed from the results of Chapter 4, the field study. It was found that some tasks consisted of greater requirements for rotations than others, as expected. Therefore, the mean numbers of rotations from the tasks studied were taken to form the basis of the experimental setup. This resulted in a between 5-8 rotations per minute, with postures held for between 6 and 15 seconds. In addition, it became apparent, that in addition to the 0°, 110° and 170° of rotation, other levels of rotation were also a component of the tasks, namely 30° and 90°.

Previous dynamic trunk rotation studies have either used an axial rotation tester (AROT) (Kumar et al., 1996) or a twisting reference plane (Marras et al., 1998; Marras and Mirka, 1990; McGill, 1991). It was necessary to consider the un-resisted levels of muscle activity and therefore, in line with previous studies within this thesis, the subject was free to determine how they attained the rotation. The posture of the subject was measured with the CUELA system, described in more detail in Chapter 8, Section 8.3.1.

In previous studies, subjects have been provided with visual target rotations displayed on a screen (Marras and Mirka, 1990; Kumar and Narayan, 1999) and physical targets (McGill, 1991). Clinical trials have placed visual targets for direction of rotation around the subject (Schenkman et al., 1995). From the previous studies within this thesis, it has become clear that the visual target may have been a little large to accurately direct the rotation. Therefore it was decided that for this study LEDs were mounted around the subject to direct rotation. The lights were programmed to light up in configuration to replicate the tasks studied in Chapter 4. A diagram of the setup is illustrated in Figure 90.

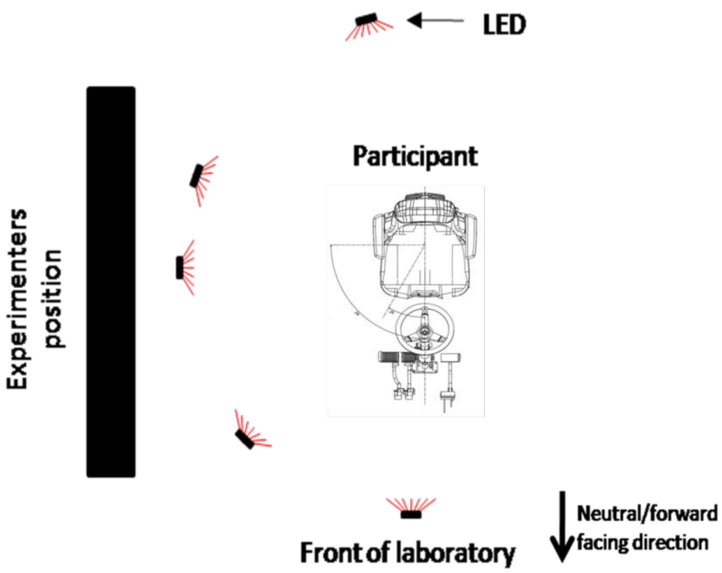


Figure 90 Diagrammatic of light positions within the laboratory

A typical example of a subject seated with the seat base rotation at 30° is provided in Figure 91. The light at 110° can be seen in the image, as can the CUELA system applied to the subject. The backrest height on this seat is lower than that used in the previous studies, and is typical of that used in agricultural vehicles. The steering wheel and pedals were mounted in the same position as in the previous studies.

Figure 91 Subject with seat base rotated at 0°, with 170° target light activated

The program to run the lights was written within DasyLab (v.10, Adept Scientific). This program detailed which light would illuminate and how long the light would remain illuminated (A text file of the program is included in the Appendix c). Each light had equal representation in the 7 minutes experiment duration. The sequence was optimised so that the operator was required to often switch between fore and rear facing postures to replicate scenarios often seen in agriculture. The lights were mounted 1.8m off the floor, eye height for subjects seated in the chair on the lab. The lights were all 2m away from the subject whilst seated in the chair.

9.3.2 Seat base rotation

Subjects were seated on a Grammer suspension seat, which was capable of rotating on its base. The effect of seat base rotation was an additional independent variable in the experiment. The seat was capable of being locked in three positions, 0°, neutral facing forward; 30° to the right and 90° to the right. The three settings for seat base rotation are illustrated below in Figure 92.

Participants were free to determine how they achieved the rotation (wholly trunk, neck or both) although a foot and a hand were required to be placed on the pedals and steering wheel at all times, to simulate a driving scenario, the instruction was given that they must be seated as if they were in control of the mock-vehicle at all times.

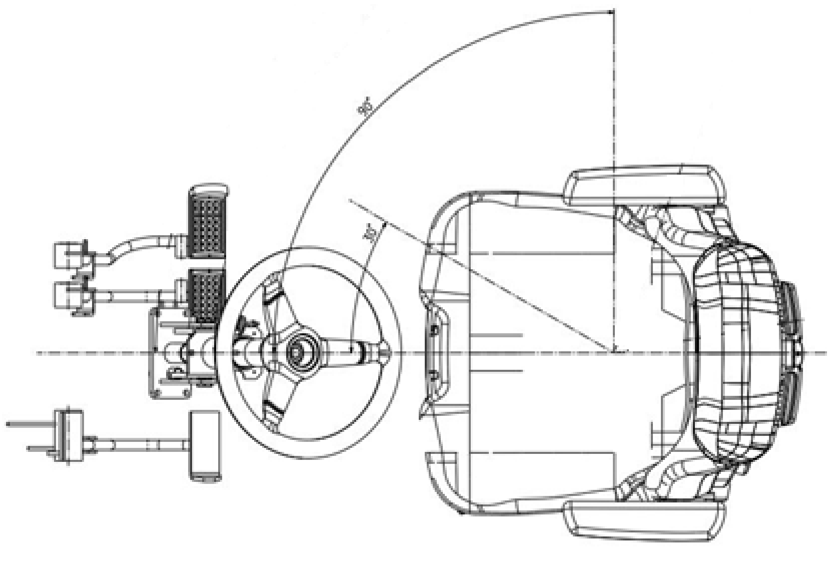


Figure 92 Schematic of available seat rotations, provided by the seat manufacturer

The seat base was locked at the chosen rotation for the duration of each trial. In discussions with operators, many noted that once the seat base was rotated, they did not return the seat to forward facing for periods of travel, therefore the effect of forward facing driving whilst seat base is rotated is also investigated. Due to restrictions on time, and considering the accumulation of stress applied to the back muscles, no investigation of forward facing driving whilst seat base rotated at 90° was included. The vibration used in all experimental conditions was $0.5m/s^2$, which was the lower level used in the other experiments.

This results in 6 exposure combinations:

- 0° seat base rotation, static forward facing, no vibration(Control)
- 0° seat base rotation, static forward facing, with vibration (SB0:P0)
- 0° seat base rotation, moving rotation, with vibration (SB0:Pmov)
- 30° seat base rotation, static forward facing, with vibration (SB30:P0)
- 30° seat base rotation, moving rotation, with vibration (SB30:Pmov)
- 90° seat base rotation, moving rotation, with vibration (SB90:Pmov)

9.3.3 Dependent variables

The posture of the subject is measured using the CUELA measurement system. The methodology involved in the use of CUELA is outlined in more detail in Chapter 8. Briefly, CUELA is a system of goniometers and gyroscopes that attach to the subject and record the subject's posture. This data is recorded on a datalogger which can be transferred to a computer for analysis.

EMG measures of muscle fatigue and subjective ratings of discomfort are collected in-line with the previous laboratory studies outlined in this thesis. For a detailed methodology, please refer to Chapter 3, Experimental Methodologies. The duration for each exposure was kept at 7 minutes in line with the previous study, Chapter 8. This was chosen to allow the recovery time to be limited to <10 minutes (Lariviere et al., 2003) and therefore allowing a same-day repeated measures design to be employed increasing the reliability of the EMG results. In the expert opinion survey and field studies, it had become apparent that operators also felt discomfort in the buttocks and thighs under these exposures. Therefore, these body regions were added to the Porter's body map. Subjects are therefore required to score discomfort for the left and right buttocks and left and right thighs in addition to the previous body parts.

The analysis of the EMG and subjective data is analysed as with the previous laboratory studies. This involves time domain analysis of both the electrical and spectral parameters of the EMG, and also the subjective ratings of discomfort, provided every 60s. EMG cannot easily be compared while the muscle is moving, due to the effect of changing fibre length on the measured frequency content of the muscle activity. Therefore at commencement of measurement the EMG measurement is synced with the CUELA measurement. This allows periods of the same posture (i.e. when the operator is looking at a specific light) to be compared. The methodology employed here is similar to the method of using test contractions (Hägg et al., 1987; Hägg, 1991), although here the 'test contraction' is part of the work phase. The CUELA analysis will allow the posture with the least deviation between start posture and end posture to be identified and then this may be used as the test contraction for the EMG analysis.

The procedure followed in the experiments is outlined below:

1. Participant provided with information sheet and completes health screen questionnaire and informed consent form
2. Height, weight, age and gender data captured
3. Electrodes applied (following protocol outlined in Section 3.3.1)
4. CUELA system applied and normalised
5. Participant reminded of instructions and right to withdraw and seated in chair
6. Chair adjusted to appropriate level of rotation
7. Light program commenced
8. Vibration commenced (if applicable)
9. EMG start synced with subjective and EMG
10. 6 conditions are completed (with 10 minute break)
11. Subjective scores recorded online throughout
12. Participant removed from seat, debriefed and thanked for participation
13. EMG data downloaded from logger, coded and saved
14. Posture data downloaded from logger, coded and saved
15. EMG sensors cleaned and lab prepared for next participant

9.4 Results

9.4.1 Subjects

Subjects were recruited from the staff and student cohort at Loughborough University. Participants comprised healthy males and females (Table 25) who were screened for a history of back problems, those with a history were excluded. Volunteers completed informed consent forms before commencement of experiment. Subjects were not paid for their participation.

Table 25 Demographic data of experimental sample (Values are presented as mean ±standard deviation (range))

	N	Age (yr)	Height	Weight
Male	4	22.5 ±3.7 (17-25)	1.8 ±0.1 (1.8-1.9)	75.8 ±11.3 (63.2-86.6)
Female	10	20.3 ±2.2 (19-23)	1.7 ± 0.1 (1.6-1.7)	59.8 ±5.0 (50.5-68.0)
Total	14	20.9 ±2.7 (17-25)	1.7 ±0.1 (1.6-1.9)	64.7 ±10.4 (50.5-86.6)

9.4.2 Vibration

System characterization was carried out to ensure that the vibration profile on the seat surface was as similar as possible to that on the previous seats' surface. Due to the 10% tolerance set on the seat vibration, one of the original subjects is omitted from the remainder of the analysis. The vibration on the seat for the 13 remaining subjects was within 10% for all experimental conditions. Therefore a PSD of the vibration at the seat during only one condition, for all subjects is shown below.

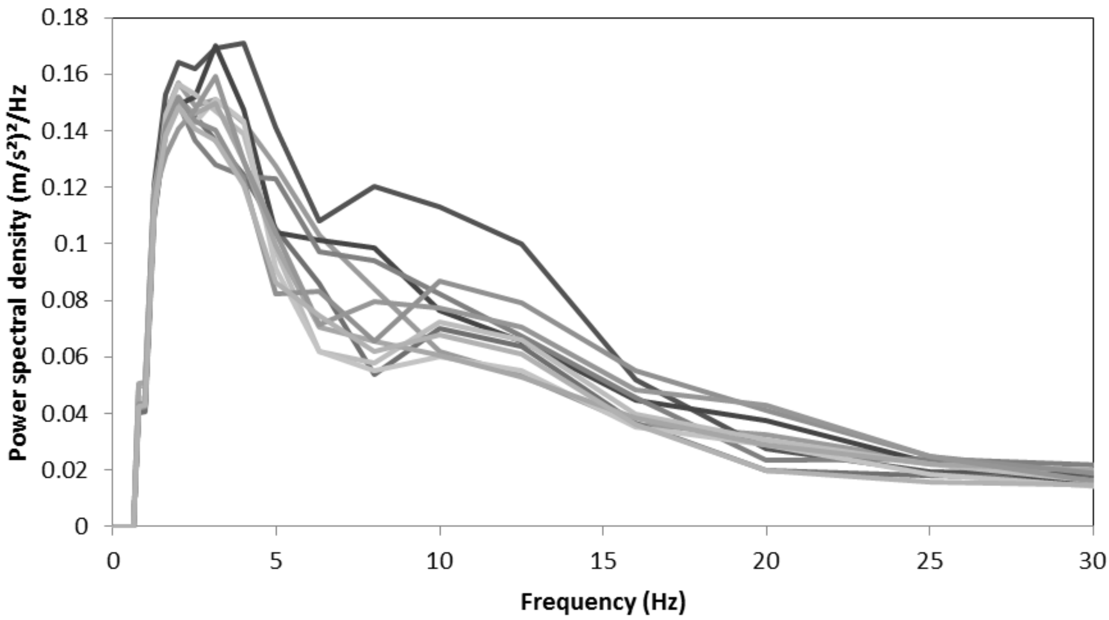


Figure 93 Weighted PSD (z-axis) at the seat for SB0:P0 condition, all participants

The vibration at the seat, was therefore 0.31x (±0.01), 0.21y (±0.01) and 0.44z (±0.06) m/s^2 r.m.s.

9.4.3 Posture

Due to some corruption within the CUELA measurement system, a further 3 participants had to be excluded from the analysis. The method of torsion measurement had defaulted to the extreme position and therefore no measures of cervical or trunk torsion could be obtained from the sensors. The graphs below illustrate the level of cervical, trunk and total rotation when participants are rotated to focus on the specific lights. These are shown for the differing levels of seat base rotation.

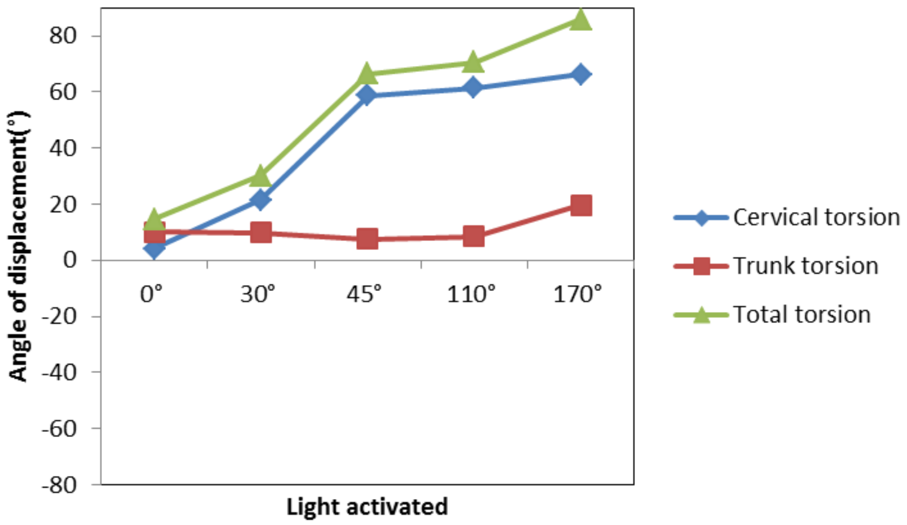


Figure 94 Angle of rotation when seat base was 0° rotated

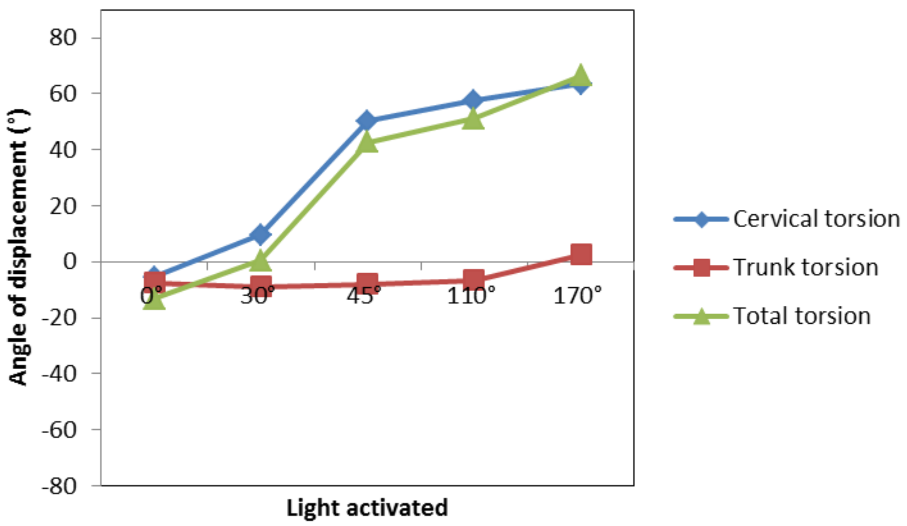


Figure 95 Angle of rotation when seat base was 30° rotated

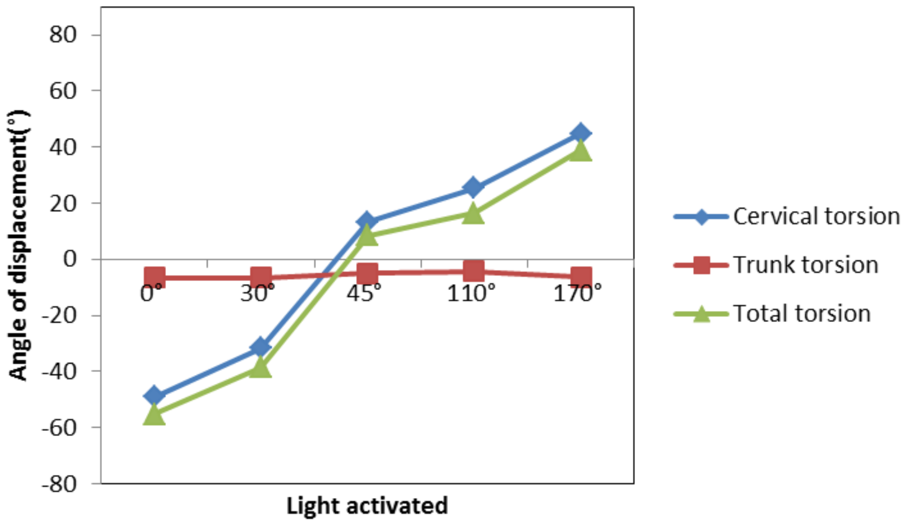


Figure 96 Angle of rotation when seat base was 90° rotated

The trunk contributes less to achieve the rotation in the conditions where the seat base is rotated, in both the 30° and 90° seat base rotations. The seat base rotation also reduces the amount of rotation required to focus on the targets. With 90° seat base rotation, the rotation to the rear (positive on the graphs) and to the front (negative on the graphs) are equal therefore suggesting that although there was a requirement to maintain control of the vehicle, the upper body posture was dictated by the seat more than the pedal and steering wheel placement. Figure 97 displays the levels of rotation in the conditions where the subjects were required to face forwards (Control; SB0: P0; SB30:P0).

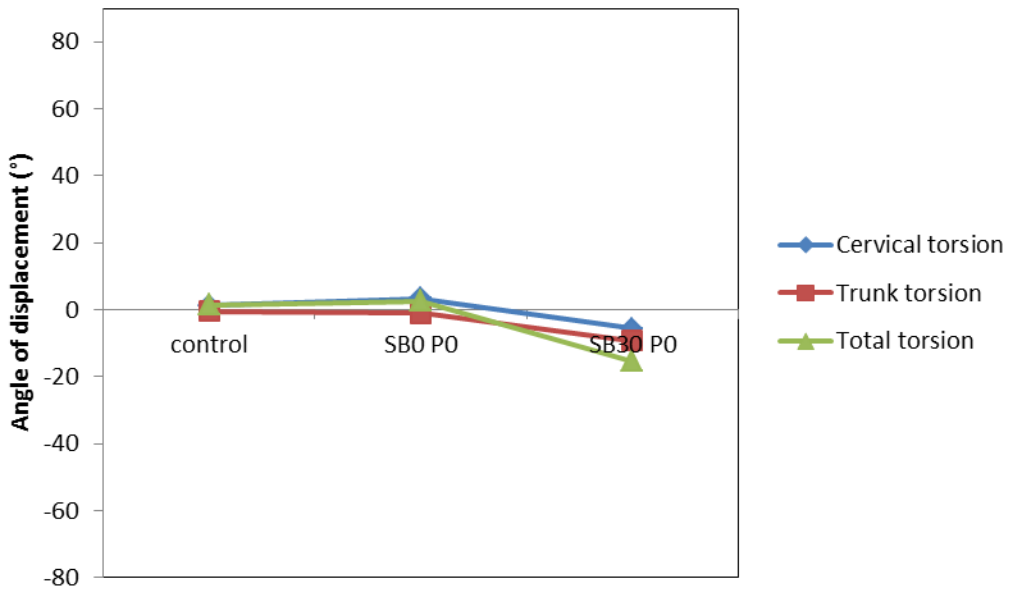


Figure 97 Trunk, cervical and total torsion during the forward facing conditions

As can be seen from Figure 97, when the seat base is rotated to 30°, the subject is required to rotate to the left for forward attention to counteract the seat base rotation.

9.4.4 Subjective Discomfort

9.4.4.1 Effect of condition on discomfort

The effect of condition on discomfort is investigated by comparing each condition at the 7th minute across body parts. The overall levels of discomfort across all conditions were generally lower than seen in the previous study, where static rotation was investigated. The conditions where subjects were rotating instigated greater discomfort than those where the subject was forward facing. Although discomfort was felt in the middle back when the subjects were asked to face forwards, whilst the seat base was rotated at 30°.

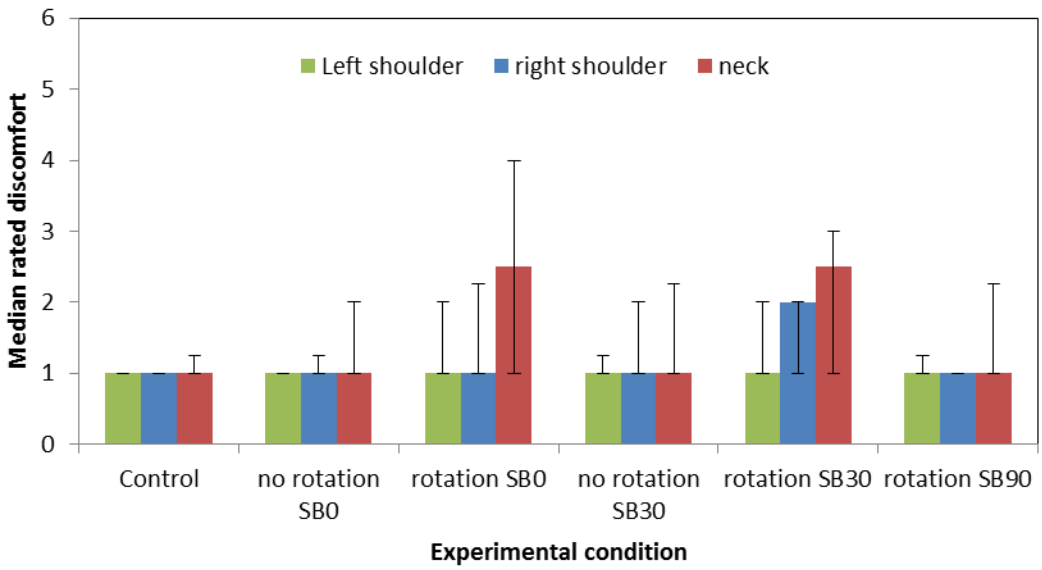


Figure 98 The effect of condition on rated discomfort at the 7th minute of the shoulders and neck (error bars show 25th and 75th percentile values)

The neck discomfort in the dynamic rotation with SB0 and SB30 is significantly different from the control ($p<0.05$) in both cases, however, the discomfort is not significantly different between the two seat base positions. The discomfort in the neck is not different from control in any of the other conditions. The discomfort in the left shoulder does not significantly increase above that in the control in any experimental condition. The discomfort in the right shoulder in the rotation SB0 and rotation SB30 is significantly more than that in the control condition ($p<0.05$), but are not significantly different from each other.

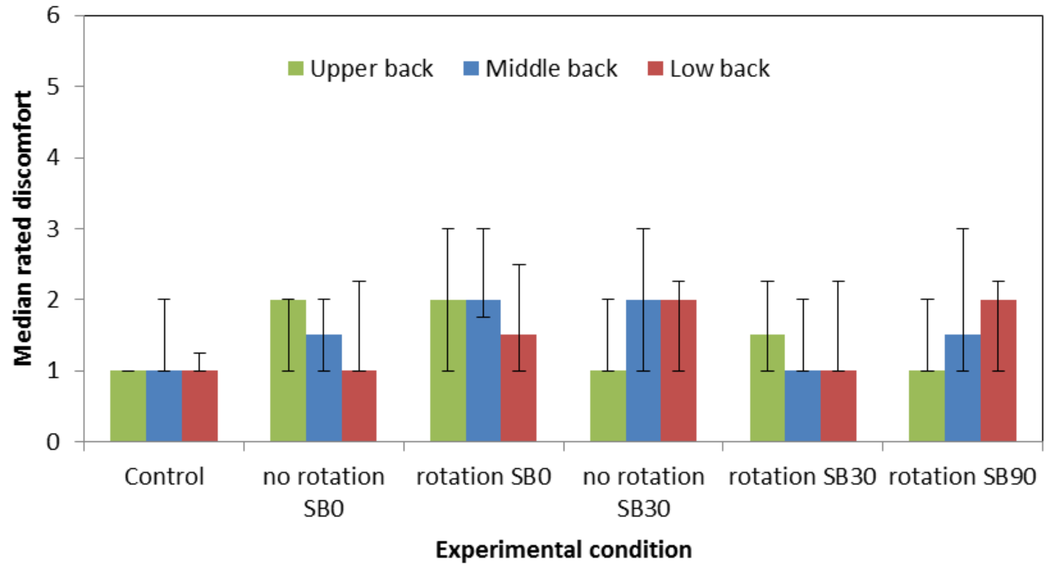


Figure 99 The effect of condition on rated discomfort at the 7th minute of the upper, middle and lower back (error bars show 25th and 75th percentile values)

The discomfort experienced in the upper back is not significantly different from control. The discomfort in the middle back was significantly greater than the control in the rotating SB0 and no rotation SB30, but the discomfort experienced was not significantly different between the two conditions. In contrast the conditions causing greatest discomfort in the low back were all three conditions where the subjects were rotating.

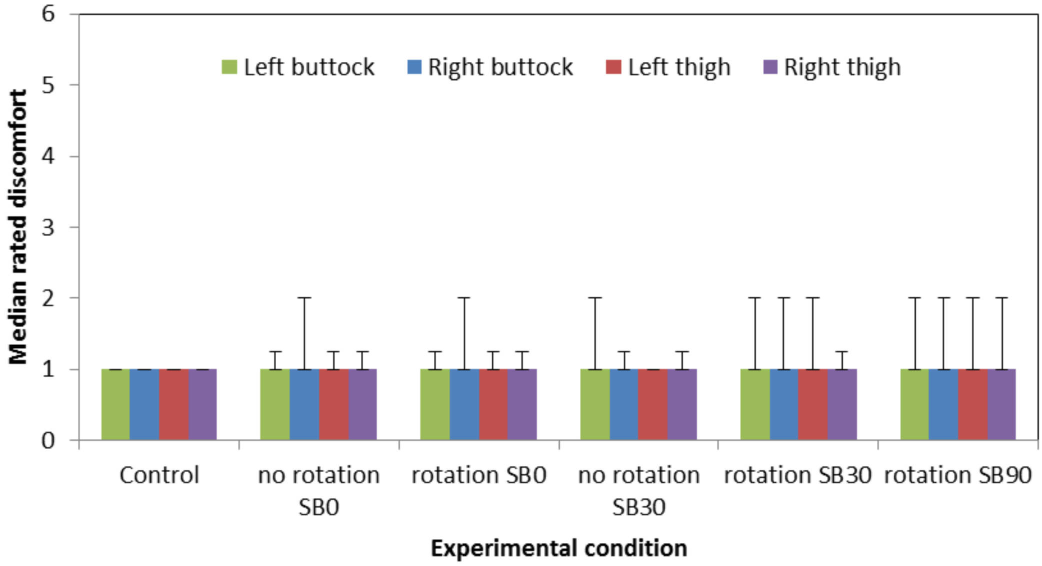


Figure 100 The effect of condition on rated discomfort at the 7th minute of the buttocks and thighs (error bars show 25th and 75th percentile values)

The discomfort of the buttock and thighs in any of the conditions do not significantly exceed that of the control in any condition ($p>0.05$). However, from the percentiles it can be suggested that the rotation conditions, particularly with seat base rotated at 90°, some participants were increasing their discomfort ratings.

9.4.4.2 Effect of Duration on discomfort

Due to the relatively low levels of discomfort across the body parts, it was felt limited benefits would be gained by investigating discomfort development over time for each body part for each condition. Therefore, the total discomfort across all body parts was collated into the 6 discomfort categories, so that progression of discomfort over time can be seen. Therefore in the first minute of the control 87% of all participant ratings across all body parts were '1 – not uncomfortable' and 13% were '2 – a little uncomfortable', the results of this analysis can be seen below.

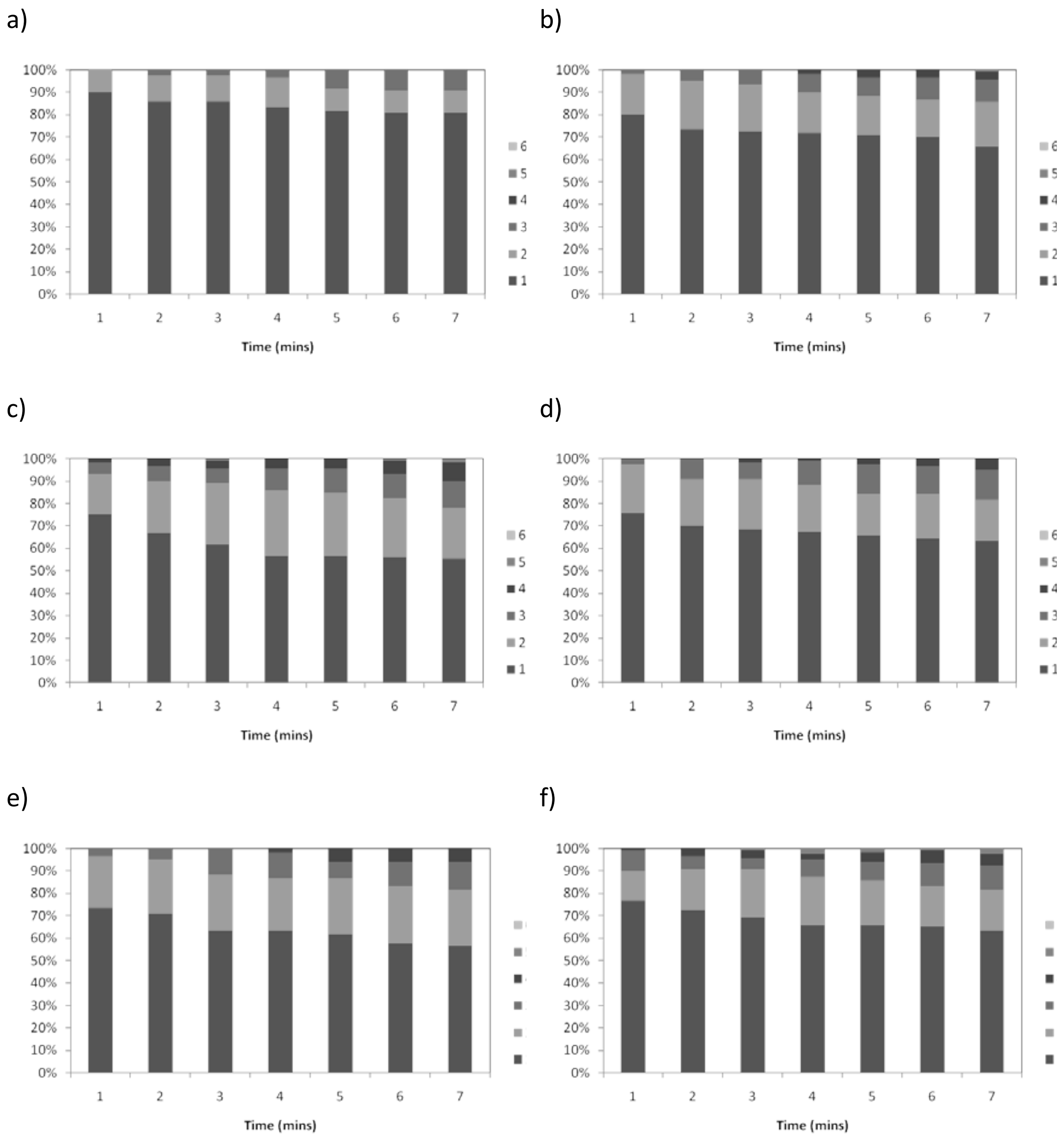


Figure 101 Total discomfort across all body parts: expressed as percentage of each level of discomfort in each condition, a)control; b) SB0 no rotation c) SB0 with rotation d) SB30 no rotation e) SB30 with rotation f) SB90 with rotation

When the discomfort is compared over time, as in Figure 101 it can be established that the increase in discomfort is quickest in the rotating SB0 condition and secondly the rotating SB30 condition. Aside from the control, which shows low levels of discomfort throughout the 7 minutes, the other conditions show a similar level of discomfort increase over time. Maximum discomfort, at level 5 or 6, is not rated for any body region in any condition. In general more discomfort development is seen in the moving conditions than the static ones.

9.4.5 EMG fatigue analysis

Due to the moving nature of this experiment, reference contractions are required (Luttmann et al., 1988; Hagg et al., 2000). Instances when subjects were focusing on light 3 (at 90°) were chosen as the reference contraction points for 3 main reasons:

- This light was present both early (23s - 36s, referred to as T1) and late (6min 42s – 6min 52s, referred to as T2) in the test allowing the maximum time between test contractions
- The light was activated for a relatively long period resulting in a static posture
- Statistical analysis (Wilcoxon) of the posture recorded by CUELA the first time the subject focuses on a light and the last revealed that there was no significant difference between neither the cervical ($p = .161$) or thoracic ($p = .779$) torsion when viewing light 3 between the T1 and T2.

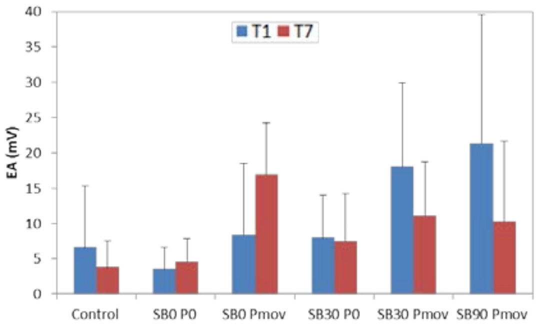
For those conditions where there is no movement i.e. subject is facing forward, the same time points will be used for comparison.

9.4.5.1 Electrical Activity

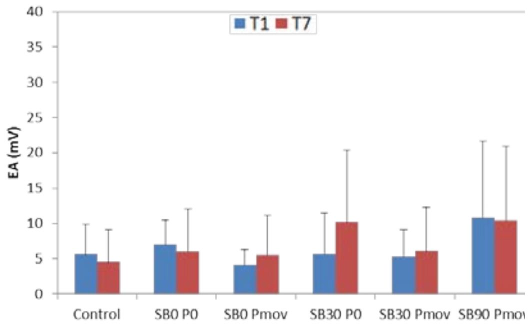
Comparison of EA between the first minute (T1) and the 7th minute (T7) is presented below. The differences in activity are not clear between the two time stamps, and there are low levels of activity in some muscles, particularly TA R.

In line with the previous studies, statistical testing of differences over the experimental duration for each muscle in each condition was applied. A t-test comparison between T1 and T7 showed that an increase in electrical activity over time was present in the moving condition with the seat base in the forward facing neutral position (SB0 Pmov) in both the TD L and R, signifying fatigue. This suggests that the neck is under greatest stress when required to twist without the assistance of seat base rotation. In addition, fatigue was shown in the TD R in SB30 P0 condition.

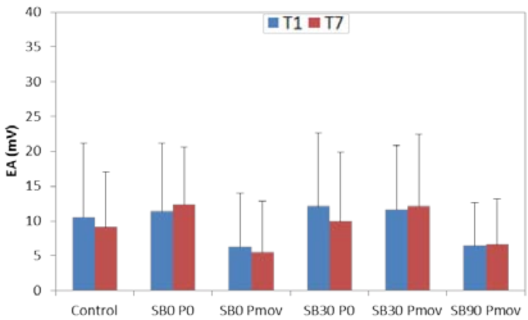
TD L



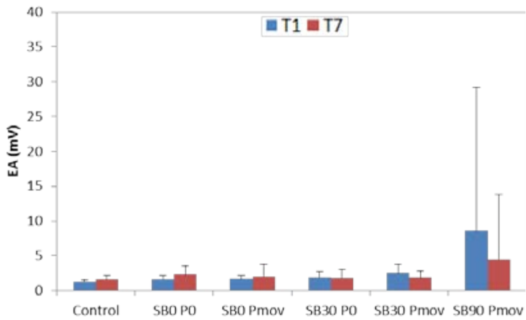
TD R



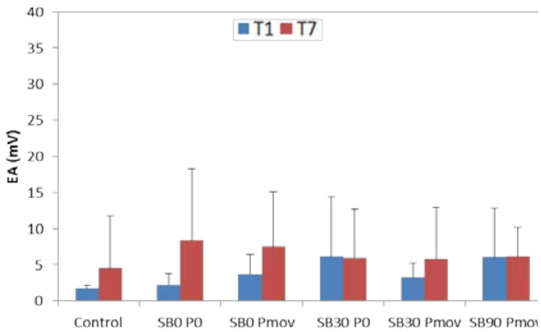
TA L



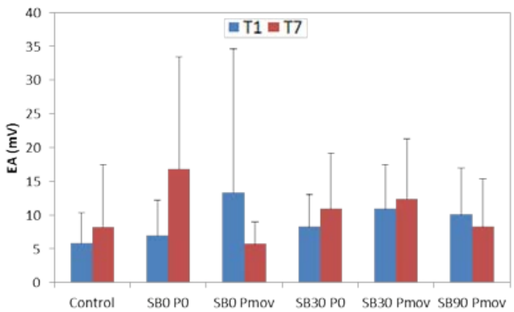
TA R



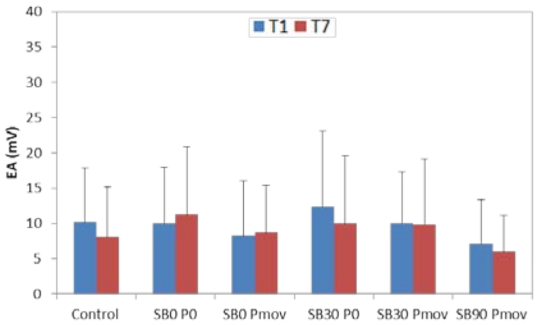
ES L



ES R



MF L



MF R

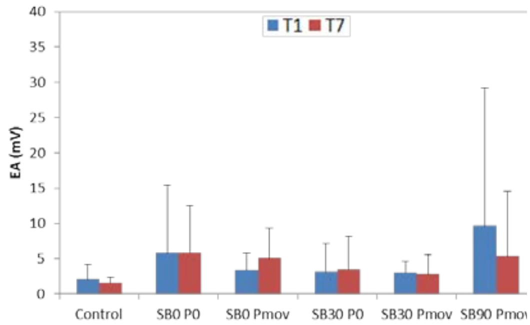


Figure 102 Mean EA at 1st and 7th minutes across conditions. Error bars designate 1 standard deviation

However, if the mean activity in each condition is used as an illustration of any possible trend then the effect on activity of the exposures can be seen. Presented below in Figure 103 are the results of the EA for all participants across the 6 conditions. There is differing amounts of variability among the participants in some muscles. Those muscles showing the least variability and also the least activity across all conditions are the right side trapezius decendens and ascendens. In the TD L, there is a clear increase in activity in the experimental conditions for most participants in comparison to the control. There are no clear trends across the other muscles however. Here it is clear that in all cases the activity in the experimental conditions is greater than the control condition (p= 0.01, repeated measured ANOVA). The greatest activity is seen in the TA L, with activity peaking in the SB30 Pmov condition, closely followed by the SB90 Pmov. The trends seen in the right side muscles, with the exception of the ES are all similar, with little difference between the SB0 and SB30 static and moving conditions, activity peaks for these muscles in the SB90 Pmov condition. The response of the TA L and MF L are similar also, with a peak activity response in the SB0 P0 condition, which is vibration only. The results of the ES muscles are most variable, with clear peaks in the static conditions in comparison to the moving conditions, which may illustrate their stabilising role.

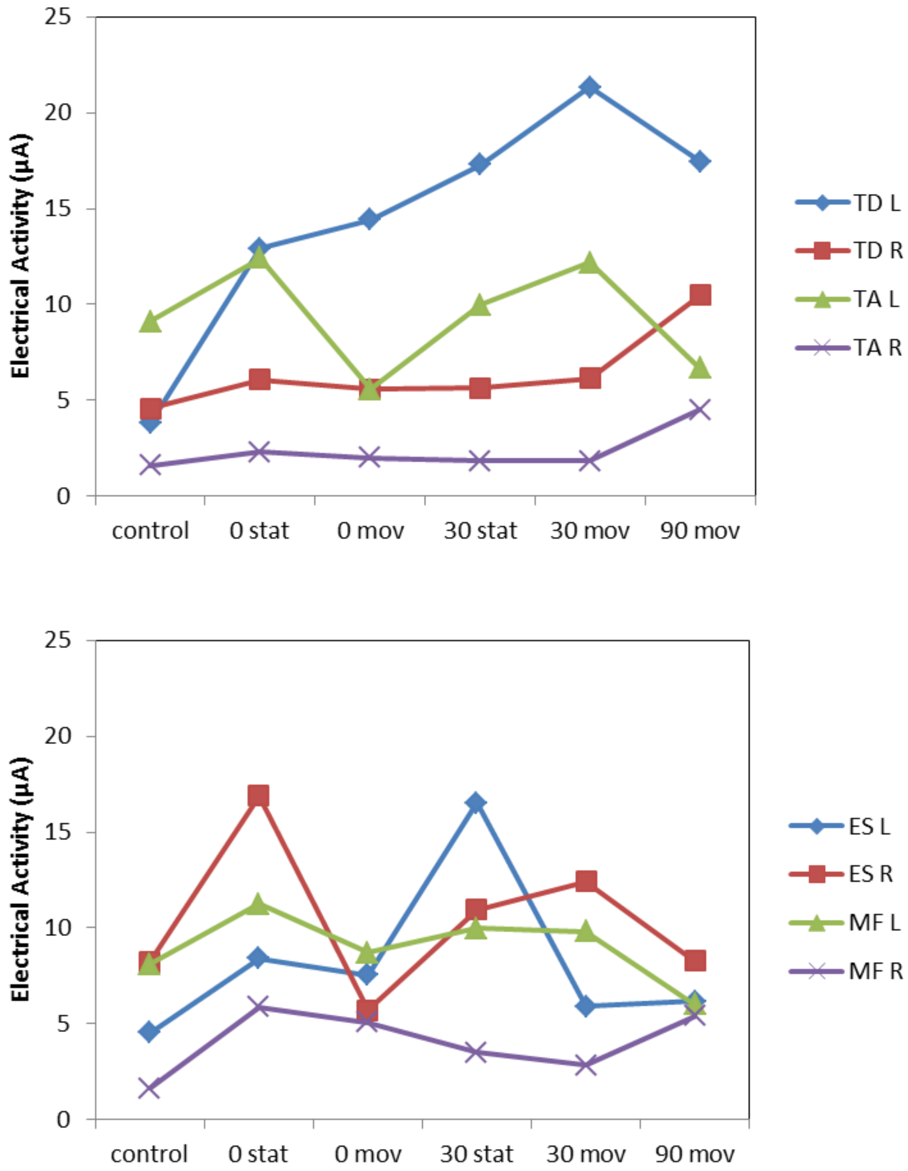
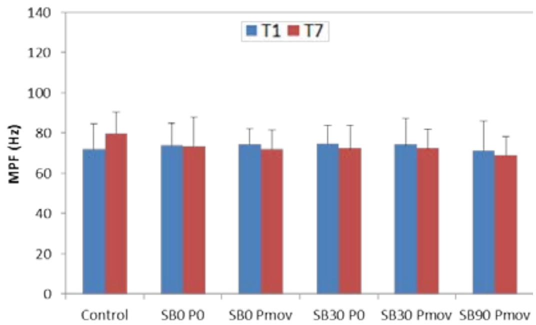


Figure 103 Mean activity per condition for the muscles shown at 7th minute

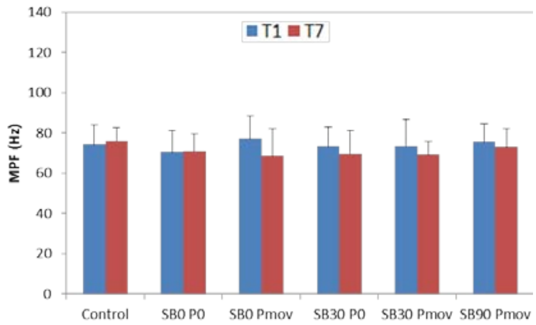
9.4.5.2 Mean Power Frequency Analysis

Figure 104 illustrates the change in mean MPF over the experimental duration. As can be seen from the graphs, there is little variation in the data, shown by the small standard deviations. In addition, there is little movement over time, in many of the conditions.

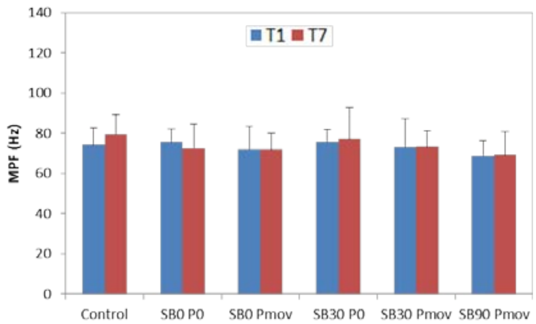
TD L



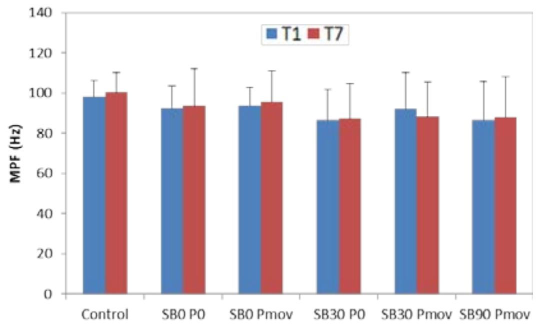
TD R



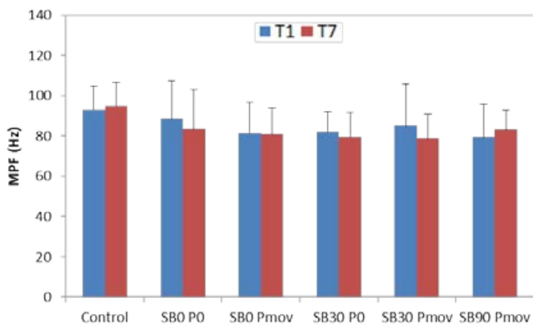
TA L



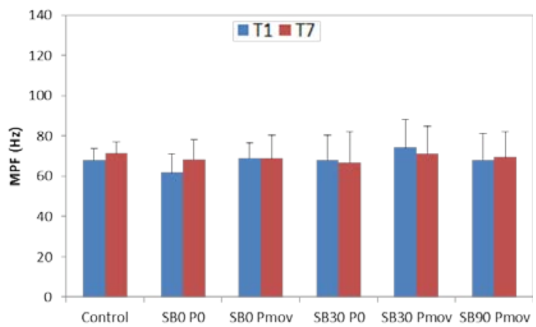
TA R



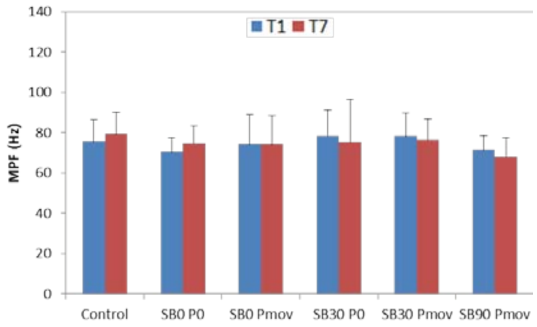
ES L



ES R



MF L



MF R

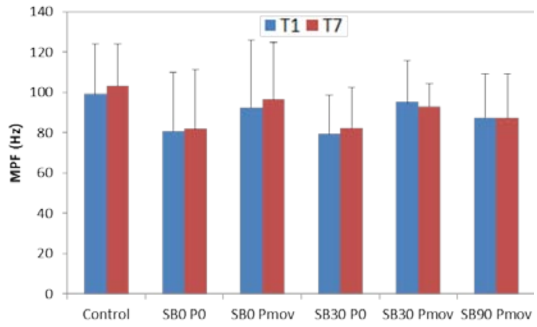


Figure 104 Mean MPF at 1st and 7th minutes, error bars designate 1 standard deviation

A paired t-test was used to test for changes over time in each condition. Significant decreases over the 7 minute experimental duration were found in the SB0 Pmov condition in the TD R, and in the SB90 Pmov condition in the MF L. This result is particularly interesting as it may suggest that when the seat base is moved, the stress is reduced in the neck, although the requirement for feet placement on the pedals is having an effect on the lower back.

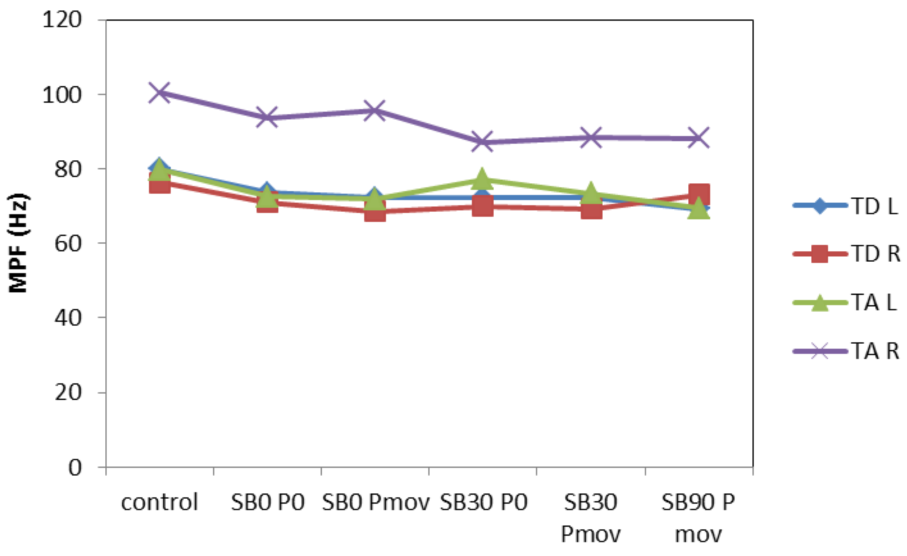


Figure 105 Mean MPF per condition (TD and TA)

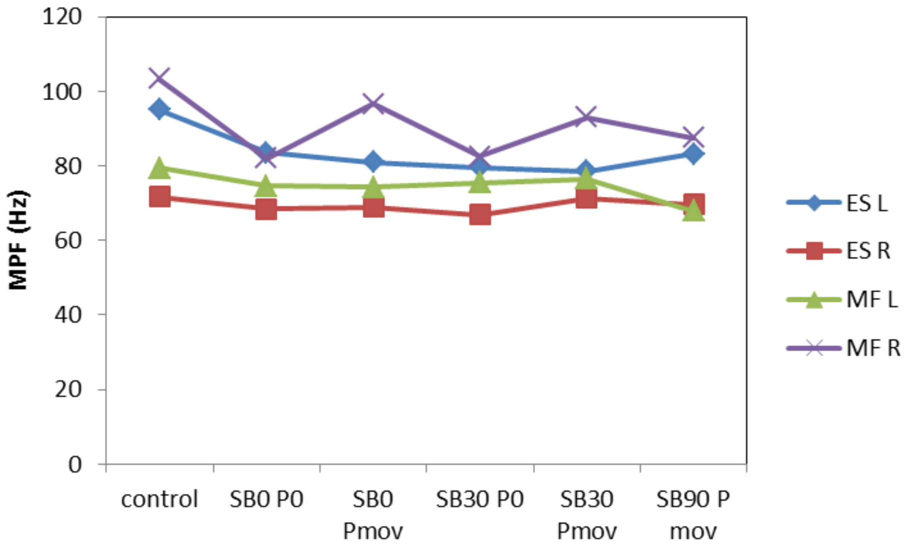


Figure 106 Mean MPF per condition (ES and MF)

9.5 Discussion

Previous research has suggested that motion, in particular velocity, is important in defining the risk of low back disorder (LBD) development, in addition that trunk velocity is often more predictive of LBD than position, range of motion or acceleration (Marras et al., 1995). There have been few previous studies investigating this, but they have not included vibration exposure or the subjective effects of such exposures. This study aimed to fill a gap in the knowledge of such exposures, which are experienced by many operators on a daily basis.

The condition with the most areas of rated discomfort was SB0 Pmov, where discomfort greater than the control was rated in the neck, right shoulder, middle and low back. When the seat base was rotated to 30°, with the subject still rotating, the discomfort was reduced in the middle back, in comparison to the previous result. Therefore it appears that rotating the seat to 30° reduces discomfort in the middle back. Under the same rotation requirements, when the seat base was rotated to 90°, discomfort was only rated for the low back. Observations during the field study (Chapter 4) suggested that operators did not re-adjust their seat base rotation when travelling forward after a period when seat base was rotated. The condition SB30 P0 was included to test the effect of this. From the discomfort results it appears that discomfort is caused in the middle back by this seat positioning. In the buttocks and thighs only marginal discomfort was experienced, and therefore there was little distinction in the rated discomfort between cases. The areas of discomfort development are very similar to those marked by the operators in the survey of expert opinion. Again, the neck assumes more of the discomfort than the other body parts during the exposures, which is in line with the results from Chapters 6 and 8. The overall discomfort experienced in all conditions was less than experienced in the other laboratory studies investigating rotation within this thesis (Chapters 6 and 8). There is no known study within the literature investigating subjective discomfort under dynamic axial rotation with which to directly compare the discomfort results here.

The inclusion of investigation of buttock and thigh discomfort to the subjective discomfort analysis was in response to some feedback during the field study (Chapter 4). In fact the buttock and thigh discomfort remained low throughout the study, with a few participants increasing their ratings to 'a little uncomfortable' in the rotation SB30 and SB90 conditions.

The parameters investigated indicate that the moving conditions with the seat base un-rotated and rotated at 90° instigate muscular fatigue. Activity increases and frequency decreases were present in the TD R in the SB0 Pmov condition. Significant activity increases were also present in the TD L in that condition, and in the MF L in the SB90 Pmov condition. No indication of fatigue was found in the moving condition with the seat base at 30°, or in either of the conditions where the subject was forward facing. Previous investigations of dynamic twisting have mostly considered the percentage MVC activity when twisting (McGill, 1991) or whilst standing (Marras et al., 1993, 1995). The muscles considered in these investigations are also different, excluding the ES, making comparisons difficult. However, in comparison with the previous studies detailed in this thesis, the pattern of muscles exhibiting fatigue is similar, illustrating that the stress response is similar in both static and moving twisting postures.

The rotating conditions appear to cause greater discomfort than the static forward facing conditions. Results from the other experiments in this thesis indicate that when twisting it is at the neck, shoulders and upper back where the greatest discomfort is experienced. Of the three SB rotations, muscular fatigue was only displayed with SB0 and SB90, therefore suggesting that SB30 is the optimal seat position for a task including rotation. The research by Bottoms and Barber (1978) suggested that 20° seat base rotation reduced operator discomfort and muscular fatigue. The research here goes further in the comparison of the additional 90° seat base rotation, although the fatigue in the low back suggests that this seat placement places additional stress on the operator. During the 90° seat base rotation condition, subjects were required to maintain contact with the steering wheel and pedals, which remained to the front (left when rotated to 90°) of the operator. This could be the cause of this fatigue in the MF L. Whilst it is unlikely that during a driving scenario the driver would be required to maintain contact with the pedals, during breaking this contact would be required. Through observing the subjects in the experimental conditions, it was evident that for some subjects, retaining contact with the foot pedals whilst rotated was difficult. This therefore implores the question of how this seat position would affect the operators response to an emergency situation, when in control of a real vehicle. One operator raised this issue during the expert opinion survey. He suggested that although beneficial, rotating the seat base to 30° changed the placement of the feet in the cab, and therefore he found it difficult re-orientate with the pedals when required. It is suggested that this issue is explored further in future research.

The data attained from the CUELA measurement system illustrate that either the full desired rotation was not attained, or that the CUELA measurement system was not measuring the full posture range. From the previous studies in this thesis, it is evident that subjects found it difficult to attain the higher levels of required rotation. However, from observations, there was a clear distinction between the postures of the subjects between 45°, 110° and 170° which is not captured in Figure 94. The method of measuring cervical torsion is a metal rod attached to the head by a strap encircling the head, and attached to the support straps between the shoulder blades. The resulting issue is that once the back of the head passes the (left) shoulder when twisting to the right, the movement of the measurement tool is restricted. This may account for the slightly reserved measures of cervical torsion seen above.

9.6 Conclusions

H_1 Discomfort, assessed subjectively, will be greater when the subject is rotating than when they are seated in a neutral forward facing posture

Discomfort was greatest when subjects were rotating with the seat base at 0° and 30°. However when the seat base was rotated to 90° the discomfort was reduced to that of the static forward facing postures. The areas of greatest discomfort were the neck, right shoulder, middle and low back.

H_2 Fatigue will be exhibited in the dynamic rotation conditions (Marras and colleagues, 1995, 1998)

Fatigue was exhibited in the dynamic rotation condition when the seat base was at 0° and at 90°, but not at 30°. No fatigue was seen in the forward facing conditions, or in the control.

H_3 Evidence of muscular fatigue and discomfort will show a decrease in conditions where the seat base is rotated, so that the maximum required trunk rotation is reduced (Bottoms and Barber, 1978)

The results suggest that rotating the seat to 30° does not reduce discomfort from dynamic rotation, but does prevent muscular fatigue. Rotation of the seat base to 90° causes fatigue in the lower back when the subject is required to place hands and feet on the steering wheel and pedals respectively. Maintaining the seat at 30° rotation when subject is required to face forward induces discomfort in the middle back that is not present during a similar condition when the seat base is in the neutral forward facing position.

9.7 Limitations of the laboratory studies

This study was not without limitations. The recruitment of additional participants would have added strength to the statistical analysis. There was also a bias toward female participation in 3 out of the 4 laboratory studies. Unfortunately, recruitment of participants is difficult, and to a certain extent control of this aspect is limited. However, if there was equal participation from both genders, this would have allowed the possible influence of gender on the results to be investigated.

When vibration was an experimental parameter, the vibration frequency was based on a 1-30Hz flat spectrum. This may not be wholly representative of agricultural exposures; however it also does not narrow the application of the results. The magnitudes of exposure were not as high as one might expect to experience in agriculture, however, in the interests of on-going participant health, they were limited to reflect likely exposures

The chosen postures attempted to simulate the postures employed by operators in agriculture. The postures attained by the subjects did not reach the originally desired levels, however, the levels attained across the studies were comparable. In addition, for the higher rotation condition, participants were aiming for 170° rotation, although not achieving this, they did achieve what appeared to be the physiological maximum. It is suggested that this condition should be considered as the maximum voluntary rotation of the participants.

The seats used in Chapters 6, 7 and 8 was a full back-rest seat taken from a non-agricultural off road driving vehicle. For the final experimental study, Chapter 9, the seat was exchanged for a seat from an agricultural tractor. This switch adds limitations to the comparison of data between the studies, further discussion is given to this within Chapter 10, discussion.

The exposure duration in Chapters 6 and 7 was 10minutes, and in Chapters 8 and 9 it was 7 minutes. This was because it was important to maintain a same day methodology for the EMG reliability, and therefore unfortunately necessary. This shorter duration in the latter studies may amount for the differences in reported discomfort. The exposure time is still in excess of other comparable studies in the literature (e.g. Wikstrom, 1993).

Determining the posture of the operator from photographic evidence, proved difficult in Chapter 6. It was therefore considered that an additional method of posture assessment would be beneficial in the latter studies, and so the CUELA posture measurement system was employed. However, the CUELA measurement system did not fully represent the twisted posture of the subject. The method for measuring trunk rotation was affected by the back rest in some cases (when the sensors were affected, it was possible to delete these sections from the evaluation). The shoulders appeared to obscure the head torsion sensor once the back of the head rotated past the shoulders. However, despite the inaccuracies, with further development I believe CUELA could be a helpful tool in assessing workers postures.

There was considerable variation in the EMG results both within and between subjects. This makes graphical analysis of trends in the data particularly difficult. Careful statistical analysis, based on previous published studies allowed the results to be confirmed. Detailed inspection of the data prior to the analysis ensured that noise artefacts and inexplicable outliers were removed to avoid contamination of the statistics. Despite the appearance of the graphs, the results corroborate with similar investigations by other authors. It is suggested that meticulous attention to detail when dealing with the EMG data is required to ensure the correct results are obtained.

CHAPTER 10: General Discussion

The overall aim of the thesis was to determine the influence of exposure to WBV and axial rotation either separately or in combination on the musculoskeletal discomfort of the neck and trunk. The results may be used in the development of new guidelines on acceptable exposures, and also help prioritise future engineering solutions in agriculture. There have been previous studies on the exposures singularly, but none considering the range of exposures investigated here. In 2010 the ISO technical committee 108, SC 4, working group 14 considered that the effect of unfavourable postures on the risk for low back pain. This signifies a noteworthy step from the international community of academics and occupational experts working within the field of whole-body vibration exposures on the acknowledgement of the possible additional effect of adverse postures. Many have noted the need for a comprehensive assessment of the effects (Seidel, 1993) and some literature has started to answer this (Wikstrom, 1993; Toren, 2001; Newell, 2007; Eger et al., 2008). However, in the research results and subsequent versions of standards, the issue of the posture of the operator has remained un-quantified and confined to the annex sections. Therefore, through the various methods employed in this thesis, it was anticipated that some additional information could be provided for use when considering the effects of such exposures. The approach taken within the thesis was to conduct a series of laboratory studies, all with a focus on the specific musculoskeletal effects of WBV and axial rotation, and then to supplement these findings with the broader studies of the field study and the survey of expert opinion. The combined laboratory results are discussed first, followed by the methods used, then by the agreement between the laboratory results and the survey and field studies.

10.1 Laboratory studies

10.1.1 Subjective effects of axial rotation and WBV

In each of the laboratory studies, measures of subjective discomfort were acquired from the participants at 60s intervals. The results can therefore be compared across the Chapters, so that an evaluation may be made as to the effect of any interactions. To compare the discomfort across experimental conditions, the 7th minute median discomfort can be used. Although in Chapters 6 and 7, the subjective discomfort was measured for longer (10 minutes), the discomfort was recorded every 60s and therefore the 7th minute discomfort can be determined and used. In all of the laboratory studies, a comparable control condition was used. For this the subjects were required to be seated in the seat used in the associated experimental conditions, forward facing, with no vibration. This control condition was repeated in every study and can therefore be considered as a baseline for comparison. Figure 107 presents the subjective discomfort at the 7th minute for the control condition in all studies. The median rated discomfort remained at the lowest point in all of the control conditions, with the exception of the upper and lower back in the twist only study, and the middle back in the twist and vibration study. The differences between the subjective discomfort in the control conditions is not statistically significant (p>0.05, Kruskal Wallis) for any body part investigated, therefore suggesting that the baseline discomfort for each of the experimental groups is comparable.

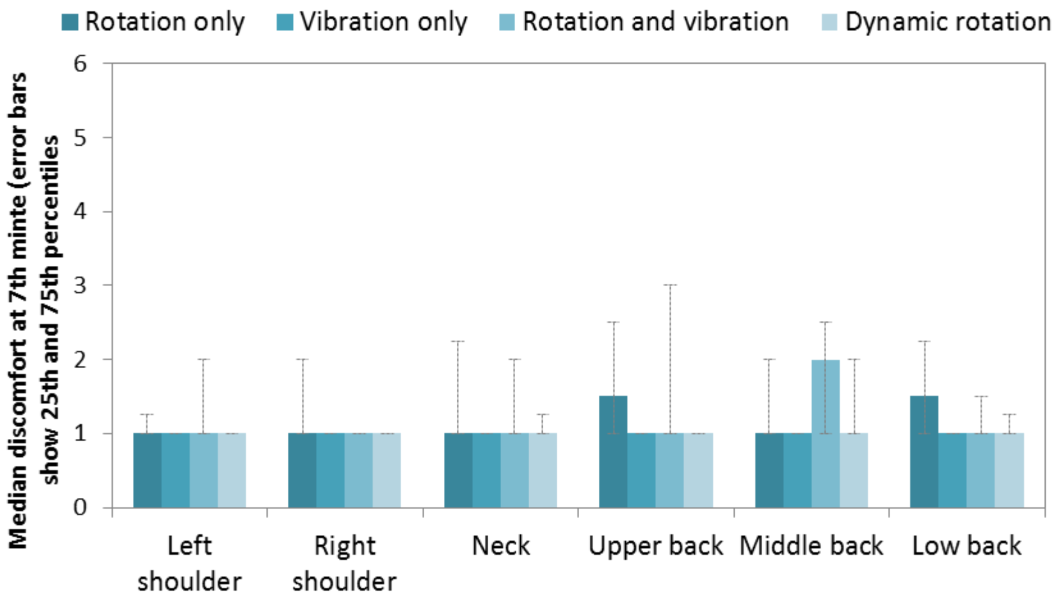


Figure 107 comparison of discomfort at 7th minute across controls in each study

Although the baseline discomfort is low in all conditions, and there is no statistically significant difference between the conditions, it is clear from the 75th percentiles, that some participants did feel slightly greater discomfort than 1 ‘not uncomfortable’. Although a latin square was employed to reduce order effects, the discomfort from the previous condition the subject experienced could have an effect. It is suggested that this is not the case for these results for two main reasons. Firstly, the results presented here are 7th minute, therefore if the discomfort was from a previous study it should be the same as or less than that experienced in the first minute – this does not appear to be the case. Secondly, the areas where the discomfort appears to be greatest e.g. low back in rotation only condition, are not the areas where the greatest discomfort was felt in the experimental conditions in that study. Unfortunately, the number of participants allocated to each experiment is not sufficient therefore a statistical comparison to determine any possible interaction effects is not possible.

The 7th minute discomfort can also be compared across experimental conditions from each Chapter. The low back is an area frequently investigated in the literature, and the neck was often the area of greatest discomfort, therefore these two areas are used for comparative discussion. Figure 108 illustrates these compiled results.

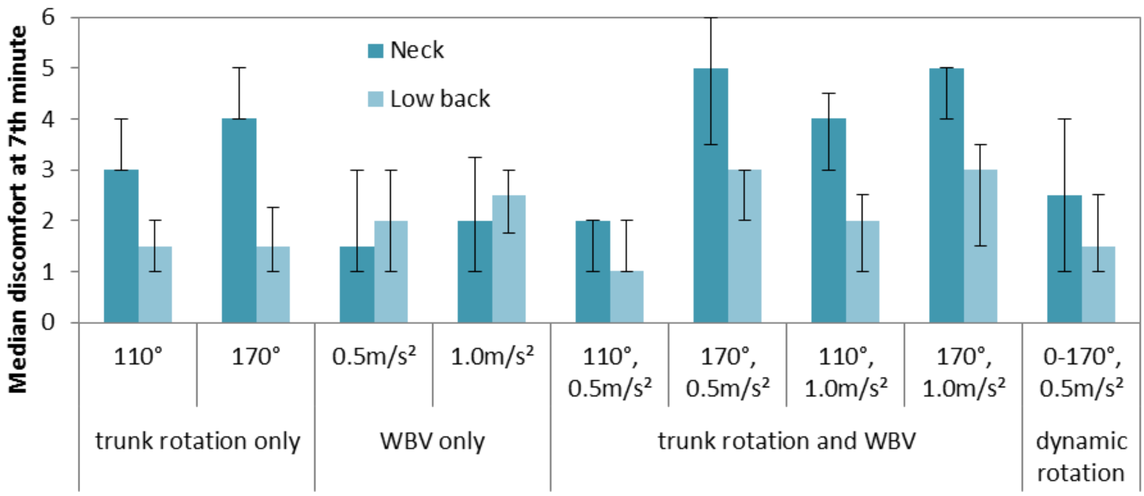


Figure 108 Comparison of median discomfort (with 25th and 75th percentiles) at 7th minute across experimental conditions.

From Figure 108, the only exposure where discomfort in the low back exceeds that in the neck is the vibration only study. However this difference between the neck and low back is not significant ($p > 0.05$, Wilcoxon). The cases with the greatest median discomfort are those with both 170° rotation and WBV. The different magnitudes of the vibration investigated here do not appear to have an effect on the median discomfort. In the dynamic rotation condition shown, the discomfort was comparable to 110° twist and the lower vibration exposure. The results of a Kruskal Wallis test indicated significantly different discomfort in the neck across the conditions ($p < 0.0001$). Additional post hoc tests are required to determine specific points of difference between the conditions. 9 post hoc tests were considered, that is between the conditions where one parameter is common, i.e. 110° and 110°, 0.5m/s² (bonferroni corrected accepted p-value of 0.006 was accepted for significance tests). Significant differences ($p < 0.0001$, Mann Whitney) were found between the vibration conditions with and without trunk rotation.

The addition of trunk rotation to the vibration exposure resulted in a significant increase in discomfort felt by the subjects. This has considerable significance for the assessment of risk from WBV exposures, which are largely based on assessments of discomfort from exposure. It is suggested that the guidance be revised in light of this analysis, to account for the increased discomfort risk from a twisted posture when exposed to vibration. The addition of vibration to the posture conditions did not result in a significant increase. It is noted however, that risk assessment for posture is rarely conducted for driving postures (there is not suitable method) and that there is no regulation on adherence to posture specific risk assessment for driving.

The neck discomfort in the 0.5m/s² condition and in the dynamic rotation with 1.0m/s² was not significantly different. However, in comparison of 0.5m/s² with 170° rotation and 0.5m/s² with dynamic rotation, the discomfort is significantly less when dynamic rotation replaces static rotation. A summary of the statistical comparisons is provided in Table 26.

Table 26 Results of statistical comparison between experimental conditions at the neck, (Mann Whitney) where significance is shown, the condition with the greater discomfort is underlined

110° versus 110° + 0.5m/s²	n.s (p=.086)
110° versus 110°+ 1.0m/s²	n.s (p=.148)
170° versus 170°+ 0.5m/s²	n.s (p=.081)
170° versus 170°+ 1.0m/s²	n.s (p=.775)
0.5m/s² versus <u>0.5m/s² + 110°</u>	p<0.0001 (p=.000)
0.5m/s² versus <u>0.5m/s² + 170</u>°	p<0.0001 (p=.000)
1.0m/s² versus <u>1.0m/s² + 110°</u>	p<0.0001 (p=.000)
1.0m/s² versus <u>1.0m/s² + 170°</u>	p<0.0001 (p=.000)
0.5m/s² versus 0.5m/s² + dynamic rotation	n.s (p=.161)
0.5m/s² + 110° versus 0.5m/s² + dynamic rotation	n.s (p=.051)
<u>0.5m/s² + 170°</u> versus 0.5m/s² + dynamic rotation	p<0.05 (p= .020)

The effect of the additional discomfort when a rotated posture is added to a vibration exposure is interesting. This suggests that when an operator is exposed to WBV, and then additionally required to maintain rearward attention that they would be at increased risk of experiencing musculoskeletal discomfort in the neck.

A repeated measures (Kruskall Wallace) test of low back discomfort across all experimental conditions investigated (control not included) revealed no significant differences in the discomfort between the conditions of this body part (p=.102). Previous research has suggested that there is an increased risk to the low back when the exposures are experienced together (Lis et al, 2007), the result presented here do not confirm their research. Magnusson et al. (1998) suggested that the cumulative effect of exposures is not confined to low back, which supports the results demonstrated by the increased neck pain in the results presented above. Wikstrom (1994) did not find an interaction effect between WBV and posture in the neck, only in the low back which is in contrast to the results. The discomfort from trunk rotation was greater than the discomfort from vibration in the studies by Wikstrom (1993), the magnitudes of vibration in that study were comparable to those investigated here, although the exposure duration was much less at <3 minutes.

In comparison with the discomfort reactions to WBV described in ISO 2631-1 (1997) the levels of discomfort experienced in the 10 minute duration of the vibration only study were slightly less than indicated by the standard. It is suggested that this is likely to be due to the relatively short exposure duration, although no duration is specified within the standard for comparison. When exposed to axial rotation at the levels investigated the discomfort is greater, as discussed above. Although the axial rotation the subjects were asked to attain were at the physiological maximum, however there is no theoretical maximum vibration exposure. To conserve the musculoskeletal health of the participants, the limits to exposure had to be placed on one of the risks. The guidance surrounding exposure levels is much clearer when assessing WBV. Therefore greater focus was committed in investigating maximum axial rotations. The conditions themselves are therefore not directly comparable, although the exposures are typical of that experienced by operators, and therefore comparison of the effects can allow differentiation between the exposures to target intervention. As the verbal descriptives for discomfort were taken from ISO 2631-1, comparison of the rated discomfort in the rotation conditions with the guidance in ISO 2631-1 suggests that the levels of axial rotation may be comparable to exposure to 1.25-2.5m/s^2 whole body vibration.

10.1.2 Muscular fatigue effects of axial rotation and WBV exposure

The control conditions in each study did not exhibit any statistically significant fatigue parameters, therefore suggesting that the control conditions were not fatiguing, and could be used as a baseline for comparison with the respective experimental conditions. Using the indication of statistically significant increases in EA or decreases in MPF as comparators, the number of muscles exhibiting fatigue with these assumptions may be used as a comparison between experimental conditions, see Table 27.

Table 27 Muscles indicating fatigue for the experimental conditions

	axial rotation		WBV		axial rotation and WBV				dynamic rotation
	110°	170°	0.5m/s²	1.0m/s²	110°, 0.5m/s²	110°, 1.0m/s²	170°, 0.5m/s²	170°, 1.0m/s²	0-170°, 0.5m/s²
TD L	✔	✔		✔✔					✔
TD R	✔	✔		✔					✔✔
TA L		✔✔	✔	✔✔				✔	
TA R	✔		✔	✔					
ES L				✔			✔		
ES R			✔✔	✔✔		✔			
MF L			✔	✔		✔	✔	✔	
MF R				✔				✔	

Key: ✔ one fatigue parameter indicated; ✔✔ both fatigue parameters indicated

The condition with the greatest number of muscles exhibiting fatigue is 1.0m/s² vibration only condition. This is in direct contrast with Figure 108 where the least discomfort was in the WBV only conditions. The magnitudes of EMG activity were elevated at the start of the WBV only studies, and then further increased throughout the experimental duration. This is similar to what was observed by Seidel (1988) and the increase in EA as a response to WBV has been the basis for the many investigations of EMG timing (Bluthner et al., 1993). Hansson et al. (1991) found that WBV in a seated posture accelerated the onset and caused more pronounced muscular fatigue. They suggested that the vibration increased muscular tension in the back which in turn caused an occlusion of blood supply, leading to fatigue. It is unclear whether this increased activity in the muscles is due in part to an induced reflex response within the trunk muscle Seroussi et al. (1989) and Seidel et al. (1986), or whether it is the stabilizing response of the trunk muscle to the vibration-induced movement (Hansson et al., 1991). It could be suggested that what was seen in the study here is a combination of both of these theories, that the initial increase in activity is the vibration induced activity, and the continuing increase throughout the experiment is the vibration induced fatigue as more muscular effort is required to stabilize the trunk under continued exposure.

Evidence for increased fatigue during combined conditions is not as strong as was found for the discomfort data. However, if the combined exposure data is considered separately, there is an increased number of muscles showing fatigue responses in the higher vibration and high twist condition. And if this is compared back to the twist only results, there are increases when the vibration component is added.

The muscles chosen for investigation in this thesis were chosen primarily for their location analogous to the areas of greatest perceived discomfort from the exposures. These muscles are not directly responsible for generating axial rotation, and this might explain why all of the investigated muscles did not exhibit fatigue under the rotation exposures. The fatigue response of the obliques to rotation has been well documented elsewhere (O'Brien and Potvin, 1997; Kumar et al., 2001), and therefore it was considered less critical that these were considered in the present study. The muscles chosen are not clearly agnonists / antagonists for rotation of the axial trunk and therefore comparison of this type is inappropriate.

There does not appear to be any distinction between the sides of the trunk affected, considering the rotation in this study was always to the right. Pope et al. (1987) reported little difference between the activities of the left and right pairs of many muscles studied. They reported the greatest magnitude of EMG activity in the erector spinae in isometric axial rotational activities. In Chapter 6 there is no clear distinction in the activity levels of the ES and the other muscles investigated. However in Chapter 8, the ES R does show increased activity above the other muscles in the higher vibration and high twist condition.

10.2 Methods of Measurements

In this thesis four groups of methods were used to assess the impact of axial rotation and WBV on musculoskeletal discomfort of the neck and trunk, namely subjective discomfort assessment, muscular fatigue assessment, surveys of expert opinion and physical measures of exposures. In Chapters 6 – 9, the subjective and objective measures of discomfort were used in conjunction with each other. These studies showed that the conclusions from the methods of analysis were not always synchronous. The methods were found to be suitable for evaluation of the musculoskeletal response to the exposures, but were also found to have limitations in certain situations.

10.2.1 Subjective Discomfort

Subjective assessments have been used in many studies assessing seating comfort and discomfort, as reported in the literature review (Gyi et al., 1994). It was considered that assessment of discomfort was more relevant for this thesis than assessment for comfort and therefore the verbal descriptives of the rating scale were amended to reflect this (Chapter 3). Although the amended verbal descriptives, taken from ISO 2631-1 (1997), were intended for the assessment of discomfort from WBV, they translated well to the assessment of postural sourced discomfort. The subjects learned quickly to perform the ratings and verbally stating the discomfort score did not appear to increase the workload of the subject. Others have considered the use of visual analogue scales, although completion of this would have been particularly difficult for subjects when rotated. Pain and discomfort can be relatively difficult to define and assess objectively (Eklund, 1988) as it refers to the individuals subjective sensations and is influenced by culture, expectations, motivation and also individual factors such as age, sex, personality and social background (Weisenberg, 1977). However, the ratings of discomfort are comparable to those reported in other studies (see discussion in Chapter 9) and the participants in the current study were well briefed before the experiment to avoid some of the issues arising from conflicting expectations. It is a recognised limitation of the study that the demographic of the participants is small, focussing on young Europeans. However, the studies are intended firstly as a comparison between the exposures, and therefore the narrow demographic distribution between the studies does not reduce validity.

The duration of experimental conditions was 10 minutes for the first two laboratory studies (Chapters 6 and 7) and then 7 minutes for the two latter studies (Chapters 8 and 9). The duration was chosen so as to allow a same day repeated measures design to be employed. Also initial pilot testing with the postures suggested that 10 minutes was approaching the maximum length of time a static maximum axial twist could be held for without extreme discomfort. The order of conditions was randomised, the order of conditions had no significant impact on the discomfort experienced in the control condition, and therefore it can be assumed that the recovery period between conditions was sufficient.

Others have considered the use of body maps for subjective discomfort scoring variable as participants have found difficulty in determining the boundaries between the body regions (Eklund, 1986). Eklund considered both the upper arms and the shoulders, and participants struggled to define the boundary between these. The participants in the current study did not appear to struggle to apply discomfort ratings to the body regions specified in Porters body map, and this difficulty has not been reported other users (Gyi, 1994).

10.2.2 Electromyography

Three parameters of the muscle activity were originally proposed for investigation: the electrical activity of the muscle, the mean frequency and the median power frequency. Overall, utility of the MPF and MF appear to be similar, this is similar to findings by others (Yassierli, 2005). Initially both the MPF and MF were calculated to ascertain which parameter would be most suited to analysis of the variables under investigation in this thesis. It was apparent in both Chapter 6 and Chapter 7 that the MPF was most sensitive to changes in the EMG signal. It has been suggested that this is due to changes resulting from low level contractions (Nagate et al., 1990). It is therefore suggested that if both parameters cannot be calculated, then MPF is preferred for analysis of work tasks unlikely to approach the maximal voluntary contraction of the muscles, or those where the muscles investigated may not be directly responsible for facilitating the movement. Measures of muscle activity appeared more sensitive to detecting changes in the muscle response than indications of spectral shift.

The effort required in the processing, analysis and presentation of the EMG data was considerable. There are few similar studies presented in the literature, and those that are published do not necessarily contain the level of detail required for a direct replication of methodologies. Personal communications with Professor Luttman (Luttmann et al., 1996; 2000; Hägg et al., 1996, 2000) and Dr Lariviere (Lariviere et al., 2002, 2003, 2004) were particularly helpful when developing the methodology used in the studies. The SENIAM guidelines (Hermens et al., 2000) and the work of Merletti (1999) have been particularly valuable in the investigation of EMG. The EMG results presented are variable and interesting. However, it is suggested that this method is best suited to investigative laboratory studies and would not be recommended for application in the field until further development work has been completed.

Luttmann et al. (1996) developed a fatigue estimation scheme by plotting amplitude and median frequency as two coordinates of the same point to estimate the combined effect. It was intended to utilise this method at the beginning of the studies. However, it became clear that although there were some muscles displaying increased activity response, these were not necessarily the same muscles displaying frequency shifts. Although this method was first presented at a conference in 1996 (Luttman et al., 1996) and then published in

2000 (Luttman et al., 2000), there has been no known publications using the method outside the research group involved in its development.

10.2.2.1 Correlation between subjective and objective results

Subjective and objective methods to assess a subject's response to a stimuli are often used concurrently to increase the amount of results and also allow for comparisons / validity between the measures to be made, exposures (Wilder, 1994). However, aligning EMG fatigue assessments with subjective discomfort is not commonly done. Often EMG investigation of specific muscle groups (i.e. erector spinae) is completed after identifying occupationally related low back discomfort from questionnaires (Balasubramanian et al., 2011). In this thesis, the areas of musculoskeletal discomfort of the neck and trunk were investigated in addition to adjacent monitoring of muscular response with EMG methods.

Wilder (1994) compared whole body discomfort with EMG assessed fatigue. In the evaluation of seated postures, the posture judged least comfortable was also that where the greatest muscular fatigue was presented. However, the muscles chosen for investigation meant aligning the discomfort scoring with the muscles assessed for fatigue was not possible. Others have been unable to demonstrate a relationship between perceived discomfort and EMG fatigue indicators (Bosch et al., 2007) when assessing similar muscle groups. The body maps illustrated in Figures 109, 110 and 111 are presented in an attempt to illustrate the disparity between the areas of discomfort and the muscles exhibiting fatigue.

Key:
Discomfort:-
A little uncomfortable (2) ◌
Fairly uncomfortable (3) ○
Uncomfortable (4) ●
Very uncomfortable (5) ●

Fatigue:-
Electrical activity increase ▲
Mean power frequency decrease ⬇

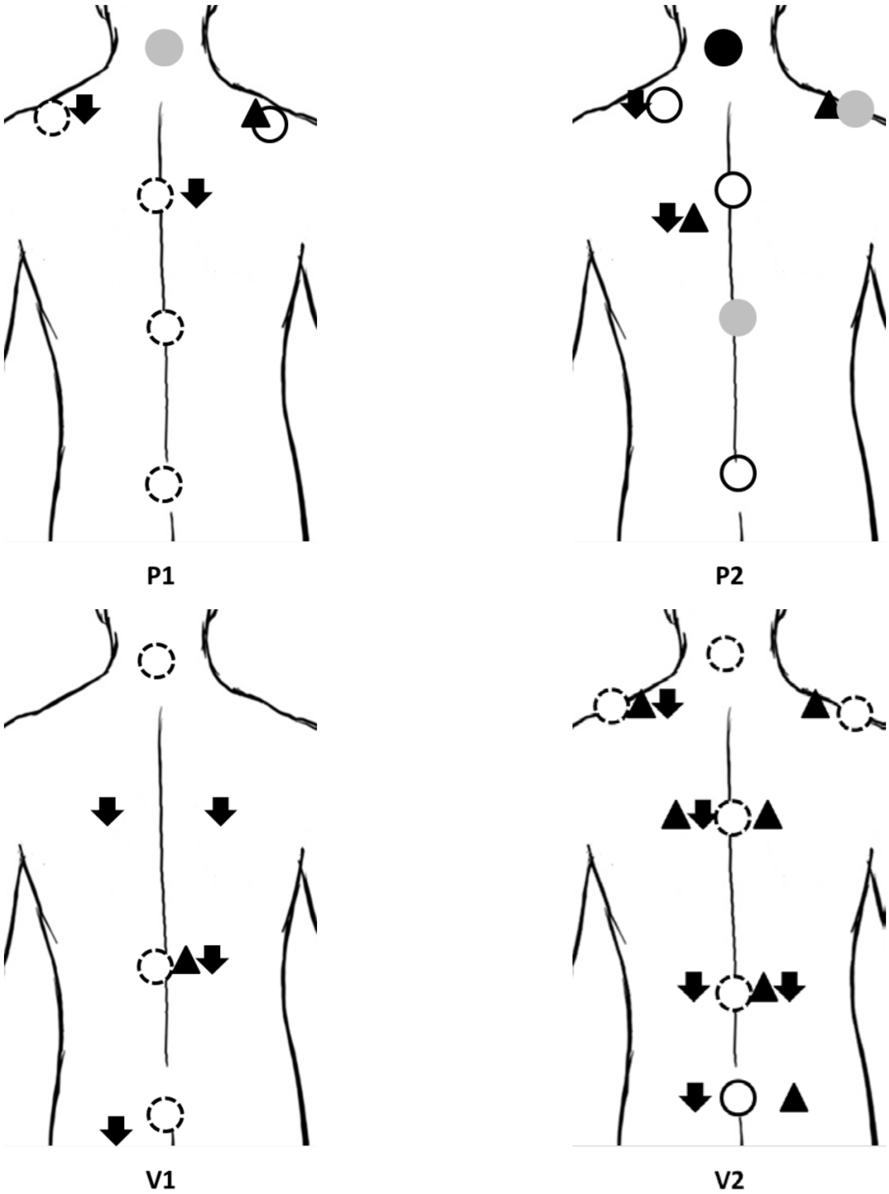


Figure 109 Images illustrate median discomfort score and muscles exhibiting fatigue for 10th minute results from Chapters 6 and 7

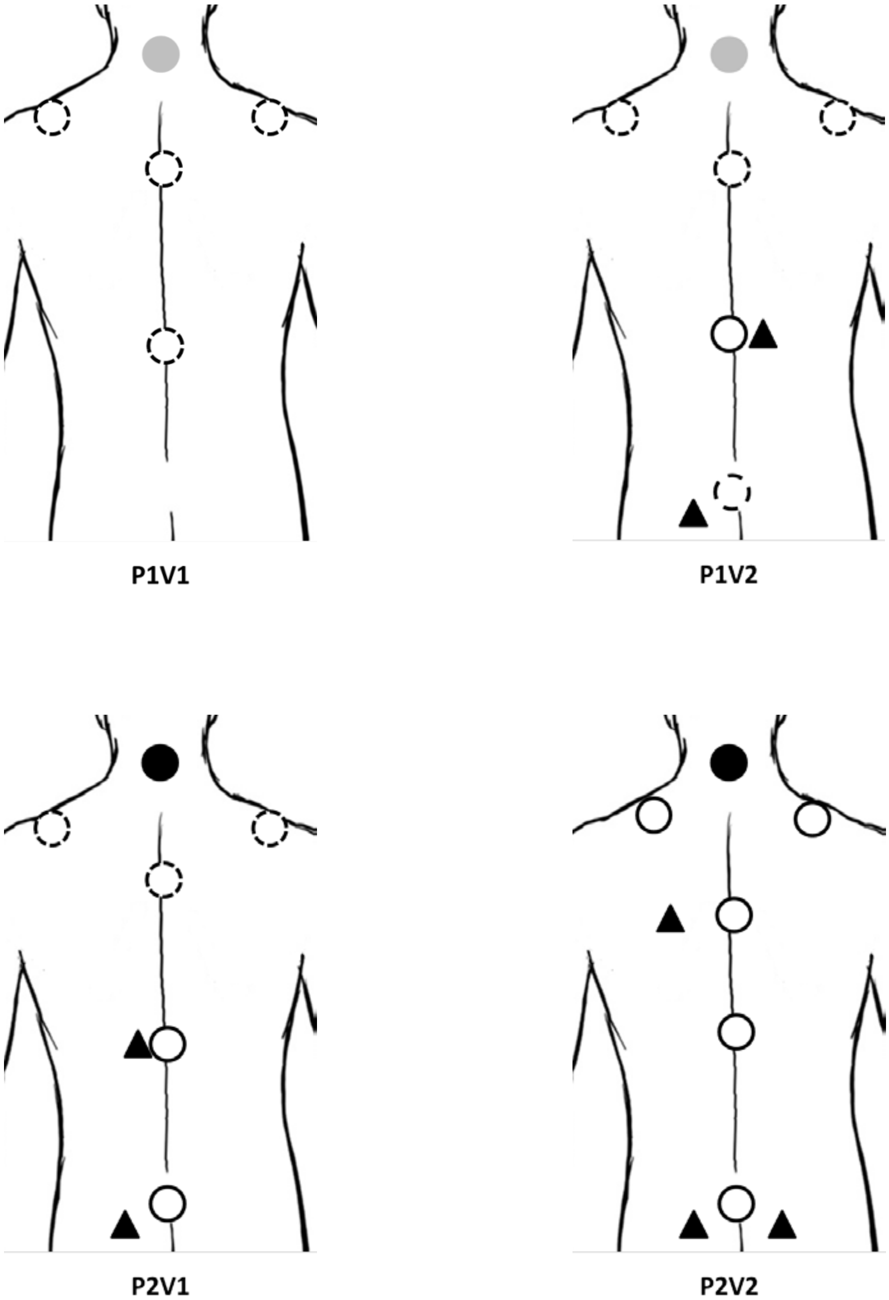
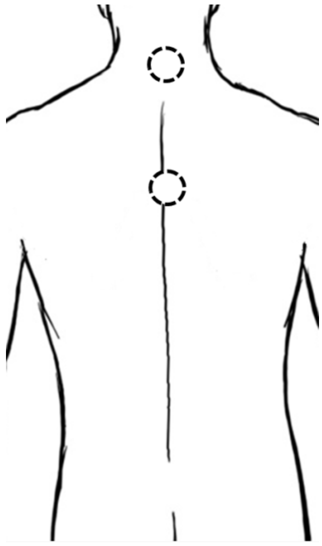
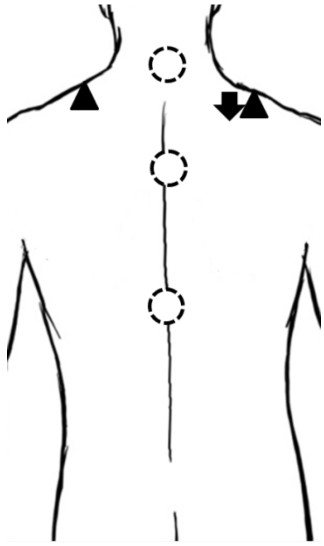


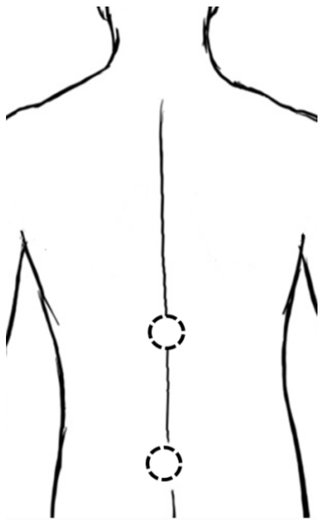
Figure 110 Images illustrate median discomfort score and muscles exhibiting fatigue for 7th minute results from Chapter 8



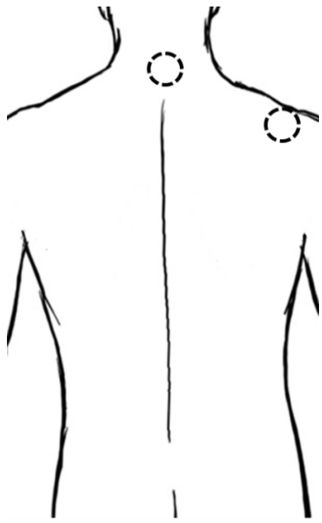
SB0 P0



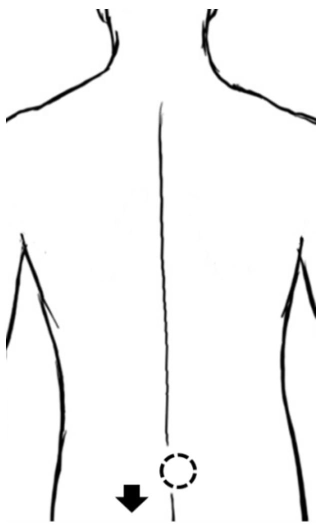
SB0 Pmov



SB30 P0



SB30 Pmov



SB90 Pmov

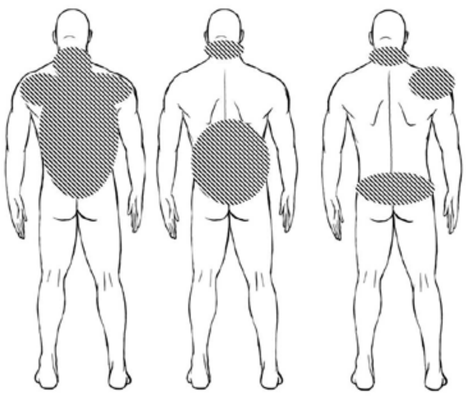
Figure 111 Images illustrate median discomfort score and muscles exhibiting fatigue for 7th minute results from Chapter 9

As can be seen from Figures 109, 110 and 111, the similarities between the muscles exhibiting fatigue and the areas of discomfort are variable. Although in some cases, the 2 methods appear to indicate similar muscles/areas for fatigue and discomfort (e.g. P1V1), in others there is greater disparity (e.g. V1 and V2). Therefore, it is suggested that the conclusions are similar to those reached by Bosch et al. (2007) in that the objective measures of fatigue, provided by electromyography does not clearly match areas of discomfort identified by the subjects involved.

Previous studies have focussed on the erector spinae for investigations of muscular response to a stimuli, particularly WBV. The results presented in this thesis indicate that consideration of the other muscles investigated (trapezius and multifidus) would provide an additional indication of the results of any exposure.

10.3 Evidence of influence from expert opinion and laboratory studies

In the survey of expert opinion, Chapter 5, 100% of ergonomists 78% of WBV experts considered exposure to high magnitudes of vibration *and* trunk rotation to be 'very' or 'extremely' risky for development of musculoskeletal disorders. 86%, 63% and 78% of operators, ergonomists and WBV experts respectively thought that the risk for LBP increased when exposures were combined. Experts were again asked to mark on a body outline where they considered operators would experience discomfort when exposed to both trunk rotation and WBV (Figure 112).



(a) (b) (c)

Figure 112 Areas where >40% judged to be uncomfortable when exposed to both whole body vibration and trunk rotation (a) ergonomists, (b) WBV experts, (c) operators

This can be compared to the results of the laboratory discomfort studies, where in the P2V2 condition, greatest discomfort was experienced in the neck, with less but equal discomfort experienced in the shoulders upper, middle and low back. The low back was noted by all expert groups aside from the operators in the twisted posture scenario. In comparison with the laboratory discomfort results, the predictions made by the operators as to where discomfort would be experienced show greatest coherence. This adds confidence to the validity of the laboratory results in that the discomfort experienced in 7-10 minutes is in similar areas to where operators would expect to experience discomfort. The varied responses of the expert groups are an illustration of the ambiguity in the area of musculoskeletal response to occupational exposures.

From the information discussed above, it is clear that the knowledge of the relationship between exposure and symptom development is incomplete. The epidemiological data cannot separate other factors (e.g. sitting duration may be an issue in addition to exposure to both trunk rotation and WBV). All expert groups considered the low back to be a concern for operators exposed to WBV, however there was little consensus on the other regions of the body. What was unambiguous though was the consideration of a likely risk increase when the exposures are combined. All experts rated more body regions at risk of symptom display, predicted higher risk levels and suggested lower exposure times for simultaneous exposures. The conclusions of the laboratory studies are less distinct. It is clear from the subjective discomfort ratings that exposures to trunk rotation caused discomfort to the subjects. The discomfort experienced from exposure to the magnitudes of WBV in this research was smaller, and did not increase above a level ‘4’ which is ‘uncomfortable’ in the discomfort ratings. The low back was the only area noticeably displaying levels of discomfort, therefore the link between the study and musculoskeletal risk is less clear. When the exposures were combined, the levels of discomfort marginally increased beyond that of a single exposure.

10.4 Experimental design

The seat used in the final laboratory study (Chapter 9) was different to the seat used in the previous laboratory studies (Chapters 6, 7 and 8). This change was to enable testing of seat base rotation within the investigation planned in Chapter 9. However, this change may have affected the ability to compare the results gained with the two different seats. The experiment in Chapter 9 has the control condition common to all other studies, but also the SB0 P0 condition was designed to be the same as the V0 condition in Chapter 7 so that the comparison between the 2 seats could be made. Analysis of the discomfort from the identical conditions with the 2 seats illustrates little difference between them. Subjects sat in seat 1 were marginally more uncomfortable.

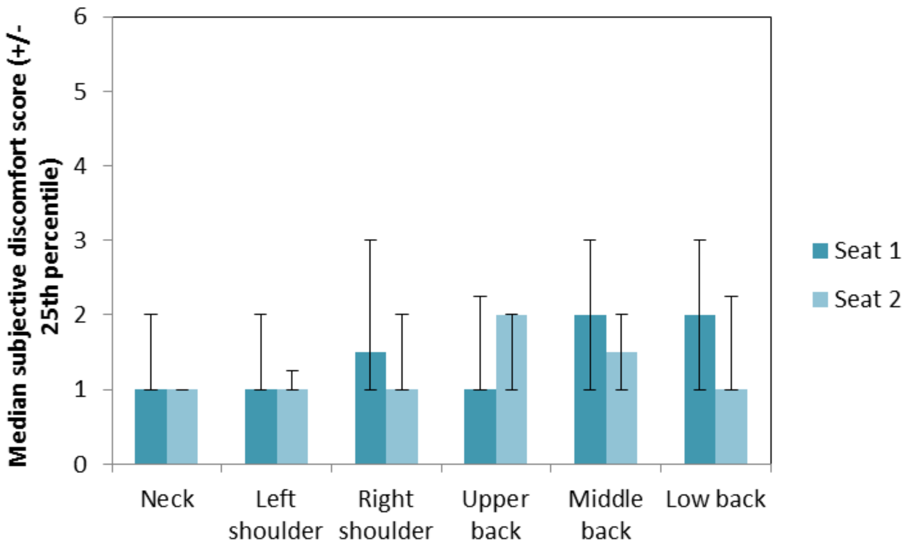


Figure 113 Comparison of discomfort between seat 1 (used in Chapter 7) and seat 2 (used in Chapter 9) in a comparable condition

Comparing the EMG data shows that when seated in seat 1, 4 of the 8 muscles fatigued, however when seated in seat 2 for a comparable condition, no muscles fatigued. There is no clear explanation of why this may be.

10.5 Future work

The results presented in this thesis illustrate both that operators are often exposed to high magnitude vibrations whilst rotating and that these types of exposures cause both subjective discomfort and muscular fatigue. The possibility of an interaction effect is not conclusive from the results. Further investigation of the nature of the interactions, employing different methodologies, with greater magnitudes of vibration would be an interesting addition to the work presented here.

Additional work would be required for the production of a new, or amending a current standard on assessing the risks from the types of exposures investigated within this thesis. It is suggested that this work would contain that outlined above.

The EMG results contained within the thesis were difficult to attain and evaluate. Further work on EMG methodologies, specifically for analysis of fatigue is needed before the use of EMG can become a widely used and trusted measure. Further investigation on the correlation, or lack thereof, between objective measures of muscle fatigue and subjective discomfort would add value to both methodologies.

The focus within epidemiology studies of driving occupations has been on the development of LBP. In the current study, neck and shoulder discomfort as a result of the exposure was more prevalent than low back discomfort when subjects are rotating. This suggests that the focus on LBP in current research may be too narrow in fully assessing the effects of WBV, widening this to encompass the neck and rest of the trunk would be beneficial to our understanding of the effects of the exposures.

Finally, many of the technical developments in agricultural vehicles, although often being of great benefit to the driver, are an optional extra when purchasing a new vehicle. This issue does not necessarily require further research attention, but does require the focus of the industry on this bad practice. It is understood that vehicles intended for use within the construction industry must not charge extra for additions such as suspension seats. It would be of great benefit to future users of agricultural vehicles if this practice could be extended.

Chapter 11: General Conclusions

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

- The field study illustrated that the postures highlighted by Bottoms and Barber in 1978 are still experienced, with high levels of axial rotation. Axial rotation is often to the physiological maximum and operators were often twisting for greater than 50% task time. The tasks with the highest frequency of twists was forage harvesting, and the task with the greater magnitude static twist was round bale wrapping

- The vibration assessments illustrated high magnitude vibration exposures are also prevalent. Many of the vibration exposures had shock exposures and resulted in PA(V)D limit values being exceeded. There was no consistent worst axis of vibration.

- Consensus of expert opinion suggested that the risks for LBP were greater when axial rotation and WBV exposures were combined. Experts were able to predict where discomfort would be greatest. Both vibration and ergonomics experts considered a greater need for recognition of the risks of combined exposures in risk assessment guidance.

- Discomfort was greatest in the neck, right shoulder and upper back when subjects were axially rotated to the right. When subjects were exposed to WBV only, greatest discomfort was in the low back. When the exposures were combined, greatest discomfort was in both the neck and low back. When exposed to dynamic rotation, discomfort was greatest in the neck, middle and low back.

- Measures of electrical activity indicated increased activity and therefore fatigue for 2 muscles in the axial rotation study, and when exposures were combined (P1V2 and P2V1). Three muscles showed activity increases in the P2V2 condition. The greatest increases in activity were when participants were exposed to vibration, when 6 muscles exhibited fatigue.

- Measures of spectral shift indicated a low frequency (left) shift in 2 muscles in the axial rotation study, 5 muscles when participants were exposed to vibration and 1 muscle when exposed to dynamic rotation

- The muscles exhibiting fatigue most frequently in response to the conditions were the Trapezius decendens and the multifidus respectively.

- The subjective results indicate evidence for an increased risk for musculoskeletal discomfort when exposed to vibration and axial rotation, in comparison to WBV solely. There is no indication that adding vibration to a condition where an operator may already axially rotated would increase the discomfort, for the vibration magnitudes investigated here.

- The EMG fatigue results indicate high levels of fatigue when exposed solely to vibration. In comparison between axial rotation with and without vibration exposure. When additionally exposed to WBV, measures of electrical activity indicate an increased risk. This is not corroborated by the frequency results.

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Appendix

a) **Survey of expert opinion: posture and vibration experts**

An Expert Review of Occupational Exposures in Agriculture: A Questionnaire

Loughborough University

Background Information

The majority of tractor-driven implements are attached at the rear of the vehicle. This factor, in addition to the requirement for forward driving focus, means that a tractor operator will spend much of their task time in a twisted posture.

Researchers at Loughborough University are conducting studies to explore the possible interaction effects between exposure to whole-body vibration and trunk rotation (twist).

Currently, whole-body vibration standards include a minor account of the posture of the driver. There are no posture assessment tools tailored to the driving environment. Those which can be loosely applied do not include whole-body vibration exposure in their analysis.

This survey aims to capture current expert opinion on some typical driving tasks seen in agriculture. The questionnaire focuses on the posture of the driver and the whole-body vibration exposure.

This survey should take approximately 15minutes to complete. There are many open-ended comment boxes distributed throughout the questionnaire, please feel free to write any additional notes in these boxes. Please deposit completed questionnaires in the box on the registration desk, or pick up an envelope for postal return.

We appreciate you participation in the research project. Please note that responses will be kept anonymous. The results of the study will serve to inform the conclusions of the research.

If you have any further questions about this survey, or would like any additional information about the wider research project, please contact the principal researcher:

Lauren Morgan (Doctoral Researcher)
Environmental Ergonomics Research Group
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Tel: 01509 228485

Many thanks for your time and participation in the study.

Context

Whole-body vibration: Occurs when a person is supported by a surface that is shaking, e.g. forklift truck driver travelling over a bumpy surface

Trunk rotation: Occurs when a person turns to face a different direction to where their knees are facing, e.g. said forklift driver looking over shoulder to reverse.

1. Please indicate your **main** area of expertise (*please tick 1 response*)

- [ ] Ergonomics - Posture
- [ ] Ergonomics - Vibration
- [ ] Ergonomics - Other
- [ ] Operator - Agriculture/Forestry
- [ ] Operator - Mining/Quarrying
- [ ] Other (Please State) ______________________________

2. Please estimate your length of experience in this area

- [ ] < 1 year
- [ ] 1 – 2 years
- [ ] 2 – 5 years
- [ ] 5 - 10 years
- [ ] 10 < years

Interaction Effects

3. Do you consider exposure to whole-body vibration to be a risk for low back pain?

- ☐ Yes
- ☐ No
- ☐ Maybe
- ☐ Not qualified to answer

a) My confidence level in assessing this is: (*please tick one*)
Low ☐ Medium ☐ High ☐

4. Do you consider trunk rotation to be a risk for low back pain?

- ☐ Yes
- ☐ No
- ☐ Maybe
- ☐ Not qualified to answer

b) My confidence level in assessing this is: (*please tick one*)
Low ☐ Medium ☐ High ☐

5. Do you think the risks posed by exposure to whole-body vibration and rotation of the trunk **increase** when the exposures are combined?

- ☐ Yes
- ☐ No
- ☐ Maybe
- ☐ Not qualified to answer

c) My confidence level in assessing this is: (*please tick one*)
Low ☐ Medium ☐ High ☐

For the next series of questions, you will be asked to estimate acceptable exposure durations for the tasks.

6. a) Please estimate what you would consider an acceptable exposure time for a seated task requiring a twisted trunk?

No twist seated posture		hrs		mins
Medium twist (70°) seated posture		hrs		mins
High twist (170°) seated posture		hrs		mins

b) The task now includes whole-body vibration of magnitude 0.5m/s² A(8), (eg. driving ???). Please estimate acceptable exposure times for this task

No twist seated posture with vibration		hrs		mins
Medium twist (70°) seated posture with vibration		hrs		mins
High twist (170°) seated posture with vibration		hrs		mins

Please rate the following scenarios on the level of risk for developing low back pain. (*Please tick one box for each scenario)*

1 – no risk
2 – low risk
3 – moderately risky
4 – risky
5 – highly risky
6 – extremely risky

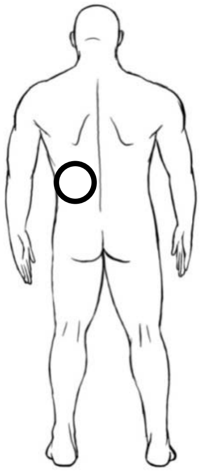
(*1 being no risk, 6 being high risk*)

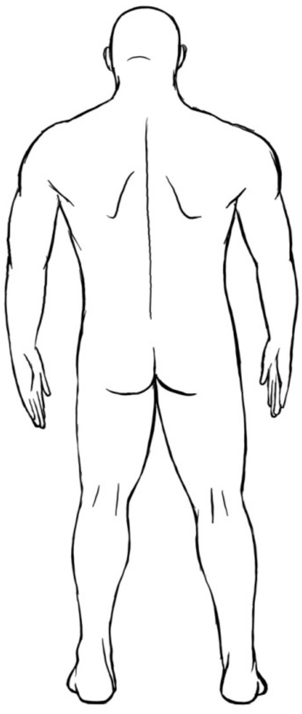
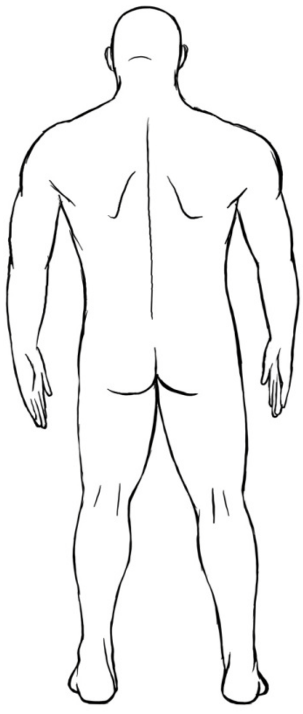
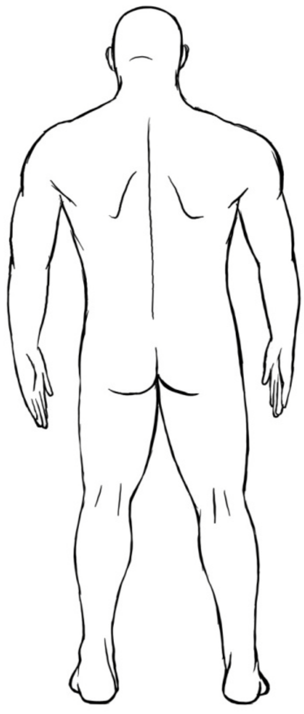
Scenario	**1**	**2**	**3**	**4**	**5**	**6**
Low vibration (road driving), no twist						
Medium vibration (off road driving), no twist						
High vibration(off road, with shocks), no twist						
Low vibration, medium twist (70°)						
Medium vibration, medium twist						
High vibration, medium twist						
Low vibration, high twist (170°)						
Medium vibration, high twist						
High vibration, high twist						

c) My confidence level in assessing this is: (*please tick one*)
Low ☐ Medium ☐ High ☐

7. Please indicate on the body maps below any areas you feel the operator may experience discomfort either during, or after exposure. Mark as many areas as you feel appropriate.

e.g. *The mark below would show discomfort in the elbow.*



a) High vibration magnitude	b) Full twist	c) High vibration and full twist
		

Further comments:

8. Do you have experience in assessing whole-body vibration exposure or using posture assessment tools?

☐	Yes – WBV assessment	*please continue to q.10 (below)*
☐	Yes – posture assessment	*please continue to q.11 (pg. 9)*
☐	No	*please continue to q.12 (pg. 10)*

9. Would you suggest the posture of the operator should be considered and reflected in guidelines on whole-body vibration?

Standard	Yes	No	Maybe
BS 6841 (1987)			
ISO 2631 (1997)			
Physical Agents (Vibration) Directive (2002)			

a) My confidence level in assessing this is: (*please tick one*)
Low ☐ Medium ☐ High ☐

b) Further comments (including recommendations if applicable)

If you also have working knowledge of posture assessment tools, please continue to q.11, otherwise please skip to q. 12.

10. a) Would you recommend a posture assessment tool for use in a driving environment was developed?

- [ ] Yes
- [ ] No
- [ ] Maybe

b) Would you recommend inclusion of whole-body vibration exposure in this tool?

- [ ] Yes
- [ ] No
- [ ] Maybe

c) My overall confidence level in assessing this is: (*please tick one*)

Low [ ] Medium [ ] High [ ]

d) Further comments (including recommendations if applicable)

Agricultural driving tasks

This section includes descriptions of some common driving tasks seen in agriculture. You will then be asked whether you would recommend some additions/modifications that have been suggested by previous research.

If you feel you do not have enough experience in this area, thank you very much for your time you have completed the questionnaire. Hand-in information is on the back page.

Task: An agricultural driver is required to plough an uneven field. This task requires constant rear and forward attention. The task will take approximately 8hours, during which time the driver will leave the cab for 30mins to have lunch. Which, if any, of the following additions would you recommend the driver uses? (*Please tick one box for each item)*

	Would recommend	Wouldn't recommend	Not qualified to comment
Full backrest seat			
Swivel Seat			
CCTV			
Enlarged mirrors			
Other (please specify):			

a) My confidence level in assessing this is: (*please tick one*)
Low ☐ Medium ☐ High ☐

Any further comments for this section:

Thank you for your time in completing this survey. Your insight and knowledge are very valuable to the development of this research project. Please use the space provided below to contribute any further comments you may have on the topic area.

Please deposit the completed questionnaire in the box situated at the conference registration desk.

b) Survey of expert opinion – for operator experts

Operator questionnaire

This survey is designed to establish the relative importance of twisted postures and vibration as risk factors for low back pain, in the opinion of agricultural professionals.

It should take approximately 15minutes to complete. There are many open-ended comment boxes distributed throughout the questionnaire, please feel free to write any additional notes in these boxes.

We appreciate you participation in the research project. Please note that responses will be kept anonymous. The results of the study will serve to inform the conclusions of the research.

If you have any further questions about this survey, or would like any additional information about the wider research project, please contact the principal researcher:

Lauren Morgan (Doctoral Researcher)
Environmental Ergonomics Research Group
Loughborough University
E-mail: l.j.morgan@lboro.ac.uk
Tel: 01509 228485

Background information:

Please indicate your **main** area of expertise (*please tick 1 response*)

- ☐ Arable
- ☐ Livestock
- ☐ Dairy
- ☐ Poultry
- ☐ Contractor
- ☐ Maintenance
- ☐ Other, please specify: ________________________________

Please estimate your length of experience in this area

- ☐ < 1 year
- ☐ 1 – 2 years
- ☐ 2 – 5 years
- ☐ 5 - 10 years
- ☐ 10 < years

Please estimate the typical driving time (per day) during busy periods

- ☐ < 1 hour
- ☐ 1 – 2 hours
- ☐ 2 – 5 hours
- ☐ 5 - 10 hours
- ☐ 10 < hours

Please estimate the number of rest periods taken during this driving time

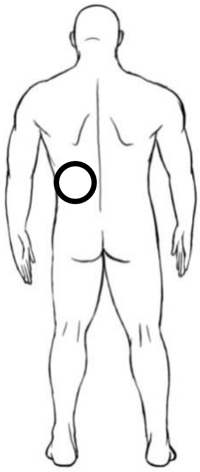
- ☐ 0
- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4 <

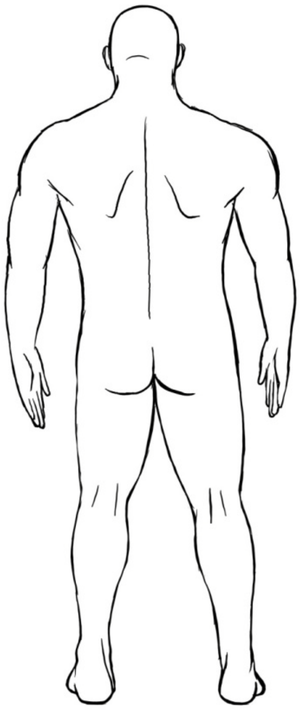
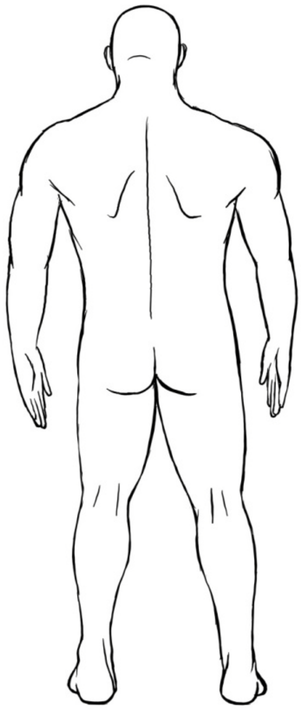
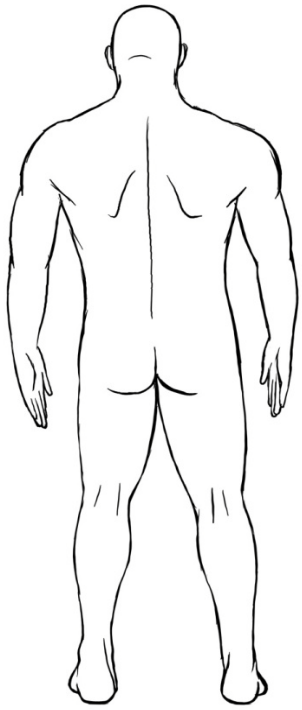
Body Map

Please indicate on the body maps below any areas you feel the operator may experience discomfort either during, or after exposure to vibration or twisted postures. Mark as many areas as you feel appropriate.

Vibration: Occurs when a person is seated on a surface that is shaking e.g. travelling over a rough road. High vibration would be equivalent to travelling on the rougher surfaces you may have experienced.
Twist: Turning to face a different direction to where the knees are facing e.g. looking over a shoulder to reverse. Full twist would be turning to look past the shoulder.

e.g. *The mark below would show discomfort in the elbow.*



d) High vibration magnitude	e) Full twist	f) High vibration and full twist
		

Further comments:

Are there any tasks in particular that cause you discomfort?

Is there a way you think this discomfort could be reduced?

Risks

Do you consider exposure to whole-body vibration to be a risk for low back pain?

- ☐ Yes
- ☐ No
- ☐ Maybe
- ☐ Not qualified to answer

d) My confidence level in assessing this is: (*please tick one*)

Low ☐ Medium ☐ High ☐

Do you consider trunk rotation to be a risk for low back pain?

- ☐ Yes
- ☐ No
- ☐ Maybe
- ☐ Not qualified to answer

e) My confidence level in assessing this is: (*please tick one*)

Low ☐ Medium ☐ High ☐

Do you think the risks posed by exposure to whole-body vibration and rotation of the trunk **increase** when the exposures are combined?

- ☐ Yes
- ☐ No
- ☐ Maybe
- ☐ Not qualified to answer

My confidence level in assessing this is: (*please tick one*)

Low ☐ Medium ☐ High ☐

Durations of Exposure

For the next series of questions, you will be asked to estimate acceptable exposure durations for the tasks.

Please estimate what you would consider an acceptable exposure time for a seated task requiring a twisted trunk, with **no** vibration?

No twist seated posture		hrs		mins
Medium twist (70°) seated posture		hrs		mins
High twist (170°) seated posture		hrs		mins

The task now includes vibration exposure, (equivalent to driving down a rough track). Please estimate acceptable exposure times for this task

No twist seated posture with vibration		hrs		mins
Medium twist (70°) seated posture with vibration		hrs		mins
High twist (170°) seated posture with vibration		hrs		mins

Driving Tasks
This section includes descriptions of some common driving tasks seen in agriculture. You will then be asked whether you would recommend some additions/modifications that have been suggested by previous research.

Task: An agricultural driver is required to plough an uneven field. This task requires constant rear and forward attention. The task will take approximately 8hours, during which time the driver will leave the cab for 30mins to have lunch. Which, if any, of the following additions would you recommend the driver uses? (*Please tick one box for each item)*

	Would recommend	Wouldn't recommend	Not qualified to comment
Full backrest seat			
Swivel Seat			
CCTV			
Enlarged mirrors			
Other (please specify):			

c) My confidence level in assessing this is: (*please tick one*)
Low ☐ Medium ☐ High ☐

Thank you for your time in completing this survey. Your insight and knowledge are very valuable to the development of this research project. Please use the space provided below to contribute any further comments you may have on the topic area.

Please hand the completed questionnaire back to Miss Morgan, or deposit in the box situated on the stand

c) Dynamic rotation text file

Fist column controls the light that is activated, second column controls the length of time that light is activated for. The duration is 7 minutes.

2	9
4	14
3	13
1	14
5	11
5	14
3	13
4	6
3	11
1	12
1	13
2	8
2	11
2	11
2	7
4	14
5	15
3	8
5	6
4	13
2	8
4	12
3	12
5	9
4	6
1	15
3	10
2	11
2	13
3	10
1	8
5	14
4	10
1	7
4	9
5	9
1	9
1	7
3	10
5	8

d) Exclusion criteria for laboratory studies

If any of the following are indicated by the participant, then they would be excluded from participating in the study

- On a hospital waiting list
- Attending GP
- Convulsions/epilepsy
- Blood disorder
- Head injury
- Digestive problems
- Heart problems
- Problems with bones or joints
- Disturbance of balance/coordination
- Numbness in hands or feet
- Disturbance of vision
- Ear/hearing problems
- Thyroid problems
- Kidney or liver problems
- Family member under age of 35 died suddenly after exercise

The following are for female participants only

- Pregnancy
- Hormone replacement therapy

e) Individual gradient data for Chapter 6

All participant results are shown for each muscle. The muscles are coded on the graphs as follows. 1 – trapezius descendens L (TD L), 2 – trapezius decendens R (TD R), 3 – trapezius ascendens L (TA L), 4 – trapezius ascendens R (TA R), 5 – erector spinae L (ES L), 6 – erector spinae R (ES R), 7 – multifidus L (MF L), 8 – multifidus R (MF R).

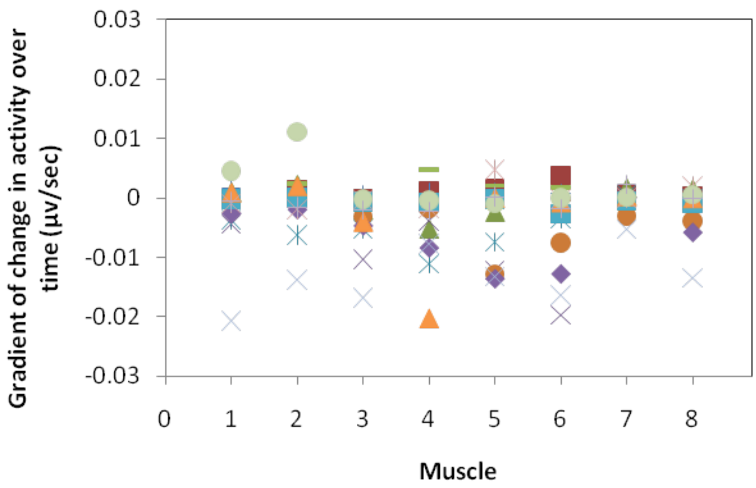


Figure 114 P0: Change in muscle activity over time, shown as the gradient (positive values indicate an increase in muscle activity).

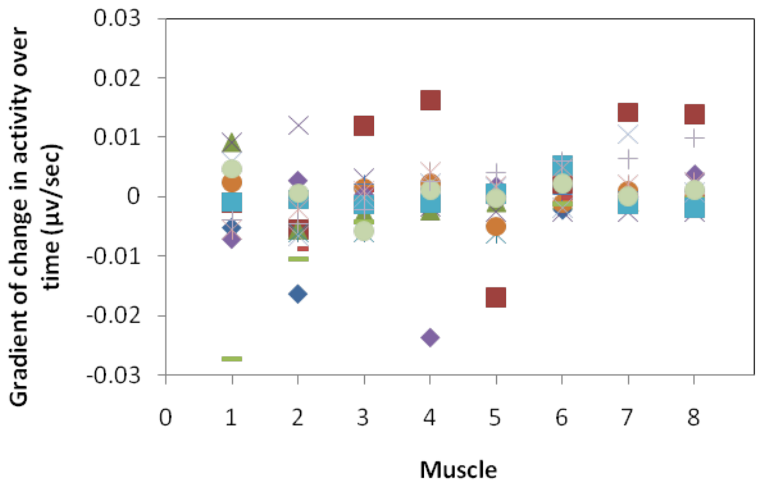


Figure 115 P1: Change in muscle activity over time, shown as the gradient (positive values indicate an increase in muscle activity)

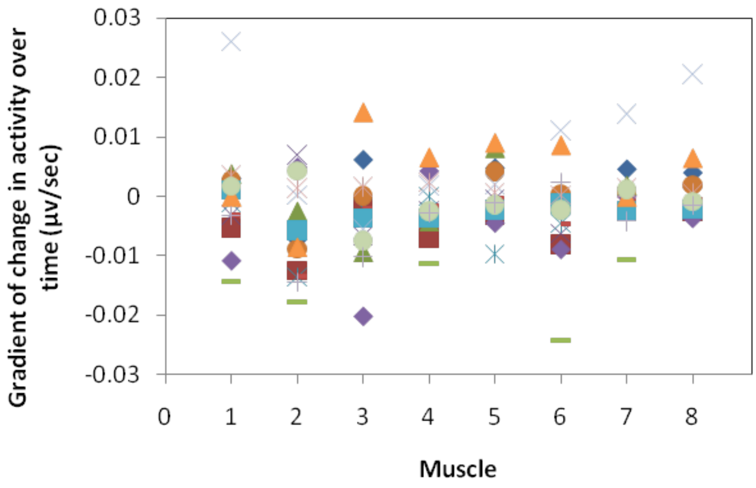


Figure 116 P2: Change in muscle activity over time, shown as the gradient (positive values indicate an increase in muscle activity)

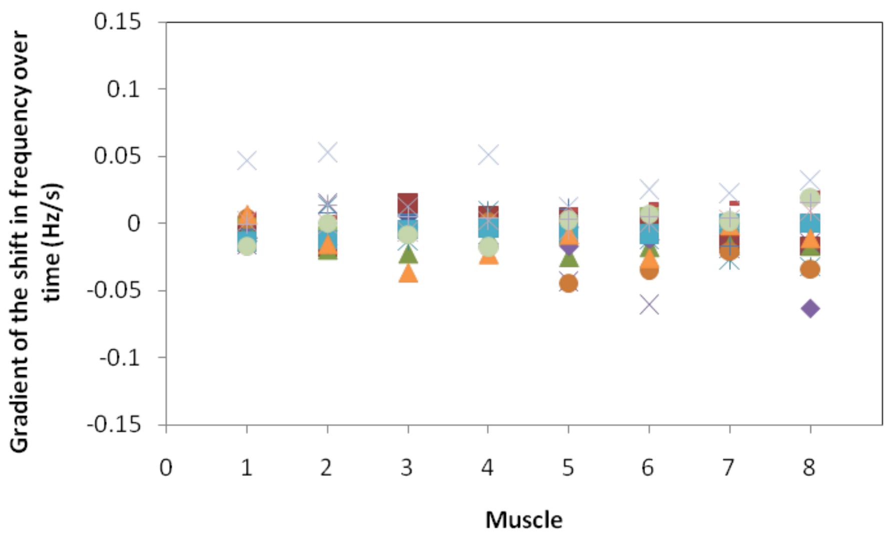


Figure 117 P0: Change in frequency spectrum over time, shown as the gradient (negative values indicate a decrease in MPF)

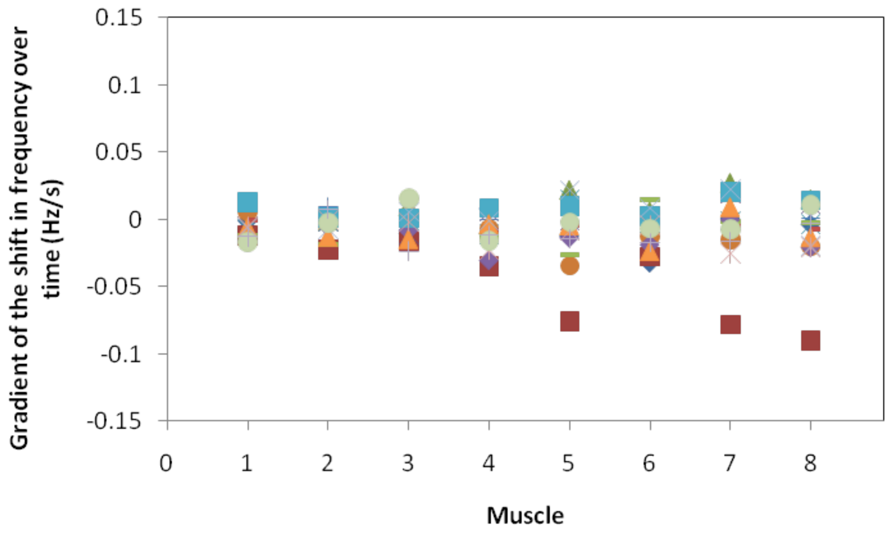


Figure 118 P1: Change in frequency spectrum over time, shown as the gradient (negative values indicate a decrease in MPF)

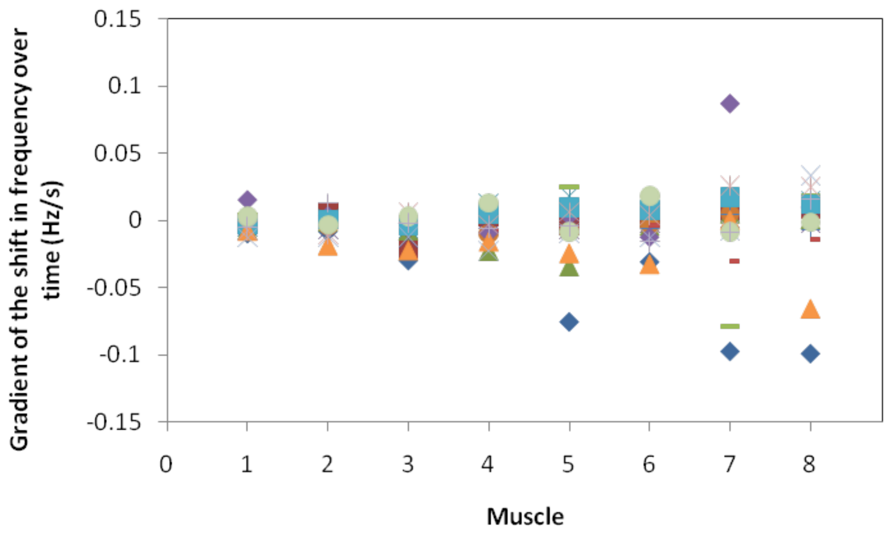


Figure 119 P2: Change in frequency spectrum over time, shown as the gradient (negative values indicate a decrease in MPF)

f) Individual gradient data for Chapter 7

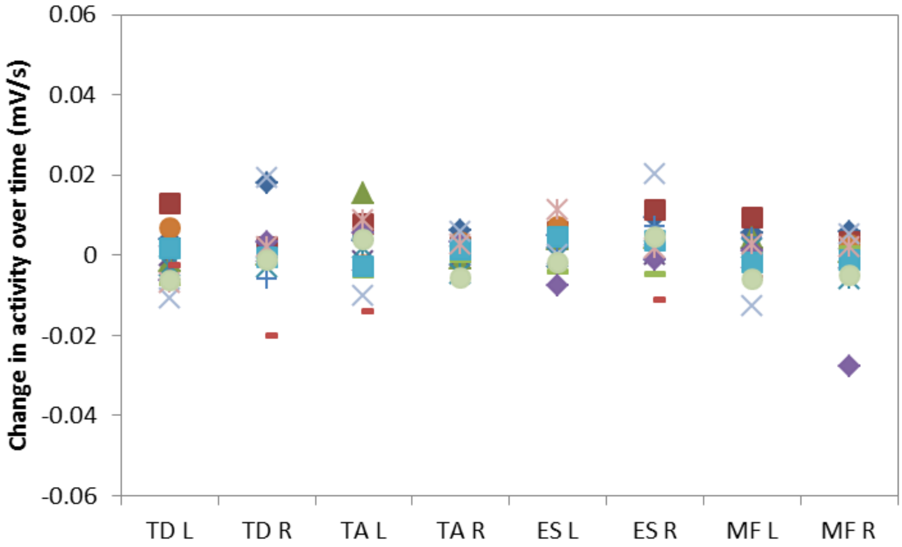


Figure 120 V0: Change in muscle activity over time, shown as the gradient (positive values indicate an increase in muscle activity).

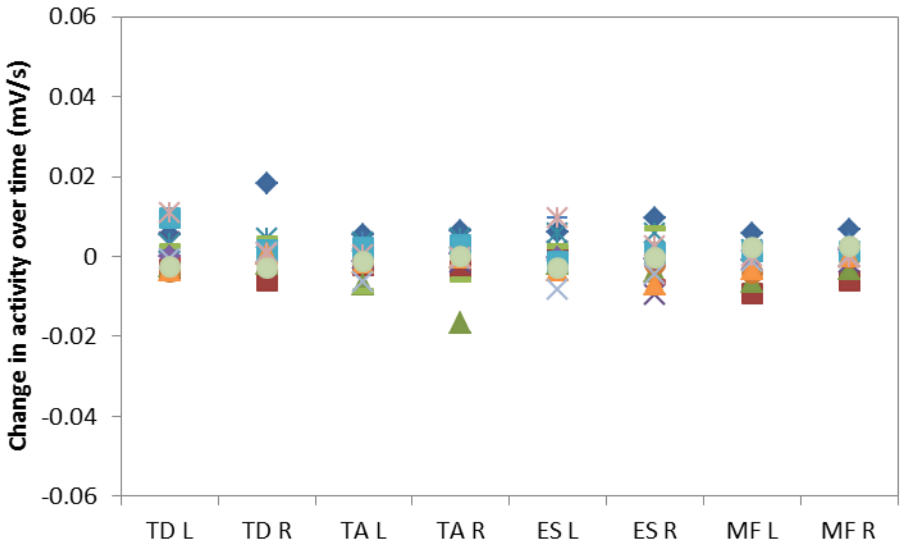


Figure 121 V1: Change in muscle activity over time, shown as the gradient (positive values indicate an increase in muscle activity).

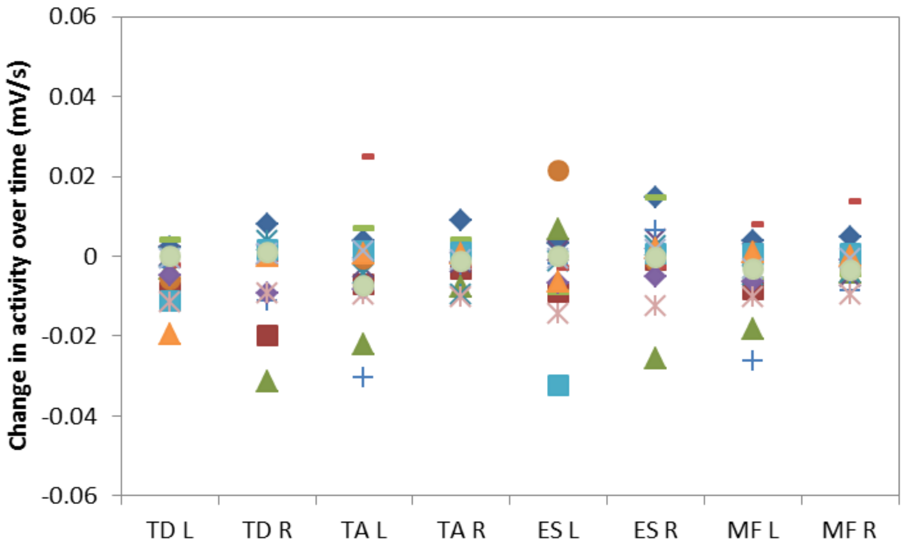


Figure 122 V2: Change in muscle activity over time, shown as the gradient (positive values indicate an increase in muscle activity).

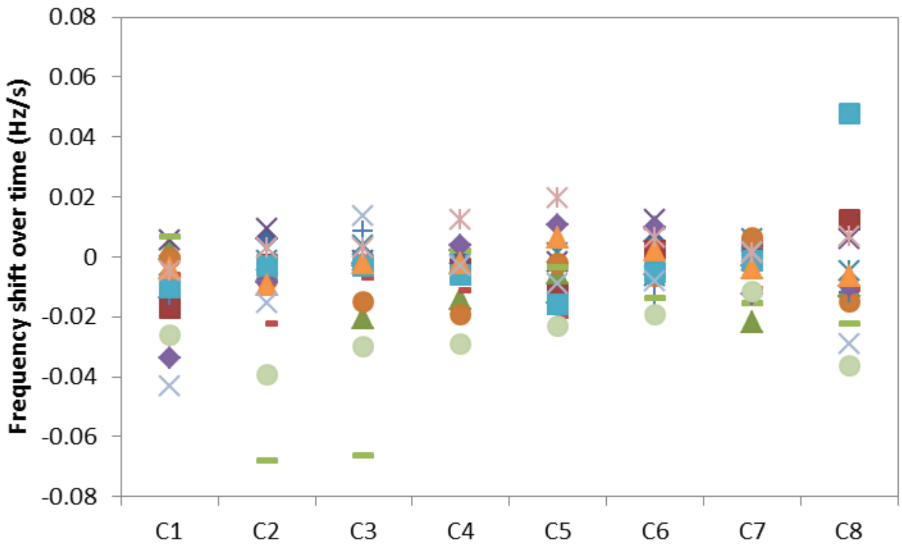


Figure 123 V0: Change in muscle frequency over time, shown as the gradient (negative values indicate a decrease in muscle activity)

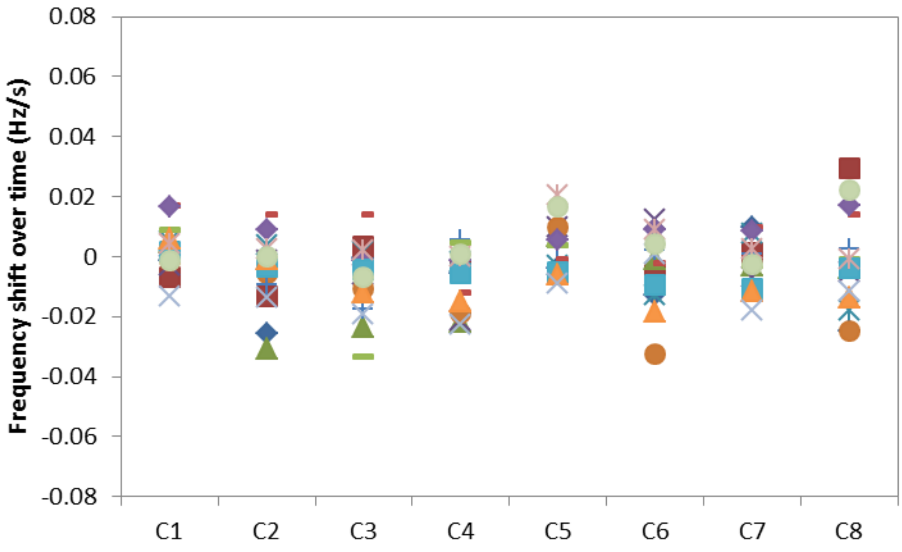


Figure 124 V1: Change in muscle frequency over time, shown as the gradient (negative values indicate a decrease in muscle activity)

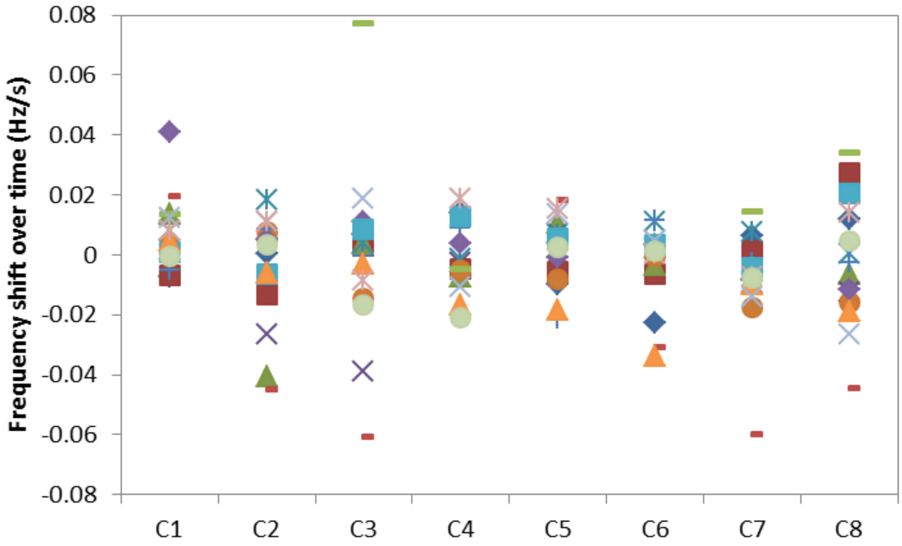


Figure 125 V2: Change in muscle frequency over time, shown as the gradient (negative values indicate a decrease in muscle activity)

g) Individual gradient data for Chapter 8

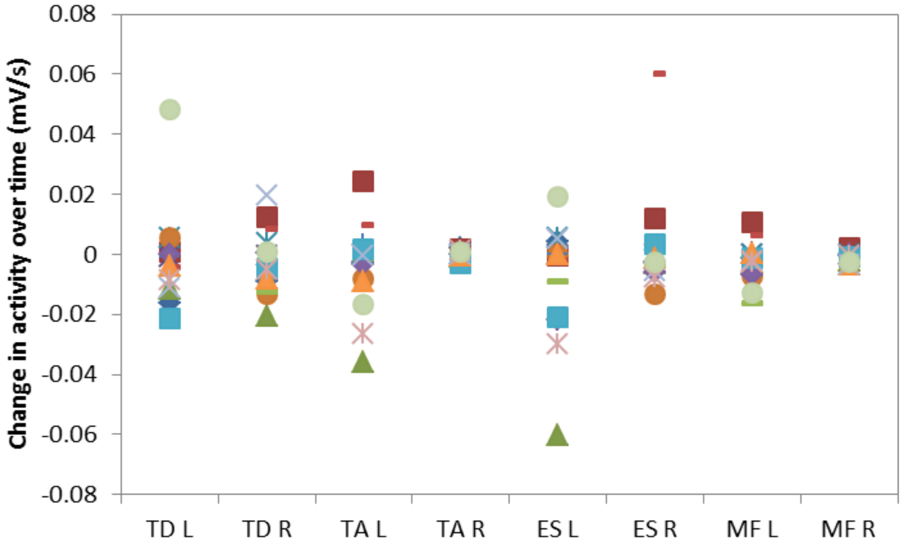


Figure 126 PV0: Change in muscle activity over time, shown as the gradient (positive values indicate an increase in muscle activity)

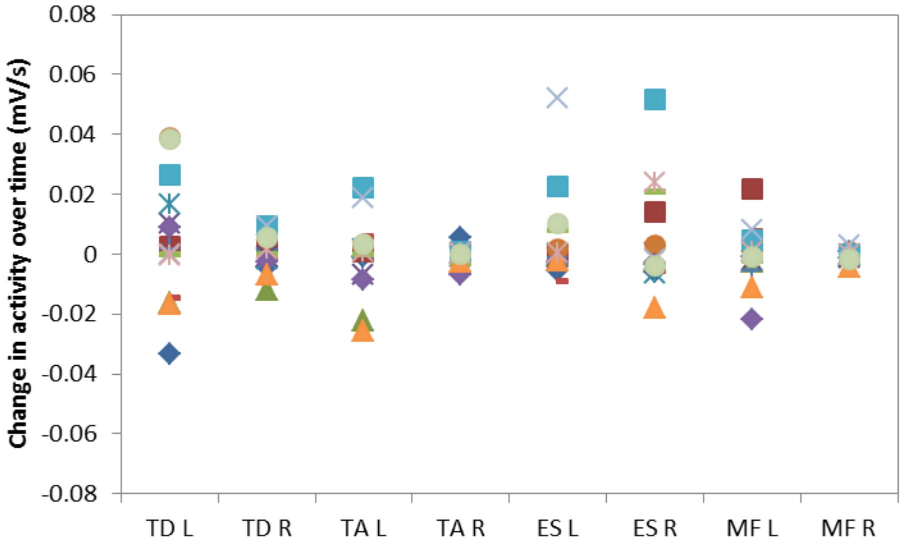


Figure 127 P1V1: Change in muscle activity over time, shown as the gradient (positive values indicate an increase in muscle activity)

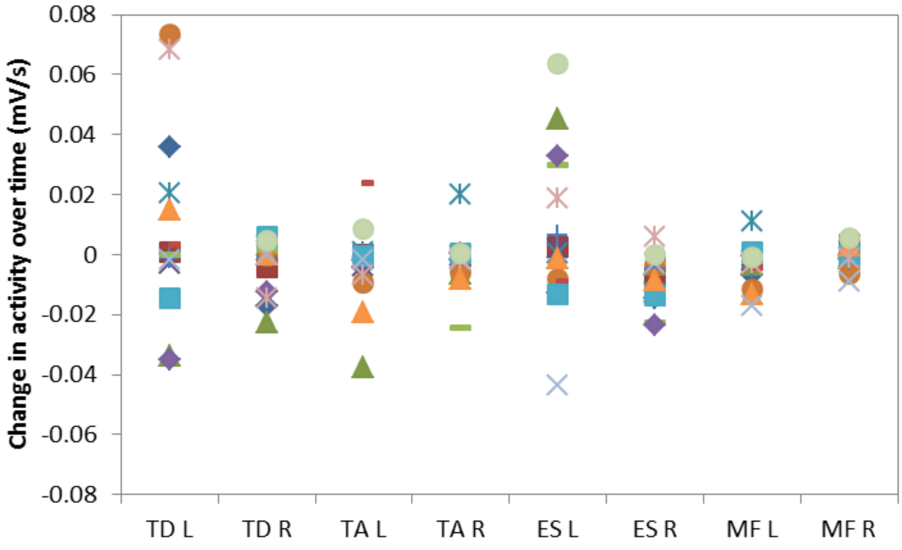


Figure 128 P1V2: Change in muscle activity over time, shown as the gradient (positive values indicate an increase in muscle activity)

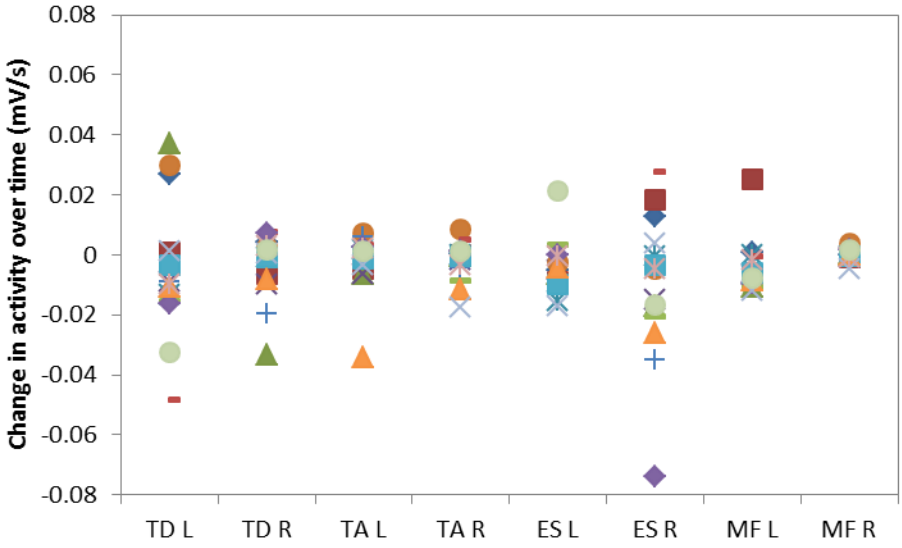


Figure 129 P2V1: Change in muscle activity over time, shown as the gradient (positive values indicate an increase in muscle activity)

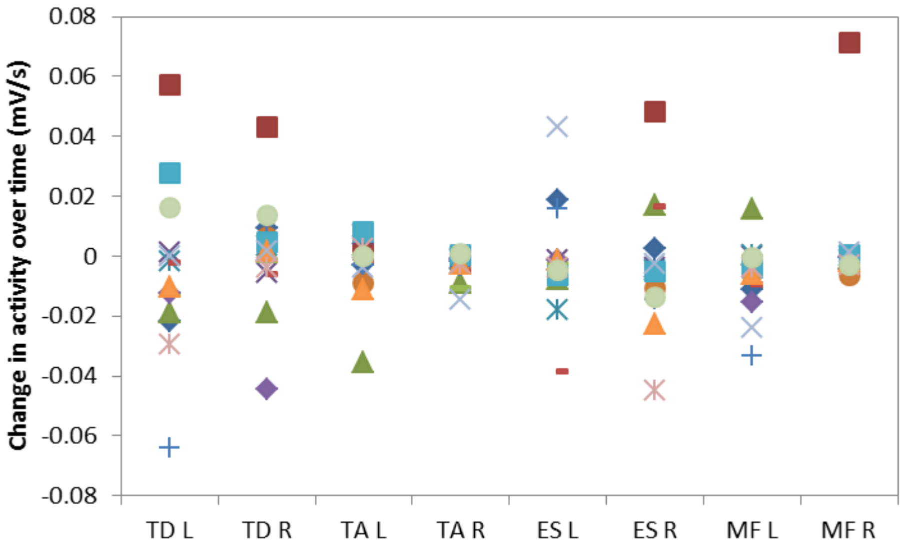


Figure 130 P2V2: Change in muscle activity over time, shown as the gradient (positive values indicate an increase in muscle activity)

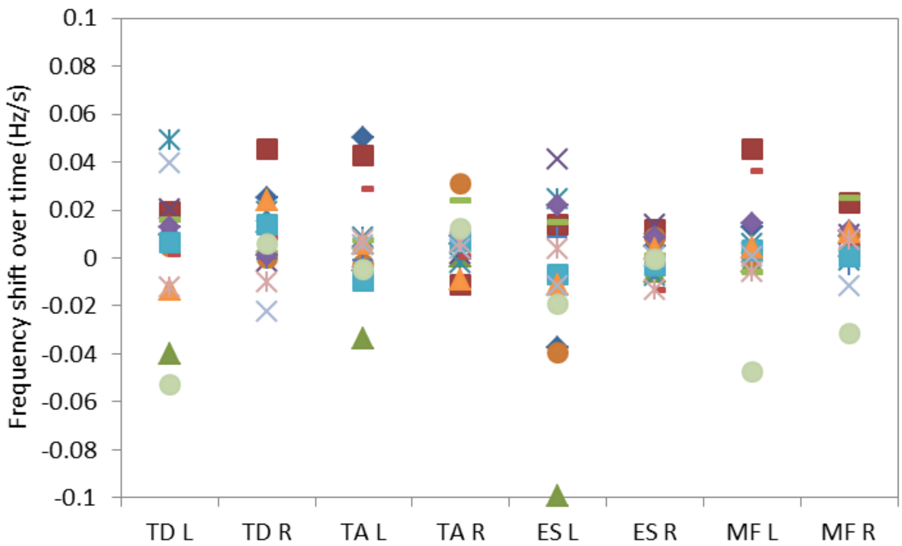


Figure 131 PV0: Change in frequency over time, shown as the gradient (negative values indicate a decrease in frequency)

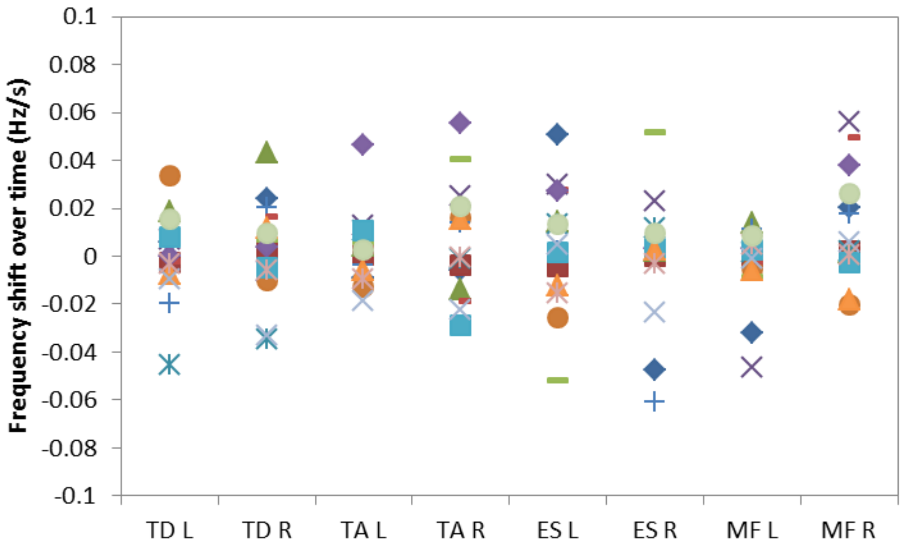


Figure 132 P1V1: Change in frequency over time, shown as the gradient (negative values indicate a decrease in frequency)

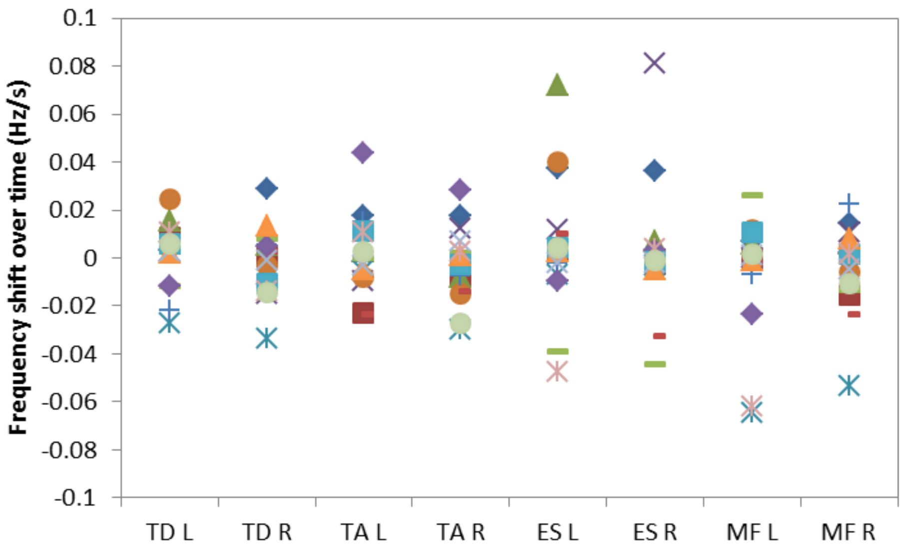


Figure 133 P1V2: Change in frequency over time, shown as the gradient (negative values indicate a decrease in frequency)

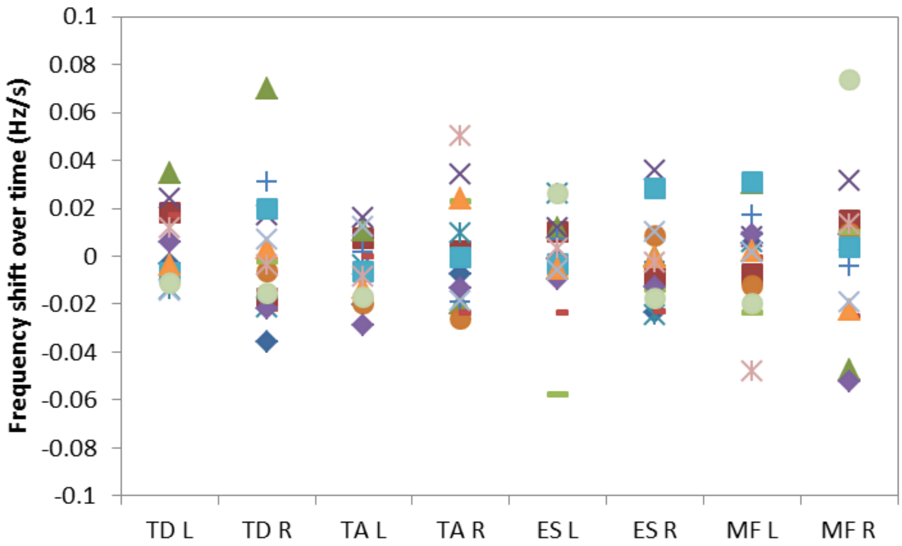


Figure 134 P2V1: Change in frequency over time, shown as the gradient (negative values indicate a decrease in frequency)

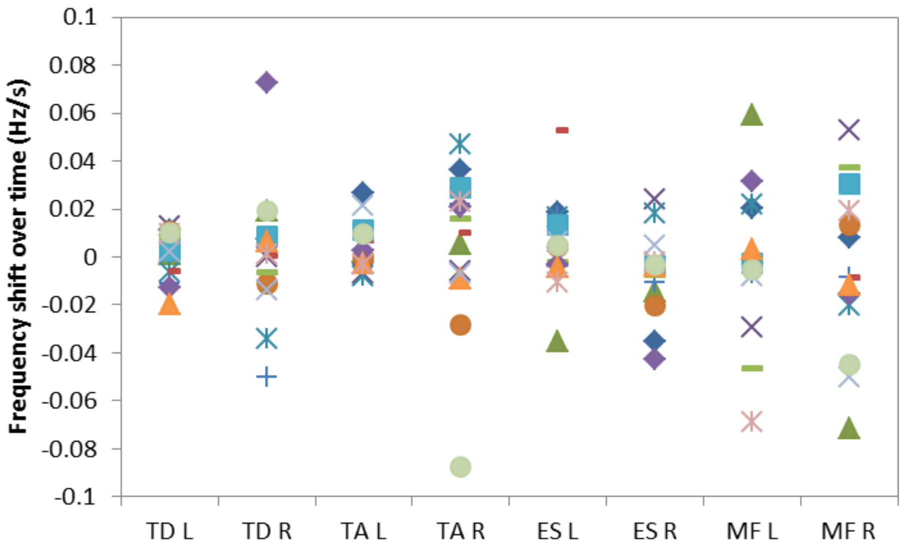


Figure 135 P2V2: Change in frequency over time, shown as the gradient (negative values indicate a decrease in frequency)

h) Individual gradient data for Chapter 9

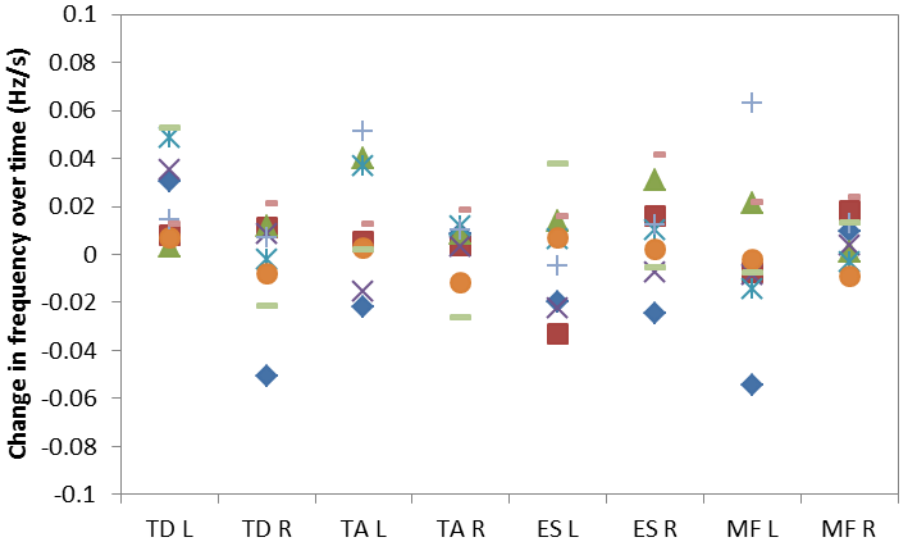


Figure 136 Control: Change in frequency over time, shown as the gradient (negative values indicate a decrease in frequency)

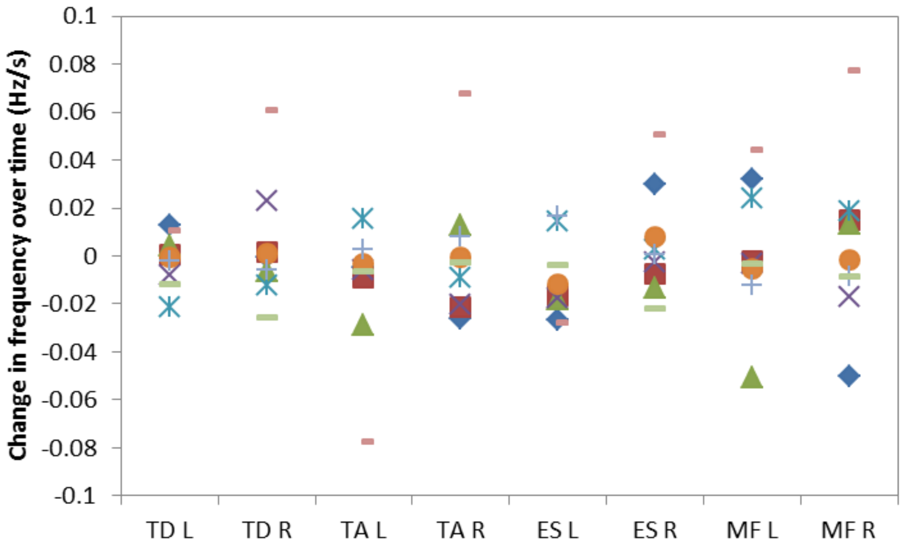


Figure 137 SB0 P0: Change in frequency over time, shown as the gradient (negative values indicate a decrease in frequency)

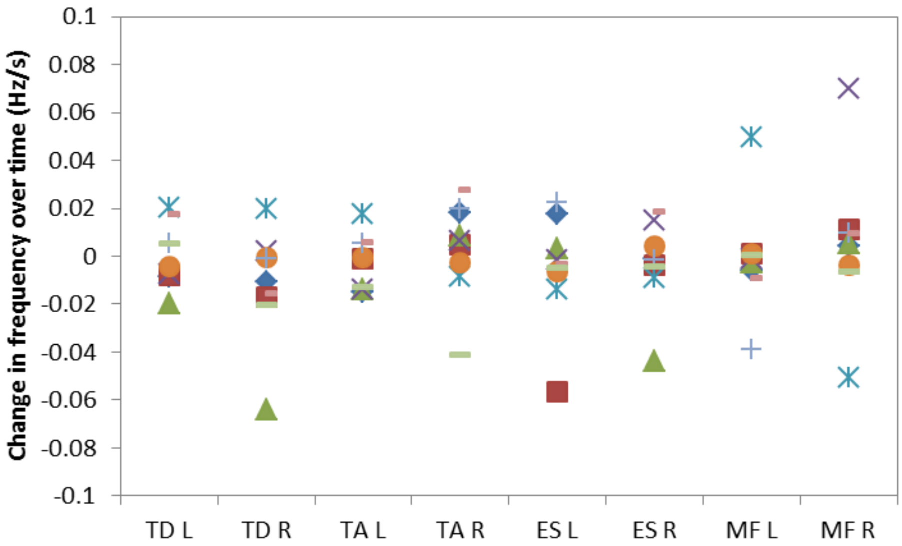


Figure 138 SB0 Pmov: Change in frequency over time, shown as the gradient (negative values indicate a decrease in frequency)

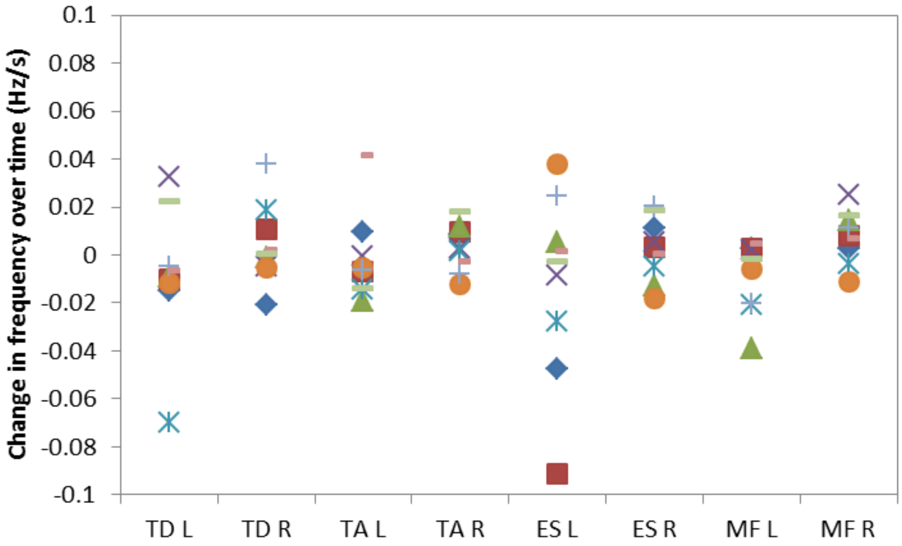


Figure 139 SB30 P0: Change in frequency over time, shown as the gradient (negative values indicate a decrease in frequency)

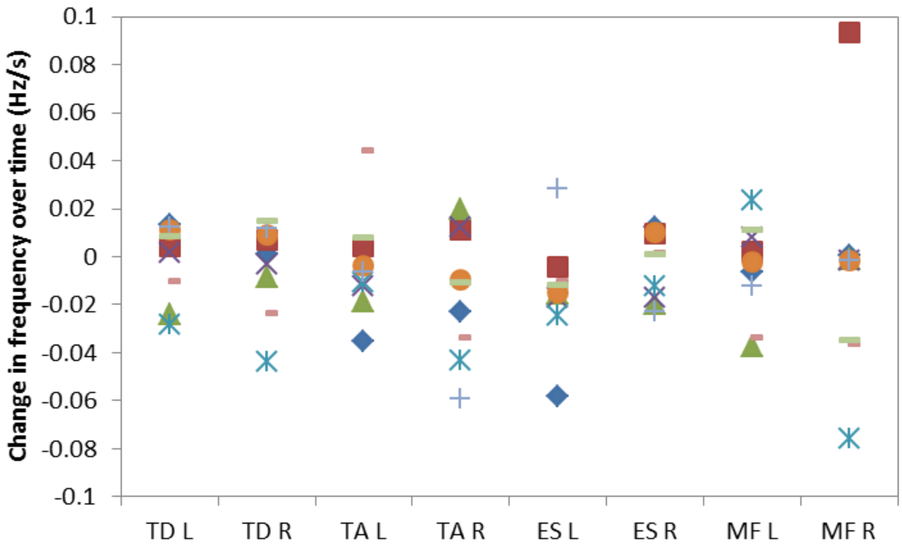


Figure 140 SB30 Pmov: Change in frequency over time, shown as the gradient (negative values indicate a decrease in frequency)

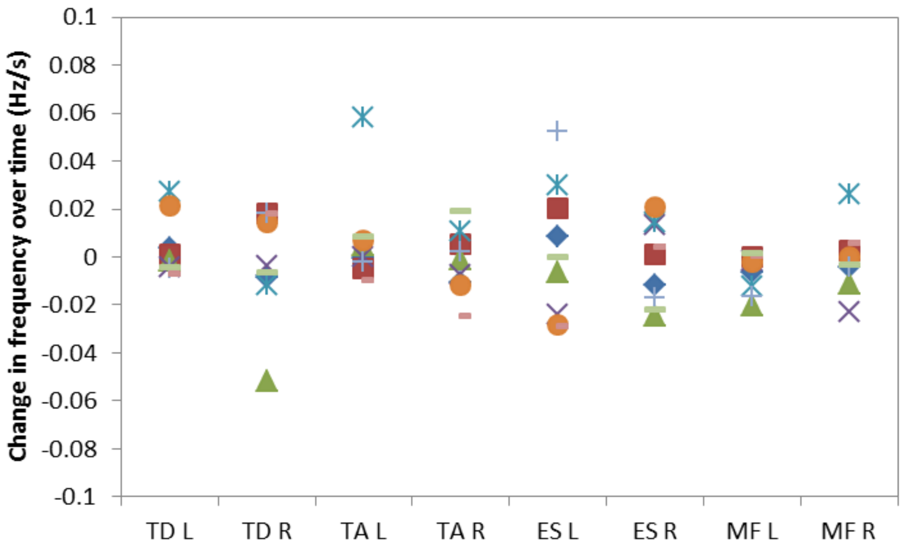


Figure 141 SB90 Pmov: Change in frequency over time, shown as the gradient (negative values indicate a decrease in frequency)