INVESTIGATING WHOLE-BODY VIBRATION INJURIES IN FORESTRY SKIDDER OPERATORS: COMBINING OPERATOR VIBRATION EXPOSURES AND POSTURES IN THE FIELD WITH BIODYNAMIC RESPONSES IN THE LABORATORY

by

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ABSTRACT

INVESTIGATING WHOLE-BODY VIBRATION INJURIES IN FORESTRY SKIDDER OPERATORS: COMBINING OPERATOR VIBRATION EXPOSURES AND POSTURES IN THE FIELD WITH BIODYNAMIC RESPONSES IN THE LABORATORY

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The purpose of this thesis was to investigate potential links between trunk stiffness, vibration transmission and whole-body vibration (WBV) injuries. The investigation was comprised of field and laboratory studies. Tri-planar trunk postures, operator injury histories and 6-degree-of-freedom (DOF) vibration exposure data were collected from eight forestry skidders during normal field operations in Northern Ontario. Using this skidder posture and vibration exposure data, the laboratory investigation examined interactions between WBV exposure levels and spectra, seated trunk postures, trunk muscle activity, and trunk stiffness on the transmission of 6-DOF vibration from the seat to several levels of the spine.

The field study revealed that when driving, skidder operators were exposed to vibrations with higher accelerations and lower frequency exposures while adopting the most neutral postures. When dropping-off (DOAL), picking-up (PUAL) or ploughing a load, operators were exposed to vibrations with lower accelerations and higher frequency exposures while adopting the postures furthest away from neutral. Furthermore, operators who adopted the greatest lateral trunk bending and forward flexion for the greatest percentage of time reported low-back and neck pain, however, interestingly were not exposed to the greatest exposure accelerations. Operators who complained of neck pain as a result of twisting to see the rear of the vehicle while DOAL and PAUL experienced some of the highest translational and rotational vibration exposures during those operating
conditions. This suggests that WBV exposures and postures may interact to produce operator injuries.

The laboratory study revealed a number of interactions between vibration exposure (magnitude, spectra and axis), posture, muscle activity, trunk stiffness, vibration transmissibility, dominant transmission frequency and spinal level. In general, experiment conditions expected to increase trunk muscle activity and stiffness typically did. In contrast, the expected increase in vibration transmissibility and dominant transmission frequency with increased muscle activity and trunk stiffness was not present under many of the simulated field conditions. Trunk muscle activity patterns necessary to maintain required trunk postures were often out of phase with input accelerations, reducing trunk stiffness and increasing transmissibility. These results are contrary to findings from previous studies thus bringing into question the appropriateness of literature based vibration exposure guidelines.
AUTHORSHIP

This thesis contains material from published manuscripts (Chapters 2-4 and Appendix B) and manuscripts in final preparation (Chapters 5, 6 and Appendix A, C). Authorship or intended authorship is as follows:


Chapter 5: Jack, R.J., Oliver, M., Dickey, J.P., Cation, S., Hayward, G. and Lee-Shee, N., In Final Preparation. Characterization of 6-degree-of-freedom whole-body vibration exposure spectra during forestry skidder field operation.

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Appendix C: Jack, R., Oliver, M. and Hayward, G., In Final Preparation. Validation of the Vicon™ 460 motion capture system for whole-body vibration acceleration determination.
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1.1 MOBILE MACHINE OPERATION AND INJURIES

The operation of mobile machinery has been connected to nervous, digestive, and cardiopulmonary system problems, noise induced hearing loss, and degenerative spine changes (Wilson and Corlett 1990; Wasserman and Taylor 1992; Bovenzi 1996; Thalheimer 1996; Wilder and Pope 1996; Kroemer, Kroemer and Kroemer 1999). Several studies have found that vehicle operation was positively related to back disorders and low-back pain (Frymoyer et al. 1983; Damkot et al. 1984; Hulshof and Veldhuijzen van Zanten 1987; Bongers et al. 1988; Boshuizen et al. 1988; Johanning 1991; Wilder 1993; Bovenzi and Betta 1994; Bovenzi 1996; NIOSH 1997; Scutter et al. 1997; Bovenzi and Hulshof 1998; Schwarz et al. 1998; Teschke et al. 1999; Koda et al. 2000; Ling and Leboeuf-Yde 2000; Rehn et al. 2002). In addition, mobile machine operation has been linked to neck and shoulder pain in mobile machine operators (MMOs) (Village et al. 1989; Johanning 1991; Scutter et al. 1997; Hagen et al. 1998; Koda et al. 2000; Rehn et al. 2002). These musculoskeletal injuries in MMOs are likely the result of a combination of whole-body vibration (WBV) exposure, static driving postures, and repetitive movements associated with the operation of hand and foot controls (Axelsson and Ponten 1990; Harstella 1990; NIOSH 1997; Hagen et al. 1998; Synwoldt and Gellerstedt 2003). A more comprehensive understanding of the interactions between these risk factors will help to elucidate strategies to decrease the incidence of injuries in MMOs.

This thesis focused on forestry skidders for its investigation into those aforementioned risk factor interactions. This focus on forestry skidders was the direct result of industry partnerships and operator complaints. Although a specific industrial vehicle and sector was explored, the vibrations, postures and operation of controls present during the operation of a
CHAPTER 1: General Introduction

skidder are common to many other vehicles. Thus, the findings of this thesis will provide insight into operator injury mechanisms for other vehicles and industries.

1.2 FORESTRY SKIDDERS AND THEIR OPERATION

Typically, skidders are wheeled mobile forestry machines with either a grapple (Figure 1.1) or cable attachment (Figure 1.2) at the rear to couple and drag harvested trees. These vehicles are used to gather and transport timber from harvesting sites to a central location. This is accomplished through five separate tasks. The first task requires the skidder operator to drive over rough terrain to the location of some harvested trees. Typically these trees (with all of their limbs intact) are left in a pile by the operator of a feller/buncher machine. The skidder operators will then pick-up the load of trees. Here the operator will either drive directly over top of the trees or back-up the skidder until a grapple or cables are in place. At this point the operator will use the grapple controls to grab the trees, or in the case of a cable skidder, the operator will leave the skidder cabin to manually attach the cables to the logs. Once the operator has picked-up the load, they again drive over rough terrain to the location at which the logs are to be dropped off. At this point the task of dropping off the load occurs. Here operators will maneuver the load into position and then release it. This entails opening the grapple or once

Figure 1.1: Grapple skidder with the grapple on the left side of the skidder and a plough blade on the right.
again leaving the skidder cabin to manually release the cables holding the logs. The four aforementioned tasks encompass one complete operating cycle. The fifth task, ploughing logs, entails pushing logs into place for pick-up, or once they have been dropped off at a desired
location, with a plough blade attachment at the front of the skidder. Ploughing does not necessarily occur every operating cycle, or for every operator.

1.3 MUSCULOSKELETAL INJURIES AMONG MOBILE FORESTRY MACHINE OPERATORS

Reports of injuries and/or pain to the arm, neck, shoulder, legs, neck, and lower back are common in mobile machine operators (MMOs) in the forest industry (Axelsson and Ponten 1990; Hansson 1990; Harstella 1990; Slappendel et al. 1993; Hagen et al. 1998; Rehn et al. 2002; Synwoldt and Gellerstedt 2003; Cation et al. 2007). Rehn et al. (2002) found that the forestry MMOs were 2.3 times more likely to report musculoskeletal symptoms in the neck, 1.9 times more likely to report shoulder symptoms, 2.4 times more likely to report upper back symptoms, and 1.1 times more likely to report lower back symptoms than a control group. Hagen et al. (1998) found that harvester and forwarder operators in the forestry industry were 1.76 times more likely to develop a low-back disorder than administrative workers (i.e., clerks and managers). WBV has also been linked to neck and shoulder pain in MMOs, with harvester and forwarder operators being 3.37 times more likely to develop neck and shoulder pain than administrative workers (Hagen et al. 1998). Focusing solely on forestry skidders, Cation et al. (2007) found that 43% of skidder operators surveyed reported low level neck pain and 29% reported moderate levels of back pain. These injuries have financial repercussions for employers as increased insurance premiums and the costs to replace and/or hire new workers are incurred. Furthermore, revenue losses are incurred by employers from lost production when employees are injured (Leigh et al. 2001).

1.4 RISK FACTORS FOR MUSCULOSKELETAL INJURIES IN MOBILE FORESTRY MACHINE OPERATORS

Several risk factors have been attributed to the musculoskeletal injuries found in forestry MMOs. Of these risk factors, translational whole-body vibration (WBV) exposure along with the adoption of static postures and the duration over which these risk factors occur have been a major focal point in the available literature; as outlined in a literature review by Jack and Oliver
(2008 – Chapter 2). In addition, the literature review by Jack and Oliver (2008 – Chapter 2) indicated that rotational and transient vibrations, vibration transmission, compressive and shear spinal loading, the performance of repetitive movements of the trunk and limbs, muscle fatigue, and spine stability/stiffness can all play a role in the injuries seen in forestry MMOs. Under field operating conditions, forestry MMOs are exposed to the aforementioned risk factors simultaneously. Understanding how these risk factors interact under actual operating conditions is a necessary step to successfully reducing MMO musculoskeletal injuries.

1.5 KNOWLEDGE GAPS AND GUIDELINE LIMITATIONS

A number of ergonomic guidelines have been published in an attempt to mitigate the adverse health effects associated with the operation of industrial mobile machinery. Unfortunately, despite greater awareness and ergonomic improvements, the current literature indicates that vehicle operators are still being injured. The continued injury to MMOs is partially due to knowledge gaps in the literature and subsequent guideline limitations.

Currently, epidemiological field studies relating WBV exposures to musculoskeletal injuries are limited in their exposure measurements. All of the 24 epidemiological studies (published between 1989 and 2008 – refer to Table 1.1) reviewed relating WBV exposures to low-back or neck pain/injury were limited to a few degrees-of-freedom (DOF), with minimal spectral data and virtually no rotational data available. Furthermore, in many of the epidemiological studies, the relationship between WBV and musculoskeletal injury was based on the assumption that the operators drove vehicles and they were therefore exposed to vibration. Due to the lack of field vibration measurements, the effects of varying levels and patterns of translational and rotational vibration exposures in the field on musculoskeletal injury are not fully understood. The limited DOF and spectra available from exposure investigations carries over to biodynamic laboratory studies as well. A review of 83 laboratory studies (published between 1974 and 2008 – refer to Table 1.1) investigating the effects of vibration exposure on a number of human responses were again limited to a few DOF, with limited spectral exposures. In addition, the vibration exposures that were used in laboratory studies typically are not based on any field data. As a result, guidelines used to establish low health risk vibration exposure do not consider rotational vibrations, and the frequency weightings and exposure thresholds that they do
### Table 1.1: Biodynamic and epidemiological studies reviewed.

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CHAPTER 1: General Introduction

utilize may be inaccurate because of the discrepancies between the vibrations studied in the laboratory and those found in the field.

Aside from the current WBV exposure guidelines being hindered by the limited vibration exposure data used to create them, these guidelines (i.e. ISO 2631-1:1997 and EU Directive 2002/44/EC) focus solely on vibration exposure magnitudes and durations while ignoring operator postures. Jack and Oliver (2008 – Chapter 2) highlight several risk factors which interact with WBV to increase the operator’s risk of injury. One such risk factor is operator posture. To date, the current authors have located eleven published studies that link MMO posture to musculoskeletal complaints for the low-back or neck. While these studies describe operator postures as they operate their machines (i.e. flexed, extended, bent or twisted trunk), only three of the studies linking posture to musculoskeletal injuries quantified the postures (Bovenzi et al. 2006; Eger et al. 2008b; Jack et al. 2008 – Chapter 3) and only one directly measured operator trunk postures (Jack et al. 2008 – Chapter 3). As a result, very little postural information is available for use in biodynamic laboratory studies or for the development of ergonomic guidelines. This was very apparent in the review of 85 biodynamic laboratory studies mentioned previously. These biodynamic investigations commonly seat subjects in an unsupported upright forward facing trunk posture or facing forward with the back in contact with an upright or extended backrest. No studies investigating lateral trunk bending postures were found, and very few investigations into trunk flexion, unsupported extension and axial trunk twisting were uncovered. Once more, the postures utilized in these laboratory studies were seldom based on field data. Although limited, the literature has demonstrated that the posture adopted by an operator will influence the biodynamic response to vibration (Jack and Oliver 2008 – Chapter 2). How these variables interact to influence the human response to vibration in the field is still not clearly understood. This has led to vibration guidelines which mention postural hazards but have no postural provisions.

1.6 THESIS OBJECTIVES

As outlined in the previous section, there are many gaps in our current understanding of how the body responds to WBV exposure. These knowledge gaps are primarily the result of equipment limitations. Having overcome many of the equipment limitations that hindered
previous WBV research, the objectives of this thesis were to:

1) Obtain 6-DOF WBV exposure data (magnitudes and frequency spectra) at the operator seat interface during field operation of mobile machinery,

2) Obtain tri-planar trunk postures during field operation of mobile machinery,

3) Explore relationships between operator musculoskeletal injury reports and the 6-DOF WBV exposures (magnitudes and frequency spectra) and tri-planar trunk postures experienced by those operators in the field,

4) Utilize 6-DOF WBV exposures (magnitudes and frequency spectra) and tri-planar trunk postures measured in the field to investigate biodynamic responses (trunk muscle activity, trunk stiffness, vibration transmissibility, and dominant vibration transmission frequency) in a controlled laboratory investigation,

5) Explore relationships between biodynamic responses obtained in a laboratory study and operator musculoskeletal injury reports from the field.

1.7 THESIS OVERVIEW

The thesis presented here begins with an extensive overview of the literature. This literature review by Jack and Oliver (2008 – Chapter 2) outlines how translational and rotational WBV and vibration transmission through the body; transient vibrations and compressive/shear loading of the spine; static postures and repetitive movements of the trunk and limbs; spine stability/stiffness; work duration and muscle fatigue all interact to place MMOs at risk for musculoskeletal injury. It was also evident that current vibration standards do not account for many of the previously mentioned risk factors or their interaction. This oversight was largely due to a lack of comprehensive field and laboratory investigations, both of which have been hampered by limited measurement technologies. As a result, meticulous field (Jack et al. 2008 – Chapter 3; Jack et al. 2010 – Chapter 4; Chapter 5) and laboratory studies (Chapter 6) were conducted with the intention of closing some of the knowledge gaps found.

The first step to addressing the vibration standard limitations was to collect 6-DOF vibration exposure data at the operator/seat interface along with simultaneously collected tri-
planar trunk posture data (Jack et al. 2008 – Chapter 3) while MMOs operated their vehicles under actual working conditions. In addition, musculoskeletal injury histories were collected. The magnitudes and patterns of the vibration exposures (Jack et al. 2010 – Chapter 4; Chapter 5) experienced by these skidder operators while they performed their regular duties, along with the postures they adopted while operating their machines, were compared to the musculoskeletal complaints of those operators. Furthermore, the vibration exposures (magnitudes and spectra) and postures found in the field were utilized in a laboratory investigation into the human biodynamic response (Chapter 6).

The laboratory study conducted for this thesis exposed subjects to simulated 6-DOF vibration which mimicked the magnitudes and patterns of vibration exposures found in the field. While exposed to these real world vibrations, the subjects also adopted the operator postures found in the field. This afforded the opportunity to gain some insight into the complex interactions between vibration exposures, postures, trunk stiffness, muscle activity and vibration transmission. The use of field vibration exposures and postures allow the findings of this laboratory study to be transferable back to the field. As such, attempts to connect the laboratory findings to the musculoskeletal injury complaints from the field were conducted (Chapter 6).

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A REVIEW OF FACTORS INFLUENCING WHOLE-BODY VIBRATION INJURIES IN FORESTRY MOBILE MACHINE OPERATORS

2.1 INTRODUCTION

Despite ergonomic improvements, injuries and/or pain to the arm, neck, shoulder, legs, and lower back are common in mobile machine operators (MMOs) in the forest industry (Axelsson and Ponten 1990; Hansson 1990; Harstella 1990; Slappendel et al. 1993; Hagen et al. 1998; Synwoldt and Gellerstedt 2003). A survey of 215 northern Sweden forestry MMOs and 167 controls conducted in 1999 by Rehn et al. (2002) found that the forestry MMOs had an elevated prevalence of neck, shoulder, upper back (thoracic) and lower back musculoskeletal symptoms. Here, forestry MMOs reported 2.3 times more musculoskeletal symptoms in the neck than controls, 1.9 times more shoulder symptoms than controls, 2.4 times more upper back symptoms than controls, and 1.1 times more lower back symptoms than the control group (Rehn et al. 2002). The aforementioned symptoms correspond to a prevalence of 61%, 56%, 20% and 47% of forestry MMOs for musculoskeletal symptoms of the neck, shoulder, upper back and lower back respectively (Rehn et al. 2002). A 2007 survey of seven skidder operators in Northern Ontario, conducted by Cation et al. (2007) revealed that three of the seven operators had low level neck pain (operators gave ratings of 1-2 on a 5-point scale with 5 being the most severe), and two of the seven operators reported more severe back pain (operators gave ratings of 3 on a 5-point scale). These injuries financially burden employers when company subsidized health care plans are used, insurance premiums are increased, and replacement workers are hired. Employers also incur revenue losses from lost production when employees are injured (Leigh et al. 2001).

The origin and cause of musculoskeletal injuries in forestry MMOs (and MMOs in general) is likely results from a combination of whole-body vibration (WBV) exposure, static
driving postures, and repetitive movements associated with the operation of hand and foot controls (Axelsson and Ponten 1990; Harstella 1990; NIOSH 1997; Hagen et al. 1998; Synwoldt and Gellerstedt 2003). A more comprehensive understanding of the interactions between these risk factors will help to elucidate strategies to decrease the incidence of injuries in forestry MMOs. The following sections provide a review of musculoskeletal injury risk factors for MMOs with a focus on forestry MMOs. In addition, an in depth discussion of the possible interactions between musculoskeletal risk factors for forestry MMOs is provided, along with the possible influences of these musculoskeletal injury risk factors on operator productivity. It should be noted that literature regarding ergonomic investigations of WBV exposures, postures and repetitive movements among forestry MMOs is limited. As a result, this article at times incorporates vehicles from other industries to illustrate some of its points, but all discussions are provided with the forest industry in mind. The desire here is to illustrate the mechanisms by which forestry MMOs could be injured, so that future vehicles and work policies can be designed with these mechanisms in mind.

2.2 RISK FACTORS FOR OPERATOR MUSCULOSKELETAL INJURY

2.2.1 Whole-body vibration

WBV has been connected to nervous, digestive, and cardiopulmonary system problems, noise induced hearing loss, and degenerative spine changes (Wilson and Corlett 1990; Wasserman and Taylor 1992; Bovenzi 1996; Thalheimer 1996; Wilder and Pope 1996; Kroemer, Kroemer and Kroemer 1999). Several studies have found WBV to be positively related to back disorders and low-back pain (LBP) (Frymoyer et al. 1983; Damkot et al. 1984; Hulshof and Veldhuijzen van Zanten 1987; Bongers et al. 1988; Boshuizen et al. 1988; Johanning 1991; Wilder 1993; Bovenzi and Betta 1994; Bovenzi 1996; NIOSH 1997; Scutter et al. 1997; Bovenzi and Hulshof 1998; Schwarz et al. 1998; Teschke et al. 1999; Koda et al. 2000; Ling and Leboeuf-Yde 2000; Rehn et al. 2002). Elevated risks for low-back disorders and vertebral disc herniation with WBV exposure range from 1.2-39.5 and 2-4.67 times respectively that of unexposed individuals (Kelsey 1975a; Kelsey 1975b; Heliovaara 1987; Bovenzi and Betta 1994; NIOSH 1997; Hagen et al. 1998). Hagen et al. (1998) found that harvester and forwarder
operators in the forestry industry were 1.76 times more likely to develop a low-back disorder than administrative workers (i.e., clerks and managers). WBV has also been linked to neck and shoulder pain in MMOs (Village et al. 1989; Johanning 1991; Scutter et al. 1997; Hagen et al. 1998; Koda et al. 2000; Rehn et al. 2002), with harvester and forwarder operators being 3.37 times more likely to develop neck and shoulder pain than administrative workers (Hagen et al. 1998).

Forestry MMOs are exposed to potentially harmful levels of WBV as they are vibrated over long time periods during which they also experience non-periodic shocks (i.e., from driving over potholes, tree stumps, and rocks). When reported, the amplitude of WBV encountered by forestry MMOs often surpasses the ride criteria proposed by various organizations and researchers (Golsse and Hope 1987; Boileau and Rakheja 1990; Neitzel and Yost 2002; Neitzel and Yost 2003; Rehn et al. 2005a; Rehn et al. 2005b; Cation et al. 2007) indicating potential risks to the driver’s health. These exposure levels increase with increases in driving speed, roughness of terrain, and decreases in driver and carried load weight, as seen in forestry skidders (Golsse and Hope 1987; Cation et al. 2007), forwarders (Rehn et al. 2005a), and forklift trucks (Malchaire et al. 1996).

WBV also has detrimental effects on visual acuity, balance, dexterity and can cause muscle fatigue since exposure to WBV can result in increased muscle activity (Seidel et al. 1980; Wilder et al. 1982; Damkot et al. 1984; Seroussi et al. 1989; Village et al. 1989; Pope, Wilder and Magnusson 1998). Greater muscle activity is associated with increased muscle fatigue due to localized reductions in blood flow and impairment of normal metabolic processes (i.e. oxygen uptake and metabolite/waste removal) (Kroemer 1999). During WBV exposure, the muscles of the back (particularly the erector spinae and trapezius muscles) contract in an attempt to absorb transmitted vibrations (Wilkstrom 1993), which can result in muscle fatigue.

The wide variety of WBV effects depend on the vibration exposure characteristics. Depending on the magnitude, direction (refer to Figure 2.1), frequency, and duration of WBV exposure, the effects can range from sensations of pleasure, pain or discomfort, to interference with performance (reading and hand control), to acute or chronic illness with physiologic and pathologic changes (Herington and Morse 1995). The body harmlessly attenuates most vibration, but frequencies between 1 and 20Hz cause the pelvis and spine to resonate, leading to structural
Figure 2.1: The basicentric orientation used to describe vibration in three translational and three rotational directions.

damage and health problems (Thalheimer 1996; Kitazaki and Griffin 1998). When considering the magnitude of WBV, Bovenzi (1996) found that WBV vector sum root-mean-square (RMS) acceleration levels between 0.7 and 0.9 m/s² (using ISO 2631-1:1985) had estimated odds ratios for LBP varying from 1.6 to 2.0, with risk estimates increasing for exposures greater than 1 m/s². A 2002 study of forestry worker exposures to WBV in Washington State (USA) by Neitzel and Yost (2002), which used the same ISO weightings as Bovenzi (1996), reported WBV acceleration levels for mobile forestry equipment that would be associated with an increased risk for LBP. Neitzel and Yost (2002), found that workers employed in logging related activities have substantial overexposures to vibration using the ISO 2631-1:1985 standard. These overexposures are also evident in a 2003 report by Neitzel and Yost (2003), where several forestry machines
and job tasks in Washington State, Alaska and Idaho forestry operations exceeded the upper limit (indicating a likely health risk) of the ISO 2631-1:1997 health caution zone for a 4-hour day (refer to Tables 2.1 and 2.2). In 2004, a research group in Ireland (Sherwin et al. 2004a), investigated the vibration levels of a cut-to-length timber harvester while felling, processing (delimbing and cross-cutting trees), and traveling (along an ISO 5008:1979 test track). The cut-to-length timber harvester was found to have ISO 2631-1:1997 weighted X-, Y- and Z-axes, and vibration total values below the ISO 2631-1:1997 health caution zone for an 8-hour day during all three operating tasks investigated (refer to Table 2.3). However, while traveling, the vibration total values determined would be associated with some discomfort according to ISO 2631-1:1997. A 2005 study by Rehn et al. (2005b) found that forwarders in northern Sweden logging operations had average ISO 2631-1:1997 RMS weighted accelerations of 0.5, 0.78, and 0.6 m/s\(^2\) in the X-, Y- and Z-axes respectively. These forwarders also had an average vibration total value of 1.5 m/s\(^2\) (Rehn et al. 2005b), which would exceed the upper limit of the ISO 2631-1:1997 health caution zone for a 4-hour day. A second 2005 study by Rehn et al. (2005a), reported that northern Sweden forwarders had average ISO 2631-1:1997 vibration total values that ranged from 0.41 m/s\(^2\) while unloading logs to 1.69 m/s\(^2\) while traveling unloaded (travel loaded was associated with a 1.1 m/s\(^2\) WBV exposure, and loading logs was associated with a 0.55 m/s\(^2\) exposure).

Except for unloading logs, all of the aforementioned forwarder tasks had vibration exposures that exceeded the lower limit of the ISO 2631-1:1997 health caution zone for an 8-hour day, with traveling loaded and unloaded exceeding the upper exposure limit after 2- and 1-hour respectively. A recent study conducted in the summer of 2007 by Cation et al. (2007), found that Northern Ontario skidder operators exceeded the upper limit of the ISO 2631-1:1997 health caution zone for a 4-hour day while driving with and without a load (refer to Table 2.4).

Bovenzi and Betta (1994) found the duration of WBV was related to low-back disorders to a greater extent than the WBV acceleration magnitude. Consistent trends are seen in Bovenzi and Betta’s (1994) study, with increasing WBV exposure in terms of driving hours, driving years, and cumulative vibration dose (i.e., WBV exposure levels multiplied by the years of exposure) being associated with increased prevalence and odds of general back and low-back pain. The influence of exposure duration on health outcomes is also reflected in current health guidelines with a given WBV exposure level being associated with elevated risks for adverse
Table 2.1: WBV exposure levels reported in the forestry industry by machine.

<table>
<thead>
<tr>
<th>Machine</th>
<th>RMS Accelerations (m/s²)</th>
<th>Daily Exposure Limit†††</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X-axis†</td>
<td>Y-axis†</td>
</tr>
<tr>
<td>Dump truck</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Excavator</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Feller/buncher</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Forwarder</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Front end loader</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Grader</td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>Harvester</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Logging truck</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Processor</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Shovel</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Skidder</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Stacker</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Yarder</td>
<td>1.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

† Constant band-width (1-80Hz range) accelerations using ISO 2631-1:1997 frequency weightings.  
Data compiled from values presented in Neitzel and Yost (2003).  
†† A vector sum of the three orthogonal axes accelerations determined from vibration dose values by removing the time component. Data compiled from values presented in Neitzel and Yost (2003).  
††† Exposure limits are based on summary equivalent exposures and the ISO 2631-1:1997 health caution guidelines.  
†††† Indicates a potential health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).  
††††† Indicates a likely health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).

Table 2.2: WBV exposure levels reported in the forestry industry by task.

<table>
<thead>
<tr>
<th>Task</th>
<th>RMS Accelerations (m/s²)</th>
<th>Daily Exposure Limit†††</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X-axis†</td>
<td>Y-axis†</td>
</tr>
<tr>
<td>Cutting wood</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Processing logs</td>
<td>2.6</td>
<td>2.5</td>
</tr>
<tr>
<td>Skidding logs</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Sorting/stacking logs</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Yarding logs</td>
<td>1.8</td>
<td>2.0</td>
</tr>
</tbody>
</table>

† Constant band-width (1-80Hz range) accelerations using ISO 2631-1:1997 frequency weightings.  
Data compiled from values presented in Neitzel and Yost (2003).  
†† A vector sum of the three orthogonal axes accelerations determined from vibration dose values by removing the time component. Data compiled from values presented in Neitzel and Yost (2003).  
††† Exposure limits are based on summary equivalent exposures and the ISO 2631-1:1997 health caution guidelines.  
†††† Indicates a potential health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).  
††††† Indicates a likely health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).
Table 2.3: WBV exposure levels reported during three cut-to-length timber harvester tasks.

<table>
<thead>
<tr>
<th>Task</th>
<th>RMS Accelerations (m/s²)</th>
<th>Daily Exposure Limit††††††</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X-axis†</td>
<td>Y-axis†</td>
</tr>
<tr>
<td>Felling Trees</td>
<td>0.060</td>
<td>0.107</td>
</tr>
<tr>
<td>Processing Trees</td>
<td>0.050</td>
<td>0.082</td>
</tr>
<tr>
<td>Traveling</td>
<td>0.088</td>
<td>0.146</td>
</tr>
</tbody>
</table>

†Constant band-width (1-80Hz range) accelerations using ISO 2631-1:1997 frequency weightings.
Data compiled from values presented in Sherwin et al. (2004a).
††A vector sum of the three orthogonal axes accelerations with ISO 2631-1:1997 multiplication factors (k-values) applied to each axis. Data compiled from values presented in Sherwin et al. (2004a).
†††Includes delimbing and crosscutting trees.
††††Exposure limits are based on vibration total values and the ISO 2631-1:1997 health caution guidelines.
††††††Indicates a potential health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).

Table 2.4: WBV exposure levels reported during Northern Ontario skidder operations.

<table>
<thead>
<tr>
<th>Task</th>
<th>RMS Accelerations (m/s²)</th>
<th>Daily Exposure Limit††††††</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X-axis†</td>
<td>Y-axis†</td>
</tr>
<tr>
<td>Driving unloaded</td>
<td>0.86</td>
<td>1.12</td>
</tr>
<tr>
<td>Driving loaded</td>
<td>0.72</td>
<td>0.96</td>
</tr>
</tbody>
</table>

†Constant band-width (1-80Hz range) accelerations using ISO 2631-1:1997 frequency weightings.
Data compiled from values presented in Cation et al. (2007).
††A vector sum of the three orthogonal axes accelerations with ISO 2631-1:1997 multiplication factors (k-values) applied to each axis. Data compiled from values presented in Cation et al. (2007).
†††Exposure limits are based on vibration total values and the ISO 2631-1:1997 health caution guidelines.
††††Indicates a potential health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).
†††††Indicates a likely health risk with daily exposures that exceed the indicated time (ISO 2631-1:1997).
health effects as the duration of that exposure increases (BS 6841:1987; ISO 2631-1:1997). Thus the duration of exposure is also very important.

### 2.2.2 Whole-body vibration transmission through the spine

While vibration has a localized source, it may also be transmitted to other areas of the body through soft tissues, and more readily through bone tissue which is assumed to be rigid (Dietrich et al. 1991). How that vibration is transmitted through the body determines the body parts affected as well as the severity. Since vibration is more readily transmitted through a rigid structure, conditions that increase the rigidity or stability of a structure will increase vibration transmission. In the case of the human body, increased rigidity and vibration transmission can be the result of posture and muscle activity, or a combination of the two (Cholewicki and McGill 1996; McGill and Cholewicki 2001). Spinal tissues become stiffer the more they are deformed (Adams 1995), leading to greater passive tissue resistance and muscle activity to overcome that resistance when adopting a bent and/or twisted posture (Bottoms and Barber 1978; Boden and Oberg 1998; Chaffin et al. 1999; Bluthner, Seidel and Hinz 2001; Toren 2001). The greater the stiffness of a motion segment, the greater the stability (McGill and Cholewicki 2001). As well, Cholewicki and McGill (1996) found that stability of the spine increased with increased joint compression and muscle activity indicating a stiffer spine. Therefore, altered postures cause increased muscle activity, compressive loads and stiffness probably leading to an increase in vibration transmission. Pope and Hansson (1992) stated that postures with lateral bending and axial rotations should be avoided as they can cause greater vibration transmission. Griffin (1990) also lends support to the argument that postures with increased trunk muscle activity and rigidity will increase WBV transmission. Griffin (1990) reported elevated seat-to-head WBV transmission as a more erect posture is adopted (i.e., in more rigid posture with greater muscle activity than a relaxed or slumped posture - O’Sullivan et al. 2002). Several other studies support the notion of posture influencing vibration transmission with reported changes in transmission and attenuation peak magnitudes and changes in the frequency at which those peaks occur when different postures were adopted (Seidel et al. 1980; Wilder et al. 1982; Wilder et al. 1994; Pope, Broman and Hansson 1990; Zimmerman and Cook 1997; El-Khatib et al. 1998; Pope, Wilder and Magnusson 1998; Matsumoto and Griffin 2000). A general pattern displayed by these
studies is that conditions with higher compressive spinal loading, a flattening of the lower back curvature (decreased lumbar lordosis), increased muscle activity, and increased stiffness/stability had transmission peaks at higher frequencies and greater vibration transmission. It has also been observed that WBV exposure frequency can mediate how posture affects vibration transmission. Zimmerman and Cook (1997) found that for frequencies of 6Hz and above, posture changes that produce increased stiffness increased transmissibility, while at frequencies below 6Hz, posture changes that produced increased stiffness decreased transmissibility. A similar result was also reported by Seidel et al. (1980).

Extremity location can also affect vibration transmission. Holding a weight in front of the body causes an increase in vertebral disc and intra-abdominal pressures, and muscle tension (Dietrich et al. 1991). These conditions will increase rigidity and vibration transmission. Leg positions can also affect the rigidity of the spine. Knee and hip angles affect spinal posture due to the muscles that insert on the pelvis and legs (Anderson et al. 1979; Chaffin et al. 1999). When the lower extremity joints are moved, these muscles rotate the pelvis, thus influencing lumbar spine posture (Chaffin et al. 1999). Postures that flatten the lower back curvature (decrease the lumbar lordosis), such as a flexed knee and hip (Chaffin et al. 1999), and increase muscle activity while sitting will increase vertebral disc pressure and vibration transmission.

Finally, larger accelerations have greater load magnitudes and the fact that the spine stiffens with increased load (Cholewicki and McGill 1996; Panjabi 2003) supports the idea that larger accelerations could be transmitted more readily. Griffin (1990) reports a general trend towards an increase in seat-to-head WBV transmission with an increase in vibration exposure acceleration levels, particularly at lower frequencies. Matsumoto and Griffin (2002) also found greater exposure accelerations were associated with greater vibration transmission at lower frequencies. It is therefore evident that posture, muscle activity, and WBV can influence vibration transmission. However, the postures and WBV exposures in the available literature are not industry specific and are limited with respect to the postures and WBV patterns studied.

2.2.3 Rotational vibration

Driving environments expose operators to translational vibrations in the X-, Y- and Z-
axes, and rotational vibrations about each of these axes in roll, pitch and yaw (Shoenberger 1988). However, actual rotational vibrations are not considered in health guidelines and little research has been conducted to investigate their effects on health due to measurement technology limitations.

MMOs exposed to WBV (which includes rotational vibration) can have torques about spinal motion segments due to applied loads and muscle activation in an attempt to stabilize the body and maintain operator field of view. Repeated lateral bend, axial twist, and flexion/extension operator movements can also be expected, while subjected to compressive loading from WBV, bodyweight and muscle activity. These conditions have been associated with human and animal vertebral disc herniation in vitro (Hardy et al. 1958; Wilder, Pope and Frymoyer 1988; Callaghan and McGill 2001; Kuga and Kawabuchi 2001). Vertebral disc herniation can occur with a high number of 1Hz flexion/extension cycles in combination with static compressive loading (Callaghan and McGill 2001). Wilder, Pope and Frymoyer (1988) reported vertebral disk herniations with 0.5Hz flexion/lateral bending cycles under static axial torsion. Wilder (1993) also reported that vertebral disc herniation can result from cyclic vibration loading but it has yet to be seen if similar loading conditions with frequencies and accelerations from field WBV exposures could affect vertebral disc herniation. Terrain-induced vibrations in forestry vehicles (i.e., skidders, forwarders and cut-to-length timber harvesters) are predominantly in the 0.5-8.0 Hz range (Boileau and Rakheja 1990; Sherwin et al. 2004a; Sherwin et al. 2004b; Rehn et al. 2005b; Cation et al. 2007). Also, compressive loading of the spine while seated can be around 700N (Magnusson and Pope 1998) and will likely be higher while driving due to the increased muscle activity associated with WBV (Seidel et al. 1980; Seroussi et al. 1989; Village et al. 1989; Wilkstrom 1993; Pope, Wilder and Magnusson 1998; Bluthner, Seidel and Hinz 2001). Interestingly, using a porcine (pig) spine model Callaghan and McGill (2001) reported higher incidences of vertebral disc herniation while repeatedly flexing and extending (at 1Hz) their specimens under 867N of compressive loading.

2.2.4 Static postures

A greater risk of back problems and discomfort in the buttocks, legs and feet has been associated with extended periods of sitting (Floyd and Roberts 1958; Bottoms and Barber 1978;
Frymoyer *et al.* 1983; NIOSH 1997; Boden and Oberg 1998; Chaffin *et al.* 1999). When the body remains in a static position, blood flow throughout the body is reduced, causing the muscles and tissues holding the body in a selected position to receive insufficient amounts of nutrients to keep them functioning optimally. Intervertebral discs (which do not have a direct blood supply) also do not receive nutrients due to reduced circulation but also because of a lack of change in intradiscal pressure (Stokes and Iatridis, 2005). This may play a role in the disc degeneration seen in MMOs with increased muscle activity due to static postures and WBV exposure further reducing localized blood flow. There is strong evidence that occupations with high levels of static contraction and prolonged static loads or extreme postures involving the neck and shoulder muscles will place workers at increased risk for neck and shoulder musculoskeletal injuries (NIOSH 1997). Neck and shoulder pain has been reported in forestry MMOs such as forwarder and harvester operators (Hagen *et al.* 1998). Harvester operators have also been reported to adopt static and twisted postures (Gellerstedt 2002). Rehn *et al.* (2005b) reported that forwarder operators in Sweden spend 10% of their time with their neck twisted greater than 15-degrees to the left, and 19% of their time with their neck twisted greater than 15-degrees to the right with durations lasting 1 to 22 seconds. In the experience of the current authors, Northern Ontario skidder operators who report neck pain associate that pain with the repeated twisting to view the skidder grapple.

Static postures can also affect trunk muscle activity (Bluthner, Seidel and Hinz 2001). When sitting, muscle activity of the lower back (lumbar erector spinae) muscles decreases when the back is in full flexion, the arms are supported, or a backrest is used (Chaffin *et al.* 1999). Tilting a tractor cab (10-degrees) and inducing a lateral bend in a seated subject was found to increase muscle activity in the shoulder and back (trapezius, latissimus, and lumbar erector spinalis) muscles in a laboratory setting (Bottoms and Barber 1978). Twisted postures often adopted by MMOs (i.e. harvester and forwarder operators in forestry (Gellerstedt 2002; Rehn *et al.* 2005b) also increase trunk muscle activity to overcome the passive resistance of the trunk tissues which increase the more the trunk is twisted (Boden and Oberg 1998; Toren 2001). Twisting in the range of 10–15 degrees involves little muscle effort, but beyond this region, increased muscle effort is required (Boden and Oberg 1998; Toren 2001). The increased muscle activity and subsequent fatigue associated with adopting non-neutral static postures likely plays a role in the reporting of pain and musculoskeletal injuries in MMOs.
2.2.5 Repetitive movements

Forestry MMOs often perform repeated trunk, neck, arm and leg movements. Rehn et al (2005b) found that Swedish forwarder operators twist their neck greater than 15-degrees 2 to 3 times per minute. Gellerstedt (2002) reported that Swedish harvester operators performed 4000 control inputs per hour (note that this is a total for both the right and left hand controls). Using data presented in Hansson (1990), Swedish processor operators conduct between 1380 to 3240 hand movements per hour (again this is a total for both the right and left hands). The repetitive movements of the arms and legs (to operate controls) in forestry MMOs has been found to increase trunk muscle activity (Hansson 1990). The amount of muscle activity depends on the magnitude, direction, and amount of repetition. These fatiguing movements may contribute to the back injuries and pain seen in forestry MMOs (and MMOs in general), as they increase spinal loading and discomfort (Haslegrave 1995). Repetitive arm movements have also been associated with neck and shoulder musculoskeletal injuries (NIOSH 1997). Movement span, shoulder and arm strength, dexterity, speed, work motivation, health, the location of armrests and controls and work technique have all been associated with differences in forestry MMO neck and shoulder health (Hansson 1990, Haslegrave 1995). The forces involved in operating controls can also cause distress on the body while driving (Haslegrave 1995; NIOSH 1997). MMOs reporting neck and shoulder problems tend to have greater control resistances than healthy MMOs (Hansson 1990).

2.2.6 Spine stability

The spinal stabilizing system is composed of the spinal column (which carries loads and provides information about the position, motion and loads of the spinal column), the muscles surrounding the spine and a motor control unit (that takes information about the spine and provides necessary adjustments in posture and stiffness via the muscles) (Panjabi 2003). Under normal conditions, these components work together and provide the needed mechanical stability (Panjabi 2003). However, low muscle activity may result in instability, thus causing unexpected vertebral body displacement whereas high muscle activity increases the system stiffness but may result in excessive loading and subsequent tissue failure (Cholewicki and McGill 1996; Brown
and Potvin 2004). In the case of low muscle activity, the resulting instability may induce a sudden need to regain stability thus resulting in muscle spasm and potential tissue overload (Cholewicki and McGill 1996).

Research has indicated that the muscular response to WBV tends to get out of phase with the vibration input, and therefore rather than absorb the effects of vibration, the forces from muscle contractions add to the effects of vibration (Wilder 1993; Wilder and Pope 1996). Additionally, the inappropriate muscle activation patterns resulting from muscle activity becoming out of phase with the vibrational load input, could lead to moments of instability and injury. As well, the terrain related transient shocks forestry MMOs experience can overload spinal tissues, and may also result in a sudden need to regain spine stability.

2.2.7 Work duration

A survey of Northern Ontario skidder operators conducted by these researchers revealed that these operators worked between 8 and 14 hours a day. In New Zealand, a majority (72.7%) of forestry MMOs reported working between 8 to 10 hours a day, and 24.2% of forestry MMOs reporting working over 10 hours a day (Lilley et al. 2002). Long work days can create problems with the accumulation of fatigue, decreased ability to maintain attention, and increased tendencies to take unsafe short cuts (Spurgeon et al. 1997). Fatigue contributes significantly to performance deterioration and leads to increased risks of human error and accidents (Spurgeon et al. 1997; Lilley et al. 2002). Lilley et al. (2002) found that close to 80% of New Zealand forestry MMOs report a low level of fatigue at work, and 28% of workers felt fatigue affected their safety sometimes, while 4% felt it often or always affected their safety. As well, a significant association between reported accident near-misses and fatigue level was found, with a high level of fatigue at work having a 9.29 times increased risk for accident near-misses (Lilley et al. 2002). What's more, long hours act as a stressor increasing the demands on a person who attempts to maintain performance levels in the face of increasing fatigue (Spurgeon et al. 1997). Long work days also increase the time that a worker is exposed to other sources of workplace stress like WBV, repetitive movements, and static postures (Spurgeon et al. 1997). Consequently, forestry MMOs can be at greater risk of injury due to increased exposure to musculoskeletal injury risk factors as well as an increased risk of a fatigue related accident.
occurring.

2.3 WHOLE-BODY VIBRATION RISK FACTOR INTERACTIONS

WBV, static postures, repetitive movements, spine stability, and work duration all play a role in the health of forestry MMOs. However, consideration of the interactions between these risk factors is necessary to understand how forestry MMOs are being injured.

2.3.1 Cab design and operator posture

MMOs are typically seated with a “slumped” posture achieved by a backward rotation of the pelvis and simultaneous rounding (kyphosis) of the spine (Chaffin et al. 1999). Twisted or bent postures are frequently adopted by forestry MMOs (Gellerstedt 2002; Rehn et al. 2005b), and these postures are often influenced by cab design (Eklund et al. 1994; Gellerstedt 2002). The positions adopted are a function of the seat design, control locations, and vision requirements where MMOs bend and twist to view driving routes and attachments as well as to reach controls (Bottoms and Barber 1978; Eklund et al. 1994; Boden and Oberg 1998; Gellerstedt 2002; Mansfield et al. 2002).

2.3.2 Operator posture and whole-body vibration

Holding seated postures for extended periods of time has been associated with increased risk for musculoskeletal problems in the neck, back, shoulders, legs and buttocks (Floyd and Roberts 1958; Bottoms and Barber 1978; Frymoyer et al. 1983; Village et al. 1989; Zacharkow 1990; Pope and Hanson 1992; NIOSH 1997; Boden and Oberg 1998; Chaffin et al. 1999). As these postures become extreme, the passive loading of joints can cause sensations of discomfort and pain, and the risk for spinal disorders increases (Toren 2001). WBV on top of these prolonged static seated postures increases the risk of back, neck and shoulder disorders (NIOSH 1997). Several studies comparing MMOs to controls report a higher incidence of LBP, vertebral disc herniation or ruptures of the annulus fibrosus, sciatic pain, headaches, neck pain and LBP with WBV (Village et al. 1989; Johanning 1991; Bovenzi and Betta 1994; Bovenzi 1996; Scutter
et al. 1997; Hagen et al. 1998; Rehn et al. 2002). Moreover, WBV has increased harmful effects when combined with adverse postures. The muscle fatigue from prolonged contractions to maintain a static posture coupled with increased muscle activity resulting from WBV (Seidel et al. 1980; Seroussi et al. 1989; Village et al. 1989; Wilkstrom 1993; Pope, Wilder and Magnusson 1998) could lead to discomfort and pain in forestry MMOs.

2.3.3 Muscle activity, repetitive movements and risk of disk herniation

Increased muscle activity has implications for vertebral disc herniation and disc degeneration, which is often seen in MMOs exposed to WBV (Kelsey 1975a; Kelsey 1975b; Heliovaara 1987; Hulshof and Veldhuijzen van Zanten 1987; Wilder 1993; Bovenzi and Betta 1994; Teschke et al. 1999). Human and animal vertebral disc herniation has been associated with repetitive movements in vitro (Hardy et al. 1958; Wilder, Pope and Frymoyer 1988; Callaghan and McGill 2001; Kuga and Kawabuchi 2001), particularly when compressive loading is involved (Adams and Dolan 1996; Callaghan and McGill 2001; Kuga and Kawabuchi 2001). Increasing the magnitude of compressive load increases the likelihood and severity of a vertebral disc herniation (Callaghan and McGill 2001). In MMOs (including forestry MMOs), these repetitive movements can result partly from postural control to stabilize the spine and maintain a visual field while operating machine controls under X- and Y-axis accelerations and rotational vibration exposures. Compressive loads can result from combined bodyweight and Z-axis accelerations, passive tissue tension and muscle activity. However, it has yet to be seen how exposures with frequencies, rotations and accelerations found in field operating conditions would affect vertebral disc herniation, but the conditions associated with operating mobile equipment in forestry and other industries are conducive to the development of this type of injury.

2.3.4 Transient loading and vertebral disc herniation

WBV also contains sudden unexpected transient accelerations (i.e. hitting a stump or pothole), which are associated with greater risk of injury (BS 6841:1987). Vertebral fractures or dislocations, ligament stretch or rupture, and intervertebral disc/end-plate lesions have been reported, with the structure affected depending on the load magnitude, direction, application
point, loading rate, and spinal posture (Oxland et al. 1991, Tsai et al. 1998). The vertebral disc herniations seen in MMOs could also be the result of a sudden transient acceleration while driving as bending and a rapid compressive load can herniate a vertebral disc (Adams and Hutton 1982).

2.3.5 Interactive effects of repetitive and sudden loading on vertebral disc herniation

An interaction between repetitive and sudden loading with respect to vertebral disc herniation is apparent from the literature. It appears that the degenerative changes seen with repetitive movements can decrease the forces needed to herniate a disc with a sudden load (Callaghan and McGill 2001). In laboratory experiments, degenerated discs herniated at much lower applied loads (Brinckmann 1986; Simunic et al. 2001) and intradiscal pressures (Iencean 2000) than did undamaged discs.

2.3.6 Muscle activity, compressive loading, repetitive motion, posture, spine stability and vibration transmission

Active muscle force (McGill and Cholewicki 2001), inherent joint stiffness (McGill and Cholewicki 2001), posture (Hardy et al. 1958; Cholewicki and Van Vliet 2002), and resulting joint compression (Panjabi 2003) all contribute to the stability of the lumbar spine. Here, increased muscle force and joint compression (Cholewicki and McGill 1996; McGill and Cholewicki 2001), and more extreme postures (bending or twisting) display greater stability. WBV also affects the rigidity of the spine with the frequency and magnitude of the loads it applies to the body. The spine becomes stiffer when exposed to greater load magnitudes (Cholewicki and McGill 1996; Panjabi 2003), and with increased loading frequencies (Simunic et al. 2001). Therefore, high frequencies and accelerations increase spine rigidity. Since vibration is transmitted through a rigid structure more readily, and natural frequency of a structure is determined by its stiffness, the way a person sits in a seat, the WBV exposure pattern, and the associated muscle activity can affect vibration transmission through the body because of the influence those factors have on the stiffness of the spine (Wilson and Corlett 1990; Michida et al. 2001).
An injury causing losses in passive tissue stiffness, like the degenerative changes in vertebral discs seen with WBV exposure, result in joint laxity that necessitate higher levels of muscular activation and stiffness to ensure sufficient stability (Oxland et al. 1991; McGill and Cholewicki 2001). This may lead to muscle fatigue, possibly resulting in pain and discomfort, which may explain the high prevalence of low back pain in MMOs (Bovenzi and Betta 1994; Bovenzi 1996; Koda et al. 2000) and forestry MMOs (Hagen et al. 1998; Rehn et al. 2002; Cation et al. 2007) exposed to WBV. Wilder, Pope and Frymoyer (1988) found increased compliance in lumbar vertebral discs with static (80N-820N) and repeated (5Hz, 80N peak-to-peak) loading. This increased compliance may also result in increases muscular activation to maintain spine stability and the subsequent muscle fatigue, pain and discomfort mentioned above. Furthermore, Wilder, Pope and Frymoyer (1988) reported lumbar spine segment buckling with sudden overloading after both static and repeated loading.

Trunk postures are not the only variable that can affect the rigidity of the spine, or the only risk factor for back and neck disorders. Static arm positions can influence spine stability and trunk muscle activity (Cholewicki and McGill 1996; Kitazaki and Griffin 1998). Repetitive movements of the arms can also increase the muscle activity in the trunk (Hansson 1990). As well, the position of the legs can have an effect on the rigidity of the spine through resultant muscle activity and spinal loading. For example, a flexed knee and hip will rotate the pelvis backwards, flattening spinal curvature and increasing back muscle activity (Chaffin et al. 1999).

### 2.3.7 Work duration, posture, fatigue and vibration transmission

Forestry MMOs work long hours with the majority spent exposed to seated WBV (Golsse and Hope 1987; Harstella 1990). Since the duration of vibration exposure is an important factor in the health effects seen with WBV (Bovenzi and Betta 1994; BS 6841:1987; Herington and Morse 1995; Bovenzi 1996; ISO 2631-1:1997), and damage to vertebral discs is cumulative (Callaghan and McGill 2001), these long hours of operation pose an increased risk for vibration related problems. The long duration of static driving postures and repeated movements to operate controls also cause distress on the body (Haslegrave 1995), and can lead to localized muscle fatigue and subsequent discomfort and pain.

Long hours of work and fatigue affect posture with the back having a tendency to round
as time goes on (Michida et al. 2001). These postural changes while exposed to vibration over time have implications for vibration transmission since different postures can create conditions that more readily transmit and attenuate vibration (in this case they may increase vibration transmission). Interestingly, fatigue affects posture, but posture can also affect fatigue. Wilder et al. (1994) found that low back (L3 erector spinae) muscle fatigue during a simulated truck drive was greatest in an upright posture when compared to a forward lean posture and a posture where the subject leaned against a backrest. Thus, some postures may be more fatiguing and lead to posture changes that can affect vibration transmission.

2.3.8 Productivity and whole-body vibration risk factors

The bottom line of any forestry operation is economics and productivity becomes perhaps the most import issue. Discomfort, fatigue and WBV exposure during forestry equipment operation can all affect the productivity of forestry MMOs. Discomfort in MMOs is influenced by WBV, operator posture, the forces required to operate controls, seat design, pressure distribution on the buttocks and thighs, and noise (BS 6841:1987; Witheford 1994; Haslegrave 1995; ISO 2631-1:1997; Park and Kim 1997; Shen and Vertiz 1997; Park et al. 1998; Mehta and Tewari 2000; Tewari and Prasad 2000; Pope, Goh and Magnusson 2002). The aforementioned variables also affect the level of discomfort of forestry MMOs, and when discomfort is present there is an increased likelihood of reduced productivity (Love et al. 1992; Haslegrave 1995).

Fatigue can contribute to poor performance and increase human error (Slappendel et al. 1993; Spurgeon et al. 1997; Lilley et al. 2002). WBV, repetitive movements and long work days can all be fatiguing and diminish productivity. Vibration exposure can produce a cardiopulmonary response similar to that during moderate exercise (Wasserman and Taylor 1992; Kroemer, Kroemer and Kroemer 1999), and can lead to higher rates of fatigue (Pope and Hanson 1992). Many drivers view WBV as fatiguing and feel that it affects work performance (Hansson 1990). Additionally, WBV acceleration levels greater than 0.5m/s² in any axis can decrease an individual’s visual acuity, dexterity, and hand manipulation abilities (BS 6841:1987; Village et al. 1989; Slappendel et al. 1993). Seidel et al. (1980) found that with increased time of WBV exposure, subject reaction times to a stimulus increased as did the number of errors in stimulus recognition. These authors found that an 8Hz exposure was more detrimental than a
4Hz exposure. Lewis and Griffin (1980) found similar results, with increased WBV acceleration levels resulting in a greater percentage of reading errors and longer reading times. In contrast to Seidel et al. (1980), these authors found that 11.2Hz was the most sensitive frequency, resulting in more errors and a longer reading time. Consequently, WBV exposure can result in inefficient and inaccurate operation of equipment, once again leading to decreases in productivity.

Longer work days have also been shown to decrease performance (Spurgeon et al. 1997), with the effects being greater at night (Lilley et al. 2002). This is likely due to the accumulation of fatigue from WBV exposures, repetitive movements, and static postures throughout the work day. Night work may also affect performance due to the disruption of normal circadian rhythms (daily sleep/rest cycles). When asked to assess the effect of fatigue on work quality and output, 38% of forestry workers in New Zealand felt that their work quality and output were affected by fatigue some of the time, while 8% reported it often or always affecting work quality and output (Lilley et al. 2002).

2.4 OVERVIEW AND RECOMMENDATIONS

Ultimately, research is focused on reducing injuries so that workers do not have to suffer through any ill health, but also to decrease healthcare and injury related costs to companies and society as a whole. In addition to decreasing injury related costs to employers, increased production and higher profits are a primary goal of any company. This chapter discussed several factors which can influence the health of forestry MMOs, along with how those factors can interact, and the effects of those factors on operator productivity. The synthesis of the large body of literature provided in this paper indicates that reductions in injury and subsequent injury cost can be accomplished by reducing biomechanical risk factors, thus resulting in concomitant productivity improvements. The following sections discuss some methods for reducing the aforementioned biomechanical risk factors.

2.4.1 Postural improvements

There are several guidelines available indicating which postures are less harmful than others, but little is known about which postures are optimal, particularly when considering
interacting factors such as: WBV exposure and transmission, spinal stability, muscle activity, repetitive forceful movements, as well as health and productivity outcomes. Determining postures that minimize WBV transmission while optimizing spinal stability can lead to improved operator cab designs. For example, it has been established that visibility requirements and control locations influence the operator’s posture. The repositioning of controls, cab frame components, working attachments, or any other object which would cause an operator to bend or twist in order to obtain the necessary field of view or operate the necessary controls for the task being performed can help improve operator postures. The use of a swiveling seat and self-leveling cabs have been suggested by operators to be a benefit and aid in providing a comfortable working posture (Bottoms and Barber 1978; Gellerstedt 1998; Gellerstedt 2002), as well as a decrease in head and trunk rotations (Eklund et al. 1994; Gellerstedt 1998).

Gellerstedt (1998) provided a review of the design and ergonomic studies of a Pendo™ self-leveling and swiveling cab manufactured in Sweden. The cab is suspended from an arched column that is in turn connected to a swiveling socket that can be controlled by the operator. This gives the operator the ability to adjust the cab for optimum visibility at all times, alleviating skewed and twisted work positions. When compared to a conventional cab, the operator’s head rotation while operating a harvester with a Pendo™ cab was reduced. Gellerstedt (1998) reported that the amount of time that harvester operators spend with their head rotated beyond 22.5° was reduced by 10 to 28 minutes per hour when a Pendo cab was used. Although the swivel seat and self-leveling or swiveling cab may not be a viable solution for all forms of forestry equipment, they do demonstrate how operator postures can be improved through cab design.

2.4.2 Reductions in repetitive movements

There are significant differences between operators with and without neck and shoulder health problems with respect to arm movement span and speed, control resistance, as well as the location of armrests and controls (Hansson 1990; NIOSH 1997). Limiting the magnitude of the movement span can lead to a decline in muscle activity (Hansson 1990). Therefore a reduction in the magnitude of these repeated motions (through control location and operational requirements) may help reduce musculoskeletal injuries. This has been demonstrated in musculoskeletal injury intervention studies that found reductions in task repetition coupled with the adoption of less
extreme working postures resulted in a reduced incidence of neck musculoskeletal disorders and an improvement in symptoms in those who were experiencing neck problems (NIOSH 1997).

2.4.3 Reductions in whole-body vibration exposure

Posture and repeated movements are only one important factor in the health and productivity of forestry MMOs. WBV exposures which can influence muscle activity and potentially influence spine stability are also an important concern. Currently interventions for WBV exposure focus on designing seat suspensions to attenuate vibration and shift exposures to less harmful frequencies (below the resonant frequency of the operator’s trunk). In addition to seat suspension systems; seat cushioning, cab/chassis and axle/chassis suspension systems, and the vehicle tires can all be used in combination to help minimize operator WBV exposures.

2.4.3.1 Seat suspensions

Donati (2002) stated that the majority of suspension seats are designed to ensure isolation only in the vertical (Z-) axis. This was demonstrated in a study by Malchaire et al. (1996), where a mechanical anti-vibration suspension was found to significantly reduce Z-axis vibrations in forklift trucks, but there was no influence on vibration levels in the X- and Y-axes. The vertical vibration isolation is done most often with scissor linkage seats that utilize a spring/damper system or an air bladder and compressor to provide the vibration attenuation. Donati (2002) notes that the suspension travel should be sufficient to prevent bottoming or topping at end stops, and that the lower the input frequency, the larger the required suspension travel to dampen the input. Thus the low frequency vibration seen in forestry vehicles requires sufficient space for suspension travel, which is likely limited and may result in a risk for impacts when high vibration input levels are present. This will result in transient loading of the spine as well as increase the overall vibration exposure levels if these impacts are repeated. In order to minimize these impacts, some suspension manufacturers will highly damp their suspensions to prevent end-stop impacts, but this is usually detrimental to suspension performance (Donati 2002). One suggestion by Donati (2002) was to utilize soft end stops, but Donati (2002) further stated that such end stops require space, which may affect the capacity of the suspension system to reduce
input vibrations. Weight adjustments are also provided so that the seat suspension sits at its mid-
travel point when the operator sits on the seat. A proper weight adjustment for a seat helps to
reduce the amount of end stop impacts as it provides the suspension system with the greatest
travel distance to dampen input vibrations before the endstops are reached.

Paddan and Griffin (2002) measured vertical accelerations on the floor and seat base of
100 vehicles fitted with both conventional (67 vehicles) and suspension (33 vehicles) seats.
These authors reported lower median seat vibration transmission (using both RMS and vibration
dose values calculated in accordance with ISO 2631-1:1997 and BS 6841:1987) with vehicles
that were fitted with a suspension seat (Paddan and Griffin 2002). However, several suspension
seats amplified the vibration they were supposed to attenuate. Seat suspensions can be described
as a second order system where frequencies above the resonance of system (1.4 times the
resonance frequency - Donati 2002) are attenuated. Thus, the stiffness of a suspension seat is
adjusted such that its resonance for a given supported weight is below the dominant input
frequency of the chassis. If the seat suspension stiffness/resonance is not properly adjusted and
overlaps with the chassis input frequencies, then the vibration inputs will be amplified. The
amplification of vibration seen with suspension seats generally happens when the suspension seat
used was not designed for the dynamic properties of the vehicle it is mounted on, under the
conditions that the vehicle is being used. Paddan and Griffin (2002) found that 94 out of the 100
vehicles investigated might benefit from changing the seat to one having the dynamic
performance of a different vehicle, demonstrating how the seats used need to be appropriate for
the vehicle and driving conditions.

A lightly damped and soft suspension is considered desirable for effective attenuation of
continuous vibration of low-to-medium levels, provided that the excitation occurs at frequencies
well above the seat's natural frequency (McManus et al. 2002). The attenuation of high-
magnitude vibration and shock, on the other hand, requires suspension designs with higher
damping and stiffness to prevent end-stop impacts from occurring (McManus et al. 2002). In
environments involving combinations of low, medium and high levels of continuous vibration
and shocks (as seen in forestry), means of achieving variable damping are therefore desirable to
adapt the seat attenuation performance accordingly (McManus et al. 2002). This can be achieved
through the incorporation of active or semi-active damping within the suspension (McManus et
al. 2002). Active suspension systems can help improve low-frequency vibration attenuation of
seats, but because active suspensions require a continuous power source and associated electronics, they have a high manufacturing cost, complexity in control, and poor reliability (Sankar and Afonso 1993). On the other hand, semi-active suspension systems (which perform relatively well in comparison to active control designs) require less power than active control systems, are more reliable, and are less costly as a result of their simpler design (Guglielmino et al. 2005).

McManus et al. (2002) compared the vibration and shock attenuation characteristics of a suspension seat fitted with a conventional damper and one which was fitted with a semi-active magnetorheological fluid (MR) damper designed for use in heavy road vehicles. It was found that the conventional suspension had a natural frequency near 1.48 Hz and a corresponding peak acceleration transmissibility of 1.51, while the MR damper suspension when set to ‘medium’ and ‘firm’ had natural frequencies near 1.37 Hz and 1.49 Hz respectively with corresponding peak acceleration transmissibility values of 1.63 and 1.59 (McManus et al. 2002). These results suggest that at the optimal mid-ride position, the seat with a conventional damper offered higher damping capabilities than that provided with the MR damper, for both medium and firm settings (McManus et al. 2002). However, under a transient (pot-hole) excitation, the MR damper with a firm setting performed the best with respect to end-stop impacts as it required the most energy in terms of ISO 2631-1:1997 weighted RMS Z-axis accelerations and vibration dose values to induce an end-stop impact (McManus et al. 2002). The MR damper with the medium setting required the next most energy to induce an end-stop impact followed by the conventional damper (McManus et al. 2002). When increasing the vibration inputs by 150%, McManus et al. (2002) found that at mid-ride height, only the MR dampers (medium and firm) prevented end-stop impacts. Here, the firm setting provided the lowest Z-axis transmissibility with regards to RMS accelerations, vibration dose values, and crest factors.

Seat suspensions designed with MR dampers have a quick dynamic response, but the fast switching of the damper characteristics results in ocassional acceleration and jerk peaks that degrade ride quality (Guglielmino et al. 2005). To overcome the fast switching problem, Guglielmino et al. (2005) incorporated the use of fuzzy logic controls to smooth the control action without using low-pass filters that would reduce the system bandwidth (Guglielmino et al. 2005). Using a random vibration input and a 1998 Wei and Griffin lumped parameter seat and driver model, Guglielmino et al. (2005) found that a MR damper with fuzzy logic control
reduced the RMS accelerations transmitted to the body by 21%, as well as lowered the peak acceleration frequency when compared to the same suspension system with a traditional viscous damper. It should be noted that the MR damper was found to reduce RMS accelerations by an extra 6% when a ‘crisp’ controller was used instead of the fuzzy logic control, but the fuzzy logic controller reduced acceleration peaks and improved ride quality (Guglielmino et al. 2005).

The above seat suspension systems were designed for the Z-axis; however, the Z-axis is not the only direction of vibration exposure that designers should be concerned with (as indicated in previous sections of this paper). The attenuation of X- and Y-axis vibrations is also desired, and some attempts to attenuate these horizontal vibrations have been made. X-axis suspensions have been used with articulated and agricultural tractor seats where they were found to be particularly useful when these tractors were pulling a trailer (Donati 2002). These X-axis suspensions allow the driver's body to move in phase with seat motion (Donati 2002). Without an X-axis suspension, at about 2 Hz, a driver may move backwards while the seat moves forwards resulting in the seat striking the driver in the back (Donati 2002). This may result in injuries to the back and neck as the impact could cause the neck to extend rapidly.

Sankar and Afonso (1993) investigated the performance of a combined Y- and Z-axis suspension system during off-road vehicle use. The Y-axis isolator consists of a platform supported on a set of linear bearings with springs and a shock absorber, and the Z-axis isolator was a scissor linkage bounce suspension system (Sankar and Afonso 1993). In a laboratory test, Sankar and Afonso (1993) found reductions in Y-axis vibration magnitudes that were greater than 30% when vibration inputs had a frequency above 1Hz (the suspension resonance was tuned to 0.5Hz). When the vibration inputs were greater than 1.5Hz the Y-axis vibration magnitudes were reduced by more than 50% (Sankar and Afonso 1993). With a field test (using a dump truck on a test track), Sankar and Afonso (1993) found that their lateral suspension system improved the vibration exposures at the seat. The same Y-axis suspension system could also be used in the X-axis. A combination of a tuned X-, Y- and Z-axis suspension system would then provide triaxial translational damping of vibrations to the seat.

2.4.3.2 Saddle seats

In addition to seat suspensions, different seat designs to improve ride quality have been
investigated. One design that has shown some promise is the saddle seat. Mansfield et al. (2002) compared a standard suspension seat (typically used in forwarders) to a saddle type seat (with an identical suspension mechanism). The saddle seat height was selected such that the operator’s relative trunk/thigh angle was 130° (Mansfield et al. 2002). Both seats were mounted on a forwarder which drove over a test track (Mansfield et al. 2002). The two seats were both found to have a peak vibration transmission between 1.5Hz and 2Hz with the saddle seat having a slightly lower peak value and fewer impact occurrences (Mansfield et al. 2002). Subjectively, the operators in the study had no clear preference between seats when simply driving, but the operators preferred the saddle seat when driving over rough tracks as fewer end-stop impacts were experienced (Mansfield et al. 2002). In addition, Mansfield et al. (2002) reported that ISO 2631-1:1997 weighted RMS accelerations measured on the seat were significantly lower in the Y- and Z-axes for the saddle seat. The vibration dose values were also significantly lower for the saddle seat in the Z-axis, but the saddle seat had significantly greater vibration dose values in the X-axis (Mansfield et al. 2002). Further investigations into the seat design’s affect on contact pressure distribution between the seat, buttock and thigh should be conducted, coupled with investigations into the affect of the thigh angles on pelvic and spinal postures and concomitant influences on muscle activity and vibration transmission through the spine.

2.4.3.3 Seat cushioning

Seat cushioning can also be used to reduce vibration exposure levels and improve operator comfort ratings for the seat. Mayton et al. (2005) investigated the effects of differed seat cushion configurations in mid-coal seam shuttle car haulage vehicles. There were three seat cushions used: the original seat cushion (well worn), a seat with 13cm of Sun-Mate Extra-Soft foam padding, and a seat with a combination of Sun-Mate Extra-Soft foam and Pudgee padding that totaled 13cm in thickness (Mayton et al. 2005). Subjectively, the operators preferred the seat with just the Sun-Mate Extra-Soft foam padding (Mayton et al. 2005). When considering vibration exposure levels, Mayton et al. (2005) found that the Sun-Mate Extra-Soft foam and Pudgee padded seat performed the worst while driving fully loaded with an average daily exposure limit of 201-minutes and an average vector sum RMS acceleration of 2.19 m/s² (using 2002 ACGIH TLV guidelines for vibration exposures and analyses which are based on ISO
Mayton et al. (2005) attribute the poor performance of this seat while driving loaded to a frame mounted horizontal spring on which the foam padding was mounted. The Sun-Mate Extra-Soft foam and Pudgee padded seat, however, performed the best when driving unloaded, with an average daily exposure limit of 503-minutes and an average vector sum RMS acceleration of 1.53 m/s². The seat with just Sun-Mate Extra-Soft foam padding had average values as follows: a vector sum RMS acceleration of 2.21 m/s² with a daily exposure limit of 243-minutes while driving loaded, and a vector sum RMS acceleration of 1.41 m/s² with a daily exposure limit of 463-minutes while driving unloaded (Mayton et al. 2005). Finally, the original seat had an average vector sum RMS acceleration of 1.62 m/s² and 1.98 m/s² with a daily exposure limit of 492 and 233-minutes while driving loaded and unloaded respectively (Mayton et al. 2005).

### 2.4.3.4 Cab suspensions

Vehicle cab suspensions are another option for the reduction of operator exposures to WBV. Here, low-frequency suspension systems are incorporated between the driving cab and chassis. Donati (2002) stated that only low-frequency suspension cabs (preferably fitted with a four-point suspension) are efficient enough to reduce the vibration transmitted to the operator. The advantage of a low-frequency suspension cab over a suspension seat is that the operator's whole-body is protected from WBV with respect to several degrees of freedom (Donati 2002). Low-frequency suspension cabs can be designed to ensure isolation in all three linear axes but the main purpose is to reduce vertical movement as well as rolling and pitching. These cabs have been shown to reduce vertical vibration transmitted to the operator (Donati 2002; Lemerle et al. 2002). Lemerle et al. (2002) designed a cab suspension to isolate Z-axis, pitch and roll vibrations, and reported reductions in the Z- and X-axis vibrations during simulated driving. Lemerle et al. (2002) further validated the use of their cab suspension design during a field trial with the system mounted on a forklift truck. Pendo™ cabs described by Gellerstedt (1998) are also equipped with vibration-reducing and shock-absorbing features that provided vibration isolation for the cab in the X-, Y- and Z-axes. These Pendo™ cabs have demonstrated the ability to lower vibration exposure levels (although not at a statistically significant level) when compared to conventional cabs (Gellerstedt 1998). The improvements in vibration exposures
levels were seen in the X- and Y-axes of harvesters (note that here there was no Z-axis suspension), the Y- and Z-axes of forwarders while driving empty, and the X- and Z-axes of forwarders while driving loaded (Gellerstedt 1998).

2.4.3.5 Axle suspensions

Axle suspensions are another possible means of reducing operator WBV exposures. However, most all-terrain construction, agricultural and forestry vehicles are designed with no suspension at the axles (Sankar and Afonso 1993; Donati 2002). Donati (2002) comments on the benefits of axle suspensions in the vertical, pitch and roll axes, but investigations into the effectiveness and feasibility of axle suspensions for use in forestry machines should be conducted.

2.4.3.6 Tire inflation

Tire pressure levels can also be used to help reduce operator WBV exposure levels. Oguz and de Hoop (1998) stated that both empirical evidence and truck driver testimonials indicate that lowered tire pressures improve the ride quality for the driver. Sherwin et al. (2004b) found that increased tire pressures (20 psi increased to 60 psi) were associated with significantly increased X- and Z-axis WBV exposures in a cut-to-length timber harvester driven on an ISO 5008:1979 test track. The ISO 2631-1:1997 comfort weighted vibration total values that were reported for these tire pressures are associated with no discomfort at 20 psi (vibration total value = 0.277m/s²) and fairly uncomfortable at 60 psi (vibration total value = 0.527 m/s²), using ISO 2631-1:1997 comfort guidelines. As well, the ISO 2631-1:1997 health weighted vibration total value for the 20 psi tire pressure (0.324 m/s²) was associated with no health risk for an 8-hour day, while the 60psi vibration total value (0.561m/s²) was associated with a potential health risk for an 8-hour day according to ISO 2631-1:1997 health guidelines. Thus, lower tire pressures were associated with improved comfort and reduced injury risk for cut-to-length timber harvester operators.

Knowledge gained from further investigations into the interactive effects of tire inflation with driving surfaces, carried loads, driving speeds for specific vehicle makes and models can be
used to help minimize vibration exposure levels further through the aid of Central Tire Inflation (CTI) technology. CTI technology allows operators to adjust individual tire pressures while the vehicle is in motion (Oguz and de Hoop 1998). This can help minimize WBV exposures as operators adjust tire pressures for a given load, speed, or driving condition. CTI can also assist in improving vehicle traction, decreasing tire bounce on hard surfaces and reducing wash-boarding on soft surfaces (Oguz and de Hoop 1998). In addition, reductions in vibration levels through the tire pressure adjustments can help reduce vehicle maintenance costs in addition to the operator comfort and health benefits.

2.4.3.7 The operator and suspension systems

Although both the attenuation of vibration and the shifting of exposures to less harmful frequencies are desired, the shifting of frequencies needs to account for more than the general biodynamic response of trunk. Shifting the frequency may benefit one level of the spine but be detrimental to another. The design of these seats needs to consider how the body responds to vibration under various conditions, and currently, research that focuses on the body’s response to real life vibration exposures and adopted postures seen in the field is limited. There is also little focus on how a wide array of risk factors for back and neck injuries in forestry MMOs interact. Designing an efficient seat or vehicle for reducing WBV exposures may not be effective if static sitting postures and repetitive manipulation of controls are not considered.

2.4.3.8 Operator training

Well designed equipment does not provide a viable solution if operators do not use it properly. Driver WBV exposure levels have been shown to increase with increases in driving speed (Golsse and Hope 1987; Malchaire et al. 1996; Rehn et al. 2005a). On the other hand, proper and timely maintenance of vehicle systems can reduce vibration and noise exposure (Neitzel and Yost 2002), and proper combinations of tire inflation and seat suspension can also help reduce vibration exposure acceleration levels (Malchaire et al. 1996; Oguz and de Hoop 1998; Sherwin et al. 2004b). Thus, proper operator training (regarding speeds, maneuvering over rough terrain, tire inflation, and proper suspension seat adjustment) and vehicle
maintenance can help to reduce musculoskeletal injury risk factors. Experienced operators also display fewer control movements during the day (Gellerstedt 2002), which can help reduce fatigue and improve productivity. However, even though operators can be instructed on how to drive, sit, and operate controls, production demands and long work days will likely be counterproductive to efforts to reduce musculoskeletal complaints.

Another point to consider is the operator turnover associated with musculoskeletal injury complaints. Kirk et al. (1997) reported high employee turnover in the New Zealand forestry industry, which can create problems for the forestry industry when worker skills and the costs of their training are lost. An additional problem with high turnover is employers may discourage employee training which aims to reduce injury risks and improve productivity, since experience may affect operator efficiency and ride smoothness (Golsse and Hope 1987). It has also been reported that there is a considerable difference between trained and untrained New Zealand worker turnover rates (Kirk et al. 1997), with higher turnover in untrained workers. Thus training and experience can help mitigate some of the risk factors for musculoskeletal injuries associated with mobile machine operation, potentially reduce costs, improve productivity, and decrease operator turnover.

2.4.3.9 Rest breaks

Properly scheduled rest breaks may also benefit operators by reducing operator fatigue, and exposure to musculoskeletal risk factors (i.e., WBV, static postures, and repetitive movements). Lilley et al. (2002) reported that the odds of forestry workers experiencing high levels of fatigue were decreased when rest breaks were taken. A literature review by Tucker (2003) suggested that sufficient rest breaks may be an efficient means of avoiding fatigue-related decrements in driving performance. Tucker (2003) went on to indicate that fatigue is managed best when drivers take their rest breaks whenever they feel fatigued, and that the benefits of a rest break are enhanced when food is consumed, a short nap is taken, and a caffeine drink is consumed. Tucker (2003) continued with a discussion regarding how the optimal frequency, timing and duration of breaks for various job tasks are unknown, as research tends to focus on the overall amount of rest taken within a duty period. Optimum rest schedules are likely to be specific to the nature of the work activity being undertaken (e.g., task demands, worker’s control
of pacing) as well as differences in both the individual’s state (e.g., ability, motivation, sleep debt) and trait (e.g., circadian type, for example, a morning person versus a night person) (Tucker 2003). In addition to fatigue issues, Lilley et al (2002) stated that forestry workers working short intensive periods without adequate rest breaks were at higher risk of accidents and lost-time injury. Thus, properly scheduled rest breaks have the potential to reduce fatigue, accidents and musculoskeletal injuries, while improving driver performance. However, job/employee specific rest break schedules need to be investigated so that the benefits can be optimized.

2.5 CONCLUSIONS

In conclusion, guidelines based on WBV exposures and adopted postures associated with the operation of mobile equipment in industry, which optimize spine stability, reduce WBV transmission and minimize fatigue, will ultimately reduce musculoskeletal injuries while improving productivity. The implementation of these guidelines in the design or improvement of cabs coupled with proper forestry MMO training and work-rest schedules can help to reduce musculoskeletal injuries and costs to employers and society.

REFERENCES


CHAPTER 3

TRI-PLANAR TRUNK MOTION IN NORTHERN ONTARIO SKIDDER OPERATORS

3.1 INTRODUCTION

In the forest industry, injuries and/or pain to the arm, neck, shoulder, legs, and lower back are common in mobile machine operators (MMOs) (Axelsson and Ponten 1990; Hansson 1990; Harstella 1990; Hagen, Magnus and Vetlesen 1998; Rehn et al. 2002; Synwoldt and Gellerstedt 2003). Hagen, Magnus and Vetlesen (1998) found a high prevalence of low back disorders (22.7%) and neck/shoulder disorders (34.8%) in forestry MMOs. Rehn et al. (2002) found that the prevalence of musculoskeletal symptoms of the neck, shoulder, upper back and lower back in forestry MMOs was 61%, 56%, 20% and 47% respectively. The musculoskeletal complaints of these forestry MMOs likely result from a combination of whole-body vibration (WBV) exposure, static driving postures, and repetitive movements associated with the operation of hand and foot controls (Axelsson and Ponten 1990; Harstella 1990; NIOSH 1997; Hagen, Magnus and Vetlesen 1998; Synwoldt and Gellerstedt 2003; Jack and Oliver 2008 – Chapter 2).

Seat design, control locations, vision requirements, and the sitting habits of the operator will all influence the postures adopted by forestry MMOs as they bend and twist to view driving routes and attachments, as well as to reach controls (Bottoms and Barber 1978; Eklund, Odenrick and Zettergen 1994; Boden and Oberg 1998; Chaffin, Anderson and Martin 1999; Gellerstedt 2002; Mansfield et al. 2002; Pope, Goh and Magnusson 2002; Godwin et al. 2007). Holding these seated postures for extended periods of time has been associated with musculoskeletal problems of the neck, back, shoulders, legs and buttocks (Floyd and Roberts 1958; Bottoms and Barber 1978; Frymoyer et al. 1983; Village, Morrison and Leong 1989; Zacharkow 1990; Pope and Hanson 1992; NIOSH 1997; Boden and Oberg 1998; Chaffin, Anderson and Martin 1999). Forestry MMOs also conduct repeated arm movements (Hansson 1990; Gellerstedt 2002) and are exposed to harmful levels of whole-body vibration (WBV) (Golsse and Hope 1987; Boileau and
Rakheja 1990; Neitzel and Yost 2002; Neitzel and Yost 2003; Rehn et al. 2005a; Rehn et al. 2005b; Cation et al. 2008) while adopting these postures, both of which have been associated with neck and shoulder pain in MMOs (Village, Morrison and Leong 1989; Hansson 1990; Johanning 1991; NIOSH 1997; Scutter, Turker and Hall 1997; Hagen, Magnus and Vetlesen 1998; Koda et al. 2000; Rehn et al. 2002; Jack and Oliver 2008 – Chapter 2). WBV has also been positively related to back disorders and low-back pain (LBP) (Frymoyer et al. 1983; Hulshof and Veldhuijzen van Zanten 1987; Johanning 1991; Bovenzi and Betta 1994; Bovenzi 1996; NIOSH 1997; Scutter, Turker and Hall 1997; Bovenzi and Hulshof 1998; Schwarz et al. 1998; Teschke et al. 1999; Koda et al. 2000; Ling and Leboeuf-Yde 2000; Rehn et al. 2002). Moreover, WBV has increased harmful effects when combined with adverse postures (Village, Morrison and Leong 1989; Bovenzi and Betta 1994).

Although reports linking posture to the incidence of back and neck pain in MMOs are insightful, the current authors have found those reports to be typically qualitative in nature. The lack of quantitative postural data is largely due to the instrumentation difficulties associated with field studies in which operators perform their job tasks under real operating conditions. As a result, it is known that forestry MMOs adopt twisted and/or bent postures (Gellerstedt 2002; Rehn et al. 2005b), but one cannot accurately state the magnitudes or timing of these postures. The goal of this paper is to provide quantitative data for three planes of trunk motion (lateral bending, forward flexion/extension and axial twisting) under field operating conditions for Northern Ontario skidder operators. In addition, connections between the measured postures and self-reported musculoskeletal symptoms for the trunk, neck and shoulder will be explored, along with cab design and job task features that influenced the operator’s posture.

3.2 METHODS

3.2.1 Tri-planar trunk motion measurements

Three planes of trunk motion (flexion/extension in the sagittal plane, lateral trunk bending in the coronal plane, and axial trunk twisting) were monitored for seven male Northern Ontario skidder operators under field operating conditions (refer to Table 3.1 for a summary of operator characteristics). A biaxial goniometer (Biometrics Ltd. SG150, Gwent, UK) mounted
over the axis of rotation of the left hip was used to determine the trunk flexion/extension and lateral trunk bending (LTB) angles relative to the thigh (Figure 3.1). A torsiometer (Biometrics Ltd. Q110, Gwent, UK) mounted over the lumbar spine was used to determine the axial trunk twisting (TWST) angles (Figure 3.1). Here the angle measured represents the rotation of the lower thoracic spine (approximately T9-T12) relative to the sacrum. Upon mounting of the goniometer and torsiometer, the skidder operators entered the machine cabs and adopted an upright seated posture (i.e. a vertical trunk position, with no LTB or TWST) used to represent a 0° flexion/extension, 0° LTB, and 0° TWST posture. While adopting this upright seated posture, all goniometer and torsiometer raw voltage outputs were set to zero, as suggested by Jack and Oliver (Appendix A). This “on subject zeroing” was performed to remove any bias errors that may occur from misalignment during the mounting of the goniometer and torsiometer, as well as any biases that may have resulted from tissue displacements during the adoption of the seated posture inside the skidder cab. After the goniometer and torsiometer bias removal, flexion was then defined as any forward movement of the trunk from the initial upright posture (represented by a positive angle) used for “on subject zeroing”, and extension was any backward trunk motion from this initial posture (represented by a negative angle) (Figure 3.1). For both LTB and TWST, 0 degrees indicated an upright posture with the subject facing straight ahead, a negative angle indicated a TWST or LTB to the left, and a positive angle indicated a TWST or LTB to the right (Figure 3.1).

Raw goniometer and torsiometer voltages were collected with a SOMAT™ 2100 Field Computer (nCode, Urbana, Illinois, USA) at a rate of 500Hz while all seven skidder operators performed their normal operating duties. Five operating conditions were observed and monitored; driving with a load (DL), driving without a load (DUL), picking up a load (PUAL), dropping off a load (DOAL), and ploughing logs (refer to Table 3.2 for a full break down of the task operating times). A digital video camera (Sony DCR-PC 109, Shinagawa, Tokyo, Japan) mounted in the skidder cab was used to determine when the skidder operator was performing each of the aforementioned tasks. The video camera filmed the operators as well as the rear implements of the skidders. The video data in conjunction with an audible beep and simultaneous voltage spike recorded by a Biometrics Ltd. P98 data logger (Gwent, UK) was used to time stamp the data. The Biometrics Ltd. data logger and SOMAT™ 2100 Field Computer time histories were then aligned using a multiple resolution cross correlation procedure described...
Table 3.1: Summary of operator characteristics and driving experience.

<table>
<thead>
<tr>
<th>Operator</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>39</td>
<td>32</td>
<td>33</td>
<td>28</td>
<td>50</td>
<td>50</td>
<td>56</td>
<td>41.14</td>
<td>10.8</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>145.6</td>
<td>61.2</td>
<td>86.2</td>
<td>83.9</td>
<td>102.1</td>
<td>72.6</td>
<td>97.5</td>
<td>92.7</td>
<td>27.0</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.80</td>
<td>1.73</td>
<td>1.91</td>
<td>1.78</td>
<td>1.73</td>
<td>1.75</td>
<td>1.80</td>
<td>1.79</td>
<td>0.06</td>
</tr>
<tr>
<td>Years operating mobile equipment</td>
<td>20.0</td>
<td>11.0</td>
<td>13.0</td>
<td>5.0</td>
<td>33.0</td>
<td>15.0</td>
<td>35.0</td>
<td>18.9</td>
<td>11.3</td>
</tr>
<tr>
<td>Years operating a skidder</td>
<td>20.0</td>
<td>5.0</td>
<td>13.0</td>
<td>0.1</td>
<td>33.0</td>
<td>12.0</td>
<td>35.0</td>
<td>16.9</td>
<td>13.3</td>
</tr>
<tr>
<td>Average hours/day operating a skidder</td>
<td>11.0</td>
<td>11.0</td>
<td>8.0</td>
<td>14.0</td>
<td>14.0</td>
<td>3.0</td>
<td>8.0</td>
<td>9.9</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Figure 3.1: a) Left Sagittal view of the goniometer and torsiometer mounting placements. b) Posterior view of the goniometer and torsiometer mounting placements. Note: A indicates the goniometer used to measure trunk flexion/extension and lateral trunk bending, and B indicates the torsiometer used to measure axial trunk twisting.
Table 3.2: Average and total data collection times for the five operating conditions monitored during field data collection.

<table>
<thead>
<tr>
<th>Operator</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving With a Load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.88</td>
</tr>
<tr>
<td>Number of trials</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>96.08</td>
</tr>
<tr>
<td>Average Trial Time (min)</td>
<td>1.85</td>
<td>0.83</td>
<td>1.75</td>
<td>0.98</td>
<td>3.50</td>
<td>5.22</td>
<td>4.07</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation (min)</td>
<td>0.43</td>
<td>0.71</td>
<td>1.33</td>
<td>0.20</td>
<td>1.57</td>
<td>2.97</td>
<td>2.23</td>
<td></td>
</tr>
<tr>
<td>Total Operating Time (min)</td>
<td>5.55</td>
<td>1.67</td>
<td>10.50</td>
<td>9.78</td>
<td>21.00</td>
<td>31.30</td>
<td>16.28</td>
<td></td>
</tr>
<tr>
<td>Driving Without a Load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>217.14</td>
</tr>
<tr>
<td>Number of trials</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>11</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>97.41</td>
</tr>
<tr>
<td>Average Trial Time (min)</td>
<td>3.00</td>
<td>1.22</td>
<td>3.29</td>
<td>0.96</td>
<td>3.49</td>
<td>3.37</td>
<td>4.54</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation (min)</td>
<td>1.05</td>
<td>0.94</td>
<td>1.64</td>
<td>0.29</td>
<td>1.56</td>
<td>3.58</td>
<td>2.94</td>
<td></td>
</tr>
<tr>
<td>Total Operating Time (min)</td>
<td>11.98</td>
<td>3.65</td>
<td>16.43</td>
<td>10.57</td>
<td>20.93</td>
<td>20.23</td>
<td>13.62</td>
<td></td>
</tr>
<tr>
<td>Dropping Off a Load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>53.80</td>
</tr>
<tr>
<td>Number of trials</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>8</td>
<td>5</td>
<td>-</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Average Trial Time (min)</td>
<td>0.38</td>
<td>0.12</td>
<td>0.11</td>
<td>0.15</td>
<td>0.27</td>
<td>-</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation (min)</td>
<td>0.53</td>
<td>0.12</td>
<td>0.06</td>
<td>0.10</td>
<td>0.31</td>
<td>-</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Total Operating Time (min)</td>
<td>1.13</td>
<td>0.23</td>
<td>0.33</td>
<td>1.22</td>
<td>1.35</td>
<td>-</td>
<td>0.72</td>
<td>11.69</td>
</tr>
<tr>
<td>Picking Up a Load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of trials</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>9</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Average Trial Time (min)</td>
<td>0.41</td>
<td>0.41</td>
<td>0.54</td>
<td>0.24</td>
<td>0.67</td>
<td>-</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation (min)</td>
<td>0.09</td>
<td>0.25</td>
<td>0.66</td>
<td>0.15</td>
<td>0.20</td>
<td>-</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Total Operating Time (min)</td>
<td>1.22</td>
<td>0.82</td>
<td>3.23</td>
<td>2.12</td>
<td>3.33</td>
<td>0.42</td>
<td>0.55</td>
<td>11.69</td>
</tr>
<tr>
<td>Ploughing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.99</td>
</tr>
<tr>
<td>Number of trials</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>6</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Average Trial Time (min)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.66</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation (min)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.27</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Total Operating Time (min)</td>
<td>-</td>
<td>-</td>
<td>1.17</td>
<td>3.97</td>
<td>-</td>
<td>1.85</td>
<td>-</td>
<td>6.99</td>
</tr>
<tr>
<td>Total Operating Time (min)</td>
<td>19.88</td>
<td>6.36</td>
<td>31.66</td>
<td>27.65</td>
<td>46.62</td>
<td>53.80</td>
<td>31.17</td>
<td>217.14</td>
</tr>
</tbody>
</table>
in Jack et al. (2008 – Appendix B). The goniometer and torsimeter data were then divided into the various skidder operating conditions for analysis.

3.2.2 Data analysis

The raw goniometer and torsimeter voltages collected with the SOMAT™ 2100 Field Computer were 4th order zero-lag Butterworth low-pass filtered with a cut-off frequency of 40Hz. The filtered voltages were then converted to trunk angles by applying experimentally determined calibration equations (refer to section 3.2.3). The trunk angle data were then processed with a wavelet de-noising program (refer to section 3.2.4) to remove the majority of vibration induced motion from the data time histories while allowing as much voluntary motion as possible to remain. The wavelet de-noised trunk angle time histories were then used to determine the percentage of operating time that the skidder operators adopted a given posture. A series of 5° bins were created (i.e. -5° to 0°, 0° to 5°, etc.) and the percentage of time that the operator flexed/extended their trunk, LTB and TWST within that range of angles was determined for each trial of each operating condition. The data were then averaged for each operating condition and across all operating conditions. All data post processing was completed using custom MatLab™ 7.0.4 (MathWorks Inc., Natick, Massachusetts, USA) programs.

3.2.3 Goniometer calibration

Calibration data were collected with the SOMAT™ 2100 Field Computer. A four point calibration was conducted for trunk flexion/extension, and a five point calibration was conducted for LTB. The biaxial goniometer used to monitor both flexion/extension and LTB was calibrated in a position that reflected the position that it would be in while mounted on the skidder operators in the field. Trunk flexion/extension was calibrated with 0° of LTB, and LTB was calibrated with the goniometer flexed to 90° of flexion. A five point calibration was conducted for TWST. In all instances, three seconds of data were collected for each calibration point with a sample rate of 500Hz. Three goniometer and torsimeter calibrations were conducted, one prior to field data collection, one midway through the data collection period (i.e. after half of the
CHAPTER 3: Field Postures

skidders had been tested), and one upon the completion of field data collection. The average of the three calibration slopes was applied to the data (refer to Table 3.3 for calibration results).

Table 3.3: Goniometer and torsiometer calibration information.

<table>
<thead>
<tr>
<th>Goniometer/Torsiometer</th>
<th>Sensitivity (°/V)</th>
<th>Bias</th>
<th>r²-values Are All Greater Than†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk Flexion</td>
<td>1134.33 ± 34.30</td>
<td>67.37 ± 10.60</td>
<td>0.997</td>
</tr>
<tr>
<td>Lateral Trunk Bend</td>
<td>2420.97 ± 222.74</td>
<td>-50.71 ± 25.54</td>
<td>0.989</td>
</tr>
<tr>
<td>Trunk Twist</td>
<td>-630.21 ± 42.98</td>
<td>-4.13 ± 28.78</td>
<td>0.999</td>
</tr>
</tbody>
</table>

†Values represent the minimum r²-value from all calibration equations determined.

3.2.4 Wavelet de-noising

The human body resonates in the X and Y axes at approximately 1-7Hz (Paddan and Griffin 1988a; Paddan and Griffin 1988b; Paddan and Griffin 2000; Jack and Eger 2008) and the dominant translational and rotational WBV exposure frequencies from the skidders driven here were between 1-2 Hz (Cation et al. 2008). Therefore, much of the operator trunk motion monitored could be the result of vibration. The goal of this paper is to determine the underlying voluntary motions and postures required by the operators to perform their skidder operating duties. As a result, a wavelet de-noising procedure was performed.

The wavelet de-noising entailed an initial 3rd order Daubechies 15 level wavelet decomposition. Once the signal was decomposed, ten, 10-second data windows were used to obtain noise estimates for each wavelet decomposition level, at a time when the operator was believed to be adopting a static posture. After the noise estimation, frequency components above 10 Hz were removed because the components of voluntary human movement signals are typically below 10Hz (Derrick 2004). All wavelet decomposition levels with 0.1Hz or less were left completely intact, as vibration exposures from the skidders driven in this study were typically above 0.1Hz (Cation et al. 2008). When there was overlap between the vibration and potential voluntary human signals, the noise estimates were used to remove the vibration induced signal from the underlying voluntary human movement signal. The removal of the vibration signal was accomplished by setting a “soft” threshold to 3-standard deviations about the mean of the noise estimate amplitudes for each of the N wavelet resolutions between approximately 0.1 Hz and 10 Hz (levels E through J). This resulted in the removal of 99.7% of the potential vibration signal determined from the noise estimate and leaves only the potential human
movement signals with amplitudes above the threshold limit. Once the wavelet coefficients had been thresholded, the modified coefficients were used to reconstruct the de-noised signal.

3.2.5 Visibility, cab design and musculoskeletal health surveys

A survey was administered to the skidder operators prior to field data collection. The operators were asked to provide information regarding aspects of their skidder cab design and their job requirements that affected their posture. In addition, the skidder operators were also asked about their musculoskeletal injury history for each of the nine body regions outlined in Table 3.4. Refer to Table 3.4, Table 3.5, and Table 3.6 for the questions asked during the survey.

3.3 RESULTS

3.3.1 Posture analysis

The skidder operators observed in this study were typically seated with a forward facing and slightly extended trunk as they use the backrest for support while DL and DUL (Figure 3.2 and Figure 3.3). The operators’ spent 89% and 78% of their time between 15° of TWST to the right and left while DL and DUL respectively. While DL and DUL, operators were found to adopt an extended trunk posture 80% and 78% of the time. It was also observed that the operators adopted a prominent LTB to the left (>40°) during the DL and DUL conditions (Figure 3.2 and Figure 3.3). This observation is likely the result of operators using their arm and the armrest to support the trunk. The aforementioned results reflect pooled averages of the posture data across all seven of the skidder operators observed. It should be noted, however, that some operators adopted postures that were notably different from the overall average. Operator 4 adopted a more prominent trunk extension while Operator 6 spent much of his time flexing the trunk as they drove with and without a load. A tendency to TWST to the right (Operators 3 and 5) or left (Operator 7), while DL and DUL was also observed in some operators. In addition, the trend towards a large LTB to the left was consistent among all skidder operators, with the exception of Operator 4 and 6 while DL, and Operator 5 when DUL.


Figure 3.2: Average percentage of time spent flexing/EXTending, lateral bending, and axially twisted while driving with a load (DL). Results represent the average of all DL trials collected for each skidder operator, and the overall average of the DL condition for all seven operators.

When observing the operators PUAL and DOAL, it was found that the operators would adopt a large LTB, extend the trunk (greater than what was observed while driving), and TWST to the right (Figure 3.4 and Figure 3.5). On average, the skidder operators spent 46% of their time extending between 10° and 25° while PUAL and DOAL. These operators also TWST to the right (between 0° and 20° of axial trunk twisting) 69% of the time while DOAL, and 74% of the time while PUAL. This posture is consistent with one which would be required to view the
Figure 3.3: Average percentage of time spent flexing/extending, lateral bending, and axially twisted while driving without a load (DUL). Results represent the average of all DUL trials collected for each skidder operator, and the overall average of the DUL condition for all seven operators.

Again, it is worth noting that individual operator differences do exist. Operator 5 and 6 spent a large percentage of time PUAL with a flexed trunk, and Operators 3 and 5 both flex and extend their trunk for a large percentage of time while DOAL. It was noted though, that Operator 3 reduced the amount of time spent adopting a flexed trunk considerably, and Operator 5 spent more time adopting greater angles of trunk flexion and extension when PUAL. In addition,
several operators displayed some distinct patterns of trunk extension, spending much of their time within two or three extension angle ranges while DOAL (Operator 1, 2 and 7) or PUAL (Operator 2, 3 and 7). In contrast, Operator 6 spent the majority of time PUAL between two distinct trunk flexion angle ranges. With regards to TWST, it was found that Operators 1, 3 and 5 would TWST to the right while DOAL and PUAL, and Operator 7 would TWST to the left.
Figure 3.5: Average percentage of time spent flexing/ extending, lateral bending, and axially twisted while picking up a load (PUAL). Results represent the average of all PUAL trials collected for each skidder operator, and the overall average of the PUAL condition for all seven operators.

Operator 1 did however; spend a small amount of time TWST to the left while PUAL, just as Operator 7 also spent a fair amount of time TWST to the right while DOAL. When DOAL, Operator 1 spent the majority of his time TWST to the right within two distinct angle ranges. Also, Operator 2 and 4 were found to adopt both right and left TWST postures while DOAL, but Operator 2 only TWST to the right while PUAL. As with DL and DUL, the LTB observed in the
operators demonstrated the same trend towards a large LTB to the left while DOAL and PUAL. Similar to the driving conditions, Operator 4 spent a great amount of time (38%) laterally bending <20° to the left while DOAL, and even laterally bent to the right (59% of the time). Operator 4 did increase the amount of time he spent LTB to the left while PUAL though. It was also noted that, in contrast to the driving conditions, Operator 5, 6 and 7 adopted LTB postures within more distinct angle ranges while PUAL and DOAL.

In addition to the above tasks, three skidder operators performed a ploughing task, in which the front blade is used to push and pile logs. Since two of the three skidder operators only performed the ploughing task once, pooled averages of the data for the three operators were not calculated, as the results would be skewed to reflect the actions of the third operator who performed 6 ploughing trials. The postures adopted by each operator individually are reported in Figure 3.6. It was found that the skidder operators adopted an extended trunk, and predominantly bent and twisted to one side.

![Graph](image)

**Figure 3.6**: Average percentage of time spent flexing/extending, lateral bending, and axially twisted while ploughing. Results represent the average of all ploughing trials collected for each skidder operator (Note: n=6 for Operator 4, and n=1 for Operators 3 and 6).
### 3.3.2 Health survey

Table 3.4 provides a summary of the musculoskeletal health survey results. With the exception of Operator 7 while DL and Operator 2 while DUL, the operators with the greatest

#### Table 3.4: Summary of findings from a musculoskeletal health survey.

<table>
<thead>
<tr>
<th>Body region</th>
<th>Question Asked</th>
<th>Operators who responded “Yes”†</th>
<th>Operator Response††</th>
<th>Operator Response†††</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Have you experienced any ache, pain, numbness or discomfort?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>When was the last episode of ache, pain, numbness or discomfort?</td>
<td>1</td>
<td>1-2 weeks ago</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>How would you rate the severity of the last episode of ache, pain, numbness or discomfort?</td>
<td>2</td>
<td>Twisting to look at the rear of the skidder</td>
<td>Improve seat the placement</td>
</tr>
<tr>
<td></td>
<td>What task or activity do you think brought on the last episode?</td>
<td>4</td>
<td>Today</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Do you have any suggestions to avoid future episodes of ache, pain, numbness or discomfort?</td>
<td>6</td>
<td>Today</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Operators who responded “Yes”†</td>
<td>Operator Response††</td>
<td>Operator Response†††</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1-2 weeks ago</td>
<td>2</td>
<td>Twisting to look at the rear of the skidder</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Today</td>
<td>2</td>
<td>Twisting to look at the rear of the skidder</td>
</tr>
<tr>
<td>Neck</td>
<td>Improved seating (air-ride seats)</td>
<td>6</td>
<td>Today</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Reduce driving speed</td>
<td>Improved seating (air-ride seats)</td>
<td>Reduce driving speed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Use the arms and steering wheel to help stabilize the body while driving</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Upper Back</td>
<td>6</td>
<td>Within the last week</td>
<td>2</td>
<td>Muscle fatigue while driving</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Reduce driving speed</td>
</tr>
<tr>
<td>Elbows</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Low Back</td>
<td>1</td>
<td>1-6 months ago</td>
<td>3</td>
<td>WBV and Shock exposure</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wrist/Hands</td>
<td>3</td>
<td>Today</td>
<td>2</td>
<td>Hand-arm vibration Exposure (steering wheel)</td>
</tr>
<tr>
<td></td>
<td>Hip/Thighs/Buttocks</td>
<td>4</td>
<td>Today</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Knees</td>
<td>5</td>
<td>Today</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Ankles/Feet</td>
<td>5</td>
<td>Today</td>
<td>2</td>
</tr>
</tbody>
</table>

† Only musculoskeletal complaints attributed to the operation of a skidder are reported.
†† Operators were asked to indicate if you have had an ache, pain, numbness or discomfort in the area in the last year, month, week, or day.
††† Operators were asked to rate the severity of the last episode of ache, pain, numbness or discomfort with the following scale. 1 = mild, 2 = moderate, 3 = severe, 4 = very, very severe.
percentage of time extending the trunk >20° while DL and DUL were the ones who reported musculoskeletal symptoms for the neck (Operators 1, 4 and 6). In addition, the operators who spent the most amount of time with a trunk flexed >10° while DL and DUL (Operators 1 and 6) reported the most severe musculoskeletal symptoms for the neck. The operator who reported upper back symptoms (Operator 6) was the operator who spent the greatest percentage of his driving time (DL and DUL), and time PUAL and ploughing a load with a flexed trunk. Finally, one operator reported LBP (Operator 1), and was found to spend the most time adopting a deep LTB to the left while DL, DUL, DOAL and PUAL. It was also noted that the operator who reported LBP spent the majority of time while DOAL within two distinct flexion/extension and TWST postures indicating frequent movement between these two postures as the operator attempted to view the load.

3.3.3 Visibility and posture

When asked “When operating a skidder, are there any times when you have to adjust your posture in order see what you are doing or where you are going?”, all seven skidder operators answered “yes”. Table 3.5 provides a summary of the visibility and posture survey conducted. From the survey, the requirement to view the rear of the vehicle and the carried load was the most commonly reported reason for the operators to alter their posture, as the seat location lead to a combination of TWST, LTB and flexion or extension of the trunk to improve the operator’s view. The operator’s ability to observe the terrain while driving was another factor commonly reported to affect posture, in particular, trunk and neck rotation.

3.3.4 Cab design and posture

Two of the seven skidder operators surveyed indicated that they had to adjust their posture in order manipulate machine controls. Table 3.6 provides a summary of the cab design and posture survey conducted. In both cases, the operators stated that the location of the hand controls required them to rotate their trunk and neck, in order to perform the task at hand.
Table 3.5: Summary of findings from a visibility and posture survey.

<table>
<thead>
<tr>
<th>Question Asked</th>
<th>Response</th>
<th>The Number of Operators Who Provided the Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>What task were you performing when you had to adjust your posture in order see what you were doing or where you were going?</td>
<td>(1) Driving in reverse (to pick up a load)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(2) Observing terrain while driving</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>(3) Observing tires while driving</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(4) Monitoring the carried load</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(5) Observing axles while driving</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(6) Picking up a load</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(7) Ploughing</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(8) Adjusting the boom/load height for the grade driven over</td>
<td>1</td>
</tr>
<tr>
<td>How was your visibility impaired?</td>
<td>(1) (4) (6) (8) Couldn’t view the load/rear of the vehicle</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>(3) Couldn’t view the tires</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(2) View of the terrain was limited</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(5) Couldn’t view the axles</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(7) Couldn’t view the load/front of the vehicle</td>
<td>1</td>
</tr>
<tr>
<td>What aspect of the cab design impaired your visibility?</td>
<td>(1) (3) (4) (8) Seat placement</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>(3) Radio placement</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(2) Front fenders</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(5) Metal around the windows</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(5) A washer fluid container</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(6) Boom and Arch</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(7) Tires</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(6) Fuel tank</td>
<td>1</td>
</tr>
<tr>
<td>How did your impaired visibility affect you posture? Describe the posture of the neck, shoulders, truck, hips, and legs.</td>
<td>(1) (2) (3) (4) Rotate trunk</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(5) (6) (7) Trunk forward bend</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(6) (7) Trunk lateral bend</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(1) (2) Rotate neck</td>
<td>2</td>
</tr>
</tbody>
</table>

†If a bracketed numbers is displayed beside more than one response, that indicates that those responses are related.

Table 3.6: Summary of findings from a cab design and posture survey.

<table>
<thead>
<tr>
<th>Question Asked</th>
<th>Response</th>
<th>The Number of Operators Who Provided the Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task Description Describe why you have to change your posture to manipulate the machine’s controls during the task</td>
<td>(1) Operating hand controls/grapple</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(1) The hand controls are to the side of the seat</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(1) The hand controls are to the back of the cab</td>
<td>1</td>
</tr>
<tr>
<td>Describe the adopted posture of the neck, shoulders, trunk, hips, and legs.</td>
<td>(2) Rotate trunk</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(2) Rotate neck</td>
<td>2</td>
</tr>
</tbody>
</table>

†If a bracketed numbers is displayed beside more than one response, that indicates that those responses are related.
3.4 DISCUSSION

Knowledge of operator trunk postures under field operating conditions and the influence of those postures on health will allow vehicle designers to create cab, seat and control designs that minimize harmful posture requirements. While driving their skidders, the operators in this study typically sat with a forward facing and slightly extended trunk accompanied by a large lateral bend. Instances of more extreme extension are believed to be the result of operators pushing their trunk into the backrest with their arms and legs in order to support themselves while driving over steep terrain and during WBV exposure. This stabilizing posture was associated with musculoskeletal symptoms for the neck, knees, ankles and feet. Operators who had musculoskeletal symptoms for the neck spent a larger proportion of their time extending or flexing their trunk to greater angles than the other operators under the majority of driving conditions. It was also interesting to note that the operators who spent the most time with a trunk flexed trunk (>10° while DL and DUL) reported the most severe musculoskeletal symptoms for the neck. Extending the trunk would result in the operators flexing the neck in order to view their driving routes, while flexing the trunk would result in neck extension by the operators. Extreme forward flexion of the cervical spine and static contraction of the neck and shoulder muscles to counteract the weight of the head are noted as causative factors for musculoskeletal symptoms of the neck by Magnusson and Pope (1998). Ariens et al. (2001) found that working with a flexed neck for >70% of the work duration increased the odds for neck pain (although not significantly), and that flexion and rotation of trunk are potential confounding variables for neck pain. Harms-Ringdahl et al. (1986) investigated the occipital-C1 and C7-T1 joint loading under combinations of occipital-C1 and C7-T1 flexion and extension, along with the muscle activity of various neck, shoulder and thoracic muscles. These researchers found that a combination of occipital-C1 and C7-T1 flexion increased the load on the C7-T1 joint by a factor of 3.6, and flexing the C7-T1 joint and extending the occipital-C1 joint resulted in a 3.1 times increase in load at the C7-T1 joint (Harms-Ringdahl et al. 1986). Increased joint loading can result in overexertion of tissues and increased cumulative loading, both of which are associate with increased risk of musculoskeletal injuries (Kumar 2001). Harms-Ringdahl et al. (1986) also found that median normalized electromyography (EMG) amplitudes were significantly increased in the trapezius and cervical erector spinae muscles when the C7-T1 joint was fully flexed and the occipital-C1
joint was fully extended (Harms-Ringdahl et al. 1986). Greater muscle activity is associated with increased muscle fatigue due to localized reductions in blood flow and the impairment of normal metabolic processes (i.e. oxygen uptake and metabolite removal), that can result in sensations of pain (Kroemer 1999; Kumar 2001). Therefore, increased joint loading and muscle activity may cause the neck pain reported by the operators in this study.

In addition, to neck symptoms, upper back symptoms were also related to trunk flexion in this study. The operator who reported upper back symptoms spent the greatest percentage of time DL, DUL, PUAL and ploughing with a flexed trunk. Flexing the lumbar spine relative to the sacrum may have been accompanied by some thoracolumbar spine and neck extension to view the driving route and load. Harms-Ringdahl et al. (1986) found that thoracic erector spinae (TES) and rhomboids muscle activity was significantly increased when the neck was extended. O’Sullivan et al. (2006) found that thoracolumbar spine extension in order to maintain an upright sitting posture was also associated with significantly greater TES muscle activation. Hanson et al. (1991) found increased muscle activity and fatigue in the TES muscles while sitting with a flexed trunk and exposed to vibration. It is interesting to note that Hanson et al. (1991) had subjects flex 20° about the hip while vibrated, and the operator with the upper back pain here, spent the most time flexed 20°±5° about the hip while vibrated. Here, much like the neck, fatiguing contractions of the muscles in the upper back for extended periods of time may explain the upper back symptoms.

The trend towards a large lateral bend to the left was consistent among the skidder operators, with the exception of Operator 4 and 6 while DL, and Operator 5 when DUL. Less need for monitoring the load while driving may have allowed the operators to bend to the side, resting against the armrest as they drove. Conversely, an increased need to monitor the load may explain why Operators 4 and 6 spend less time in a deep LTB while DL. It is interesting to note that the operator who reported low-back symptoms was found to spend the most time adopting a deep LTB during all operating conditions. Pope, Goh and Magnusson (2002) discuss how high levels of contralateral muscle activity occur to the direction of trunk rotation and lateral bending, and how muscle activity is small on the ipsilateral side. This asymmetric muscle activity would differentially loads the joints and muscles of the low back. Prolonged and/or repeated differential loading can result in disproportionate demands on the various muscles surrounding a joint.
leading to different levels and rates of muscle fatigue (Kumar 2001). If these patterns of fatigue are allowed to continue, the altered muscle kinetics may result in joint kinematics and loading that differ from the normal and optimal pattern for that joint, potentially leading to alterations in joint stability, stress concentrations, and injury (Kumar 2001; Pope, Goh and Magnusson 2002). Furthermore, the operator who reported low back symptoms spent the majority of time within two distinct flexion/extension postures while DOAL and two distinct TWST postures while DOAL and PUAL indicating frequent movement between these postures as the operator attempts to view the load and perform the required task. Repeated flexion, lateral bending and twisting of the spine can cause damage to the human and animal vertebrae and vertebral discs in vitro (Hardy et al. 1958; Wilder, Pope and Frymoyer 1988; Callaghan and McGill 2001; Kuga and Kawabuchi 2001), and poses a risk for LBP. Static twisted trunk postures are also associated with LBP (NIOSH 1997). Although, no reports of ill health were associated with the tendency to TWST in this study, these postures were observed, with Operators 3 and 5 twisting to the right and Operator 7 twisting to the left while DL and DUL. Twisting in the range of 10°–15° involves little muscle effort, but beyond this region, increased muscle effort is required (Boden and Oberg 1998; Toren 2001). The aforementioned operators exceeded 15° of TWST more than 14% of the time when DL and 21% of the time when DUL. The increased muscle effort with TWST can be fatiguing and lead to pain.

The literature discussed thus far provides reasonable support for the association of the postures determined in the field with the musculoskeletal symptoms reported. In particular, the joint loading and muscle activity associated with the postures seen in these skidder operators can be linked to musculoskeletal injury, but the present study did not collect these types of data. Studies which include the collection of electromyographic (EMG) data and the determination of joint loads should be conducted in the future to support the notion of joint loading and muscle activity as injury mechanisms. In addition, the present study was a preliminary investigation with limited time and funding. As a result, only seven operators were tested, and although the data collected represents a large dataset, it is suggested that a greater number of operators be tested in the future so that the results can be more generalizable.

Table 3.5 and Table 3.6 reveal several aspects of the skidder designs that lead operators to twist their trunk and neck, LTB and flexing/extending their trunk. The repositioning of controls, cab frame components, working attachments, or any other object which would cause an
operator to bend or twist in order to obtain the necessary field of view or operate the necessary controls for the task being performed can help improve operator postures. Using computer simulation, Godwin et al. (2007) found improvements in visibility and reductions in TWST, LTB, and neck rotation with the repositioning of the seat in an underground mining load-haul-dump vehicle. In the skidders studied here, the most common aspects of vehicle design that affected posture were the location of the hand controls and the seat location. The operators reported that the controls to operate the grapple were located to the side of the seat and rear of the cab, causing the operator to twist the trunk and neck to operate them. Relocating the controls from the side/rear of the cab to location in front of the operator would help alleviate the need for the operators to twist while operating those controls. However, the operators would still have to twist in order to view the loads while PUAL or DOAL. This is because the seats face towards the front of the vehicle and the operators need to twist the trunk and neck in order to view the rear of the vehicle where the grapple and load are located. Many skidders have seats that are rotated and are not directly in line with the direction of vehicle travel, in order to reduce the magnitude of twisting required to view the rear of the vehicle; however, it appears that further improvements need to be pursued. The use of a swiveling seat and/or cab has been suggested by operators to aid in providing a comfortable working posture (Bottoms and Barber 1978; Gellerstedt 1998; Gellerstedt 2002), as well as a decrease in head and trunk rotations (Eklund, Odenrick and Zettergen 1994; Gellerstedt 1998). Although a swiveling seat and/or cab may not be a viable solution for all forms of forestry equipment, they do demonstrate how operator postures can be improved through cab design.

3.5 CONCLUSION

Of the three tri-planar trunk postures assessed, the most immediate postural concerns for the health of the skidder operators were trunk flexion, extension and LTB. The relocation of controls from the side of the seat to the front, and improvements in operator visibility through the redesign of some cab elements and the seat would help reduce the risk of injury in these operators and improve ride comfort through improvements in operator posture.
REFERENCES


CHAPTER 4

6-DEGREE-OF-FREEDOM WHOLE-BODY VIBRATION EXPOSURE LEVELS
DURING ROUTINE SKIDDER OPERATIONS

4.1 INTRODUCTION

Whole-body vibration (WBV) exposure can interfere with an operator’s ability to perform activities (detrimental effects on visual acuity, equilibrium, manual dexterity) (Village et al. 1989; ISO 1997), affect operator comfort (ISO 1997), cause muscular fatigue (Village et al. 1989), and can contribute to many health problems (Seidel 1993; Bovenzi 1996; Thalheimer 1996). These health problems can include nervous, circulatory, and digestive system problems, noise induced hearing loss, and degenerative changes to the spine (Seidel 1993; Bovenzi 1996; Thalheimer 1996; Wilder and Pope 1996). Considering the forestry industry, several studies have reported musculoskeletal injuries among forestry machine operators. These studies have reported injuries and/or symptoms (i.e. pain) for the arm, neck, cervical spine, shoulder, lower extremities, and lower back (Axelsson and Ponten 1990; Hansson 1990; Harstella 1990; Slappendel et al. 1993; Hagen et al. 1998; Synwoldt and Gellerstedt 2003; Jack et al. 2008a – Chapter 3).

The health effects seen with WBV exposure are dependent on the vibration characteristics. The magnitude, direction (axis), frequency, and duration of vibration exposure will affect the level of discomfort or pain, the level of interference with performance (reading and hand control), and the occurrence of acute or chronic illness with physiologic and pathologic changes (Herington and Morse 1995). Increased acceleration magnitudes and durations of vibration exposure have been linked to health risks like low-back pain (Bovenzi 1996; Seidel et al. 1998).

Driving environments expose operators to rotational (roll, pitch and yaw) vibrations in addition to the translational (X-, Y- and Z) vibrations (Cation et al. 2008). Rotational vibrations
are not considered in health guidelines with little research conducted to investigate their effects on health. Jack and Oliver (2008 – Chapter 2) outline how rotational WBV exposures could result in adverse health outcomes. They suggest that the combination of repeated flexion, extension and axial twisting that can be induced by six degree-of-freedom (DOF) WBV exposure could lead to the damage and herniation of intervertebral discs, a frequently reported occurrence in mobile equipment operators (Kelsey1975a; Kelsey 1975b; Heliovaara 1987; Hulshof and Veldhuijzen van Zanten 1987; Wilder 1993; Bovenzi and Betta 1994; Teschke et al. 1999). The exclusion of 6-DOF vibration exposures at the operator/seat interface (OSI) with respect to health guidelines combined with the unavailability of appropriate 6-DOF vibration sensors for the collection of these data has lead to a lack of OSI 6-DOF field exposure data for investigating the health effects of whole-body vibration. Tables 4.1 and 4.2 provide a summary of OSI WBV exposure data that is available from research articles and reports for industry and forestry respectively. There are several studies that report vibration dose values (VDV) and British Standard (BS 6841:1987) weighted data, as well as ISO 5008:2002 test track exposures. Tables 4.1 and 4.2 report only ISO 2631-1 weighted RMS acceleration data collected under actual operating conditions, so that representative field exposures can be compared (Table 4.1 was limited to the data with ISO 2631-1:1997 weightings). In all cases, the trends were similar with some papers reporting dominant axis accelerations while others report vector sum accelerations or tri-axial accelerations.

In order to obtain a more comprehensive understanding of how the human body responds to WBV, laboratory investigations which utilize realistic 6-DOF WBV exposures need to be conducted. To the knowledge of the authors, with the exception of Cation et al. (2008), there are no 6-DOF WBV exposure studies available to obtain field based 6-DOF OSI exposure information. Parsons et al. (1979) investigated 6-DOF vibration exposures at the seat, but the reported data was limited to frequency spectra. Other studies have collected both translational and rotational data (for example Boileau et al. (2002), and Dickey et al. (2008)), but these data were collected on the vehicle chassis, and do not represent the actual vibrations that the operators were exposed to at the seat. The ultimate goal of this study was to obtain 6-DOF WBV exposure levels and spectra at the OSI for use as inputs in laboratory investigations on the human biodynamic response to seated 6-DOF vibration exposure. Skidders were chosen as they represented an extreme case scenario in terms of WBV exposures (refer to Table 4.2). Some of
### Table 4.1: A summary of ISO 2631-1:1997 weighted operator/seat interface accelerations reported in industry.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Operating Conditions Tested</th>
<th>Vehicle Type</th>
<th>Average RMS Exposure Accelerations (m/s²)</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Vector Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood et al. 2010</td>
<td>Driven on city roads, new and old freeways, and a route containing speed bumps</td>
<td>Bus (3)</td>
<td></td>
<td>0.11-0.17</td>
<td>0.11-0.15</td>
<td>0.36-0.51</td>
<td>-</td>
</tr>
<tr>
<td>Chen et al. 2009</td>
<td>Driven on rural, urban and provincial roads at 55km/h and 40 km/h</td>
<td>Motorcycle (6)</td>
<td></td>
<td>0.41&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.17&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.8&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Driven on rural, urban and provincial roads at 55km/h</td>
<td>Scooter (6)</td>
<td></td>
<td>0.36&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.13&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.92&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-</td>
</tr>
<tr>
<td>Eger et al. 2008</td>
<td>Typical operating cycle</td>
<td>Load-haul-dump (7)</td>
<td></td>
<td>0.62</td>
<td>0.49</td>
<td>0.77</td>
<td>1.36&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shovel (7)</td>
<td></td>
<td>0.71</td>
<td>0.63</td>
<td>0.52</td>
<td>1.24&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dumper (5)</td>
<td></td>
<td>0.29</td>
<td>0.29</td>
<td>0.42</td>
<td>0.64&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Excavator (7)</td>
<td></td>
<td>0.27</td>
<td>0.21</td>
<td>0.22</td>
<td>0.46&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bulldozer (2)</td>
<td></td>
<td>0.47</td>
<td>0.31</td>
<td>0.63</td>
<td>0.91&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steamroller (2)</td>
<td></td>
<td>0.15</td>
<td>0.15</td>
<td>0.16</td>
<td>0.29&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lorry (4)</td>
<td></td>
<td>0.23</td>
<td>0.23</td>
<td>0.35</td>
<td>0.52&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Asphalt machine (1)</td>
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<td>0.15&lt;sup&gt;a&lt;/sup&gt;</td>
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<td></td>
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<td>Mobile crane (2)</td>
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<td>0.15</td>
<td>0.27</td>
<td>0.36&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td></td>
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<td>Tractor (not reported)</td>
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<td>0.48</td>
<td>0.95&lt;sup&gt;a&lt;/sup&gt;</td>
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<td></td>
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<td>Telescopic handler (not reported)</td>
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<td>0.65</td>
<td>1.10&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>All-terrain vehicle (not reported)</td>
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<td>0.90&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Articulated truck (not reported)</td>
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<td>0.35&lt;sup&gt;a&lt;/sup&gt;</td>
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<td></td>
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<td>Tipper truck (not reported)</td>
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<td>0.17</td>
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<td>0.33</td>
<td>0.46&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Tug-master truck (not reported)</td>
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<td>Car (not reported)</td>
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<td>Taxi cab (not reported)</td>
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<td>Bus (not reported)</td>
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<td>0.43</td>
<td>0.76&lt;sup&gt;a&lt;/sup&gt;</td>
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</tbody>
</table>

<sup>a</sup> Data in the form of vibration total values using the three translational axes with X- and Y-axis k-values equal to 1.4.

<sup>b</sup> Data approximated from a graph.

<sup>c</sup> Average value calculated from data presented by the authors.
### Table 4.1 Continued: A summary of ISO 2631-1:1997 weighted operator/seat interface accelerations reported in industry.

<table>
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<tr>
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</tr>
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<tbody>
<tr>
<td></td>
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<td>Okunribido et al. 2008</td>
<td>Typical operating cycle</td>
<td>Loading shovel (not reported)</td>
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<tr>
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<td>Excavator (not reported)</td>
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<td>Pay loader (not reported)</td>
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<td></td>
<td>Bob cat (not reported)</td>
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<td>Fork lift truck (not reported)</td>
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<tr>
<td></td>
<td></td>
<td>Helicopter (not reported)</td>
<td>0.54</td>
</tr>
<tr>
<td>Salmoni et al. 2008</td>
<td>Driven on test track for quality control testing</td>
<td>Pick-up truck (3)</td>
<td>0.06</td>
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<td>Driven with and without a load, using two different cab suspensions</td>
<td>Boom knuckle truck (2)</td>
<td>0.17-0.33</td>
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<tr>
<td></td>
<td>Typical operating cycle with two different cab suspensions</td>
<td>Overhead boom truck (1)</td>
<td>0.34-0.43</td>
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<tr>
<td>Okunribodo et al. 2007</td>
<td>Driven on asphalt and cobble stone roads, idling</td>
<td>Double decker bus (1)</td>
<td>0.07-0.45ᵇᶜ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single decker bus (1)</td>
<td>0.03-0.23ᵇᶜ</td>
</tr>
<tr>
<td>Scarlett et al. 2007</td>
<td>Ploughing, plough transport, cultivating, spraying, trailer transport</td>
<td>Mini-bus (1)</td>
<td>0.11-0.21ᵇᶜ</td>
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<tr>
<td>Burstrom et al. 2006</td>
<td>Different seat locations during landing</td>
<td>Commercial airplane (1)</td>
<td>0.20-0.30</td>
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<td>Wheeled loader (6)</td>
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<td>Excavator (4)</td>
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<td>Rock crusher (1)</td>
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<td>Articulated truck (1)</td>
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<td>Off-road car (1)</td>
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<td>Mobile crane (5)</td>
<td>0.06</td>
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<td>Fork-lift truck (21)</td>
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<tr>
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<td></td>
<td>Tracked loader (3)</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
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<td>Freight-container tractor (1)</td>
<td>0.16</td>
</tr>
</tbody>
</table>

ᵃ Data in the form of vibration total values using the three translational axes with X- and Y-axis k-values equal to 1.4.
ᵇ Data approximated from a graph.
ᶜ Average value calculated from data presented by the authors.
### Table 4.1 Continued: A summary of ISO 2631-1:1997 weighted operator/seat interface accelerations reported in industry.

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<tr>
<th>Authors</th>
<th>Operating Conditions Tested</th>
<th>Vehicle Type</th>
<th>Average RMS Exposure Accelerations (m/s²)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Number of Trials</td>
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<tr>
<td>Bovenzi et al. 2006</td>
<td>Typical operating cycle</td>
<td>Garbage truck (5)</td>
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<td></td>
<td>Garbage compactor (1)</td>
<td>0.08</td>
</tr>
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<td></td>
<td></td>
<td>Minibus (12)</td>
<td>0.12</td>
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<tr>
<td></td>
<td></td>
<td>Bus (13)</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Typical operating cycle</td>
<td>16 ton underground haul truck (1)</td>
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<td></td>
<td>150 ton surface haul truck (2)</td>
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<td>Dozer (1)</td>
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<td></td>
<td></td>
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<td>Grader (1)</td>
</tr>
<tr>
<td>Eger et al. 2006</td>
<td>Typical operating cycle</td>
<td>3.5 yard load-haul-dump (2)</td>
<td>0.81(^c)</td>
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<td>7 yard load-haul-dump (1)</td>
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<td>Locomotive (1)</td>
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<td>Jumbo drill (1)</td>
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<td>Crusher plant (1)</td>
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<td>Tractor (1)</td>
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<td>Johanssen et al. 2006</td>
<td>Typical operating cycle</td>
<td>Locomotive (51)</td>
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<tr>
<td>Newell et al. 2006</td>
<td>Vehicle in motion, leveling, loading</td>
<td>Tracked loader (6)</td>
<td>0.65-1.12</td>
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<tr>
<td>Okumibodo et al. 2006</td>
<td>Driven on good asphalt, poor</td>
<td>Van (2)</td>
<td>0.22-0.50(^bc)</td>
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<td></td>
<td>asphalt and cobble stone roads</td>
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<tr>
<td></td>
<td>Driven on good and poor asphalt, with and</td>
<td>Articulated truck (6)</td>
<td>0.14-0.29(^bc)</td>
</tr>
<tr>
<td></td>
<td>without a load</td>
<td></td>
<td></td>
</tr>
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<td></td>
<td>Driven with and without a load</td>
<td>Tipper truck (1)</td>
<td>0.14-0.19(^bc)</td>
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<tr>
<td>Els 2005</td>
<td>Vehicle in motion</td>
<td>Armored vehicle (1)</td>
<td>0.40-0.51</td>
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<tr>
<td>Hoy et al. 2005</td>
<td>Typical operating cycle</td>
<td>Forklift truck (not reported)</td>
<td>0.31</td>
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<td>Sanding a road</td>
<td>Municipal work trunk (2)</td>
<td>0.65</td>
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<tr>
<td>Marjanen 2005</td>
<td>Cultivating, driven on asphalt and gravel</td>
<td>Tractor (2)</td>
<td>0.83-1.10</td>
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<tr>
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<td>Driven with and without a load, loading and</td>
<td>Wheeled loader (6)</td>
<td>0.17-0.95</td>
</tr>
</tbody>
</table>

\(^a\) Data in the form of vibration total values using the three translational axes with X- and Y-axis k-values equal to 1.4.

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Table 4.1 Continued: A summary of ISO 2631-1:1997 weighted operator/seat interface accelerations reported in industry.

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<tr>
<th>Authors</th>
<th>Operating Conditions Tested</th>
<th>Vehicle Type</th>
<th>Average RMS Exposure Accelerations (m/s²)</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Vector Sum</th>
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</thead>
<tbody>
<tr>
<td>Scarlett et al. 2005</td>
<td>Ploughing, plough transport, cultivating, spraying, trailer transport</td>
<td>Tractor (4)</td>
<td></td>
<td>0.29-1.04&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.35-1.07&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.37-0.80&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-</td>
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<tr>
<td></td>
<td>Driven on a road, farm track and in a field</td>
<td>All-terrain vehicle (4)</td>
<td></td>
<td>0.14-0.68&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.19-0.74&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.28-2.25&lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td></td>
<td>Driven loaded on a road, farm track or spraying</td>
<td>Self-propelled sprayer (4)</td>
<td></td>
<td>0.06-0.30&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.14-0.87&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.23-0.80&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-</td>
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<tr>
<td>Cann et al. 2004</td>
<td>Driven over rough and smooth roads</td>
<td>Transport truck (39)</td>
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<td>0.10-0.50</td>
<td>0.10-0.59</td>
<td>0.01-1.07</td>
<td>0.23-1.54&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Kumar 2004</td>
<td>Driven with and without a load, loading and unloading</td>
<td>Haulage truck (4)</td>
<td></td>
<td>0.13-15.94</td>
<td>0.14-15.10</td>
<td>0.37-11.73</td>
<td>0.55-7.10&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

| Cann et al. 2003 | Typical operating cycle                                        |                                  |                                        |                 |                 |                 |            |
|                  | Large bulldozer (9)                                             |                                  |                                        |                 |                 |                 | 0.92        |
|                  | Small bulldozer (4)                                             |                                  |                                        |                 |                 |                 | 1.11        |
|                  | Excavator (14)                                                  |                                  |                                        |                 |                 |                 | 0.51        |
|                  | Scraper (4)                                                     |                                  |                                        |                 |                 |                 | 1.61        |
|                  | Grader (4)                                                      |                                  |                                        |                 |                 |                 | 0.55        |
|                  | Skid steer (3)                                                  |                                  |                                        |                 |                 |                 | 1.18        |
|                  | Mini skid steer (3)                                             |                                  |                                        |                 |                 |                 | 1.22        |
|                  | Backhoe (3)                                                     |                                  |                                        |                 |                 |                 | 1.05        |
|                  | Compactor (3)                                                   |                                  |                                        |                 |                 |                 | 0.91        |
|                  | Vibratory compactor (5)                                         |                                  |                                        |                 |                 |                 | 0.64        |
|                  | Tracked loader (3)                                              |                                  |                                        |                 |                 |                 | 1.01        |
|                  | Wheeled loader (2)                                              |                                  |                                        |                 |                 |                 | 1.16        |
|                  | Ride-on power trowel (2)                                        |                                  |                                        |                 |                 |                 | 0.36        |
|                  | Variable reach forklift (3)                                     |                                  |                                        |                 |                 |                 | 0.65        |
|                  | Mobile crane (2)                                                |                                  |                                        |                 |                 |                 | 0.15        |
|                  | Off-road dump truck (2)                                         |                                  |                                        |                 |                 |                 | 1.21        |
|                  | Forklift (1)                                                    |                                  |                                        |                 |                 |                 | 0.37        |

| Chen et al. 2003 | Vehicle in motion                                              | Taxi cab (247)                   |                                        |                 |                 | 0.17-0.55        | -          |

<sup>a</sup> Data in the form of vibration total values using the three translational axes with X- and Y-axis k-values equal to 1.4.

<sup>b</sup> Data approximated from a graph.

<sup>c</sup> Average value calculated from data presented by the authors.
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<tr>
<td></td>
<td></td>
<td>(Number of Trials)</td>
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</tr>
<tr>
<td><strong>Bovenzi et al. 2002</strong></td>
<td>Typical operating cycle</td>
<td>Straddle carriers (7)</td>
<td>0.23</td>
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<tr>
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<td></td>
<td>Fork-lift truck (7)</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mobile crane (2)</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overhead crane (2)</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Hassan &amp; McManus 2002</strong></td>
<td>Typical operating cycle</td>
<td>Transport truck (1)</td>
<td>0.37(^c)</td>
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<tr>
<td><strong>Johanning et al. 2002</strong></td>
<td>Typical operating cycle</td>
<td>Locomotives (22)</td>
<td>0.18</td>
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<tr>
<td><strong>Kumar et al. 2001</strong></td>
<td>Driven off-road, on a path, and on a paved road</td>
<td>Tractor (3)</td>
<td>0.15-1.79</td>
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<tr>
<td><strong>Melo &amp; Miguel 2000</strong></td>
<td>Driven over brick and asphalt, idling</td>
<td>Bus (1)</td>
<td>0.01-0.21</td>
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<tr>
<td><strong>Maeda &amp; Morioka 1998</strong></td>
<td>Driven on a normal and rough road</td>
<td>2 ton dump truck (1)</td>
<td>0.29-1.31</td>
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<tr>
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<td>with and without a load, unloading,</td>
<td>2 ton garbage truck (1)</td>
<td>0.3-1.67</td>
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<tr>
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<td>idling with and without a load</td>
<td>4 ton garbage truck (1)</td>
<td>0.50-94</td>
</tr>
</tbody>
</table>

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Table 4.2: A summary of ISO 2631-1 weighted operator/seat interface accelerations reported in the forestry industry.

<table>
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<tr>
<th>Authors</th>
<th>Operating Conditions Tested</th>
<th>Vehicle Type</th>
<th>Average RMS Exposure Accelerations (m/s²)</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Vector Sum</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>(Number of Trials)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cation et al.</td>
<td>Driven with and without a load</td>
<td>Skidder (7)</td>
<td></td>
<td>0.72-0.86⁺</td>
<td>0.96-1.12⁺</td>
<td>0.72-0.73⁺</td>
<td>1.27-1.53⁺</td>
</tr>
<tr>
<td>2008</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Okunribido et al.</td>
<td>Typical operating cycle</td>
<td>Harvester (not reported)</td>
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<td>0.22⁺</td>
<td>0.22⁺</td>
<td>0.39⁺</td>
<td>0.53⁺ad</td>
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<tr>
<td>2008</td>
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<td></td>
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<tr>
<td>Rehn et al.</td>
<td>Typical operating cycle</td>
<td>Snow groomer (7)</td>
<td></td>
<td>0.29⁻⁶</td>
<td>0.29⁻⁶</td>
<td>0.80⁺</td>
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<td>2005a</td>
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<td>Snowmobile (6)</td>
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<td>0.71⁻⁶</td>
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<td>0.80⁺</td>
<td>1.70⁺ad</td>
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<tr>
<td></td>
<td></td>
<td>Forwarder (6)</td>
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<td>0.50⁻⁶</td>
<td>0.79⁻⁶</td>
<td>0.60⁺</td>
<td>1.50⁺ad</td>
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<tr>
<td>Rehn et al.</td>
<td>Driven with and without a load,</td>
<td>Forwarder (7)</td>
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<td>0.26-3.08⁺</td>
</tr>
<tr>
<td>2005b</td>
<td>loading and unloading</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sherwin et al.</td>
<td>Felling and processing trees</td>
<td>Cut-to-length timber harvester (1)</td>
<td></td>
<td>0.05-0.06⁺</td>
<td>0.08-0.11⁺</td>
<td>0.10-0.14⁺</td>
<td>0.17-0.22⁺</td>
</tr>
<tr>
<td>2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dump truck (2)</td>
<td></td>
<td>0.80⁺</td>
<td>0.70⁺</td>
<td>1.50⁺</td>
<td>2.00⁺ad</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Excavator (2)</td>
<td></td>
<td>0.50⁺</td>
<td>0.30⁺</td>
<td>0.30⁺</td>
<td>0.50⁺</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Feller/buncher (2)</td>
<td></td>
<td>1.00⁺</td>
<td>0.90⁺</td>
<td>0.90⁺</td>
<td>1.60⁺ad</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Forwarder (5)</td>
<td></td>
<td>0.70⁺</td>
<td>0.60⁺</td>
<td>0.70⁺</td>
<td>1.10⁺ad</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Front end loader (5)</td>
<td></td>
<td>0.20⁺</td>
<td>0.10⁺</td>
<td>1.30⁺</td>
<td>1.20⁺ad</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grader (3)</td>
<td></td>
<td>1.10⁺</td>
<td>0.90⁺</td>
<td>1.10⁺</td>
<td>1.70⁺</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Harvester (2)</td>
<td></td>
<td>2.00⁺</td>
<td>1.90⁺</td>
<td>1.90⁺</td>
<td>3.40⁺</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Logging truck (3)</td>
<td></td>
<td>0.10⁺</td>
<td>0.10⁺</td>
<td>1.00⁺</td>
<td>1.00⁺</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Processor (13)</td>
<td></td>
<td>2.10⁺</td>
<td>2.00⁺</td>
<td>2.10⁺</td>
<td>3.40⁺</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shovel (33)</td>
<td></td>
<td>1.20⁺</td>
<td>1.10⁺</td>
<td>1.80⁺</td>
<td>2.30⁺ad</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Skidder (11)</td>
<td></td>
<td>1.60⁺</td>
<td>1.40⁺</td>
<td>1.40⁺</td>
<td>2.50⁺ad</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stacker (5)</td>
<td></td>
<td>0.10⁺</td>
<td>0.10⁺</td>
<td>0.70⁺</td>
<td>0.60⁺ad</td>
</tr>
</tbody>
</table>

⁺ Weighted in accordance with ISO 2631-1:1997.
⁻ Weighted in accordance with ISO 2631-1:1985.
⁻⁺ Weighted in accordance with ISO 2631-1:1978.
⁻⁶ Data in the form of vibration total values using the three translational axes with X- and Y-axis k-values equal to 1.4.
⁻⁶⁺ Data in the form of energy-equivalent vibration magnitude (time component not reported).
⁻⁷ Data in the form of a vector sum of the energy-equivalent vibration magnitude of three translational axes (time component not reported).
⁻⁷⁺ Data approximated from a graph.
⁻⁺ Data calculated from data presented by the authors.
### Table 4.2 Continued: A summary of ISO 2631-1 weighted operator/seat interface accelerations reported in the forestry industry.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Operating Conditions Tested</th>
<th>Vehicle Type</th>
<th>Average RMS Exposure Accelerations (m/s²)</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Vector Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neitzel &amp; Yost</td>
<td>Typical operating cycle</td>
<td>Yarder (9)</td>
<td></td>
<td>1.10¹</td>
<td>1.20¹</td>
<td>1.30¹</td>
<td>1.40¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bull dozer (8)</td>
<td></td>
<td>0.69²</td>
<td>1.96²</td>
<td>1.05²</td>
<td>3.18²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Excavator (6)</td>
<td></td>
<td>3.14³</td>
<td>2.17³</td>
<td>3.00³</td>
<td>6.30³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Front end loader (5)</td>
<td></td>
<td>6.53⁴</td>
<td>5.81⁴</td>
<td>6.80⁴</td>
<td>14.38⁴</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grader (5)</td>
<td></td>
<td>2.00⁵</td>
<td>1.70⁵</td>
<td>4.97⁵</td>
<td>6.33⁵</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Processor (7)</td>
<td></td>
<td>3.15⁶</td>
<td>2.71⁶</td>
<td>3.04⁶</td>
<td>6.68⁶</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shovel (23)</td>
<td></td>
<td>0.90⁷</td>
<td>1.07⁷</td>
<td>1.03⁷</td>
<td>2.32⁷</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stacker (12)</td>
<td></td>
<td>0.84⁸</td>
<td>1.10⁸</td>
<td>1.60⁸</td>
<td>2.60⁸</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Logging truck (17)</td>
<td></td>
<td>0.33⁹</td>
<td>0.25⁹</td>
<td>0.51⁹</td>
<td>0.80⁹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yarder (16)</td>
<td></td>
<td>1.24¹⁰</td>
<td>0.76¹⁰</td>
<td>1.47¹⁰</td>
<td>2.52¹⁰</td>
</tr>
<tr>
<td>Marsili et al.</td>
<td>Vehicle in motion</td>
<td>Articulated tracked vehicle (1)</td>
<td></td>
<td>0.11-0.26¹¹</td>
<td>0.09-0.15¹¹</td>
<td>0.24-0.40¹¹</td>
<td>0.35-0.56¹¹</td>
</tr>
<tr>
<td>1998</td>
<td></td>
<td>Cut-off-saw (2)</td>
<td></td>
<td>0.01-0.04¹²</td>
<td>0.01-0.05¹²</td>
<td>0.04-0.07¹²</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chip-n-saw (2)</td>
<td></td>
<td>0.03-1.03¹²</td>
<td>0.02-1.05¹²</td>
<td>0.06-1.09¹²</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Debarker (1)</td>
<td></td>
<td>0.04-0.09¹²</td>
<td>0.02-0.09¹²</td>
<td>0.05-0.12¹²</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Forklift (6)</td>
<td></td>
<td>0.13-0.30¹²</td>
<td>0.11-0.30¹²</td>
<td>0.16-0.39¹²</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loader (1)</td>
<td></td>
<td>0.27-0.30¹²</td>
<td>0.26-0.30¹²</td>
<td>0.32-0.35¹²</td>
<td>-</td>
</tr>
<tr>
<td>Zinck 1998</td>
<td>Typical operating cycle</td>
<td>Grapple Skidders (4)</td>
<td></td>
<td>0.81¹³</td>
<td>1.01¹³</td>
<td>1.26¹³</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dozer (4)</td>
<td></td>
<td>0.52-0.92¹³</td>
<td>0.56-1.55¹³</td>
<td>0.59-1.38¹³</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Skidder (7)</td>
<td></td>
<td>0.45-1.25¹³</td>
<td>0.47-1.18¹³</td>
<td>0.53-1.21¹³</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Harvester (1)</td>
<td></td>
<td>0.76¹³</td>
<td>0.69¹³</td>
<td>0.6¹³</td>
<td>-</td>
</tr>
<tr>
<td>Glosse 1989</td>
<td>Typical operating cycle</td>
<td>Grapple skidder (2)</td>
<td></td>
<td>0.45-0.68¹³</td>
<td>0.41-0.78¹³</td>
<td>0.55-0.93¹³</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cable skidder (8)</td>
<td></td>
<td>0.08-1.24¹³</td>
<td>0.24-1.60¹³</td>
<td>0.31-2.19¹³</td>
<td>-</td>
</tr>
<tr>
<td>Glosse &amp; Hope</td>
<td>Driven with and without a load, piling</td>
<td>Grapple skidder (2)</td>
<td></td>
<td>0.81¹³</td>
<td>1.01¹³</td>
<td>1.26¹³</td>
<td>-</td>
</tr>
<tr>
<td>1987</td>
<td></td>
<td>Dozer (4)</td>
<td></td>
<td>0.52-0.92¹³</td>
<td>0.56-1.55¹³</td>
<td>0.59-1.38¹³</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Skidder (7)</td>
<td></td>
<td>0.45-1.25¹³</td>
<td>0.47-1.18¹³</td>
<td>0.53-1.21¹³</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Harvester (1)</td>
<td></td>
<td>0.76¹³</td>
<td>0.69¹³</td>
<td>0.6¹³</td>
<td>-</td>
</tr>
</tbody>
</table>

¹ Weighted in accordance with ISO 2631-1:1997.
² Weighted in accordance with ISO 2631-1:1985.
³ Weighted in accordance with ISO 2631-1:1978.
⁴ Data in the form of vibration total values using the three translational axes with X- and Y-axis k-values equal to 1.4.
⁵ Data in the form of energy-equivalent vibration magnitude (time component not reported).
⁶ Data in the form of a vector sum of the energy-equivalent vibration magnitude of three translational axes (time component not reported).
⁷ Data approximated from a graph.
⁸ Calculated from data presented by the authors.
the driving exposure data obtained during this investigation has been reported previously by Cation et al. That dataset has subsequently been expanded to include additional skidders, exposure measurements and operating conditions. This particular paper focuses on quantifying the 6-DOF WBV exposure levels which occur in Northern Ontario skidders during typical field operating tasks. Additional attention was paid to determining the peak acceleration levels, dominant exposure frequencies, and connections between the 6-DOF WBV exposures found and the musculoskeletal symptoms reported by the operators.

4.2 METHODS

4.2.1 Field data collection

Prior to field data collection, a survey was administered to the skidder operators to document their musculoskeletal injury history for each of the nine body regions outlined in Table 4.3. Operators were also asked to comment on their ideas about the source of their musculoskeletal injury, and to suggest various means of improving the operating environment. 6-DOF whole-body vibration (WBV) acceleration exposure levels at the OSI were measured for eight male Northern Ontario skidder operators under field operating conditions (refer to Table 4.4 for a summary of operator characteristics and Table 4.5 for a summary of the operating conditions). A custom made 6-degree-of-freedom (DOF) seat-pad transducer (Figure 4.1) placed

![Figure 4.1: 6-DOF seat-pad transducer placed on the skidder seat with a basicentric orientation.](image)
on the skidder seat beneath the operator’s ischial tuberosities (the OSI) with a basicentric orientation (as outlined in ISO 2631-1:1997) was used to determine the translational accelerations in the X-, Y- and Z-axes, and the rotational accelerations in roll (rotation about X-

### Table 4.3: Summary of findings from a musculoskeletal health survey.

<table>
<thead>
<tr>
<th>Body region</th>
<th>Question Asked</th>
<th>Operators who responded &quot;Yes&quot;</th>
<th>Operator Response</th>
<th>Operator Response</th>
<th>Operator Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck</td>
<td>Have you experienced any ache, pain, numbness or discomfort? When was the last episode of ache, pain, numbness or discomfort? How would you rate the severity of the last episode of ache, pain, numbness or discomfort? What task or activity do you think brought on the last episode? Do you have any suggestions to avoid future episodes of ache, pain, numbness or discomfort?</td>
<td>1 1-2 weeks ago 2</td>
<td>Twisting to look at the rear of the skidder</td>
<td>Improve the seat placement</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 Today 1</td>
<td>Twisting to look at the rear of the skidder</td>
<td>Increase the seat rotation angle</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 Today 1</td>
<td>Long periods of sitting</td>
<td>Improved seating (air-ride seats)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 Today 2</td>
<td>WBV and shock exposure</td>
<td>Reduce driving speed</td>
<td></td>
</tr>
<tr>
<td>Shoulder</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Upper Back</td>
<td></td>
<td>7 Within the last week 2</td>
<td>Muscle fatigue while driving</td>
<td>Improved seating (air-ride seats)</td>
<td></td>
</tr>
<tr>
<td>Elbows</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Low Back</td>
<td></td>
<td>1 1-6 months ago 3</td>
<td>WBV and Shock exposure</td>
<td>Better quality seating</td>
<td></td>
</tr>
<tr>
<td>Wrist/Hands</td>
<td></td>
<td>3 Today 2</td>
<td>Hand-arm vibration Exposure (steering wheel)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Hips/Thighs/Buttocks</td>
<td></td>
<td>4 Today 1</td>
<td>Sitting</td>
<td>Change seat/seat cushion</td>
<td></td>
</tr>
<tr>
<td>Knees</td>
<td></td>
<td>6 Today 2</td>
<td>Stabilizing the body while driving</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ankles/Feet</td>
<td></td>
<td>6 Today 2</td>
<td>Stabilizing the body while driving</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

*a* Only musculoskeletal complaints attributed to the operation of a skidder are reported.

*b* Operators were asked to indicate if you have had an ache, pain, numbness or discomfort in the area in the last year, month, week, or day.

*c* Operators were asked to rate the severity of the last episode of ache, pain, numbness or discomfort with the following scale. 1 = mild, 2 = moderate, 3 = severe, 4 = very, very severe.
### Table 4.4: Summary of operator characteristics and driving experience.

<table>
<thead>
<tr>
<th>Operator</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>39</td>
<td>32</td>
<td>33</td>
<td>28</td>
<td>45</td>
<td>50</td>
<td>50</td>
<td>56</td>
<td>41.6</td>
<td>10.1</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>145.2</td>
<td>61.2</td>
<td>86.2</td>
<td>83.9</td>
<td>108.9</td>
<td>72.6</td>
<td>97.5</td>
<td>94.7</td>
<td>25.8</td>
<td></td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.80</td>
<td>1.73</td>
<td>1.91</td>
<td>1.78</td>
<td>1.80</td>
<td>1.73</td>
<td>1.75</td>
<td>1.80</td>
<td>1.79</td>
<td>0.06</td>
</tr>
<tr>
<td>Years operating mobile equipment</td>
<td>20.0</td>
<td>11.0</td>
<td>13.0</td>
<td>5.0</td>
<td>31.0</td>
<td>33.0</td>
<td>15.0</td>
<td>35.0</td>
<td>20.4</td>
<td>11.3</td>
</tr>
<tr>
<td>Years operating a skidder</td>
<td>20.0</td>
<td>5.0</td>
<td>13.0</td>
<td>0.1</td>
<td>31.0</td>
<td>33.0</td>
<td>12.0</td>
<td>35.0</td>
<td>18.6</td>
<td>13.3</td>
</tr>
<tr>
<td>Average hours/day operating a skidder</td>
<td>11.0</td>
<td>11.0</td>
<td>8.0</td>
<td>14.0</td>
<td>12.0</td>
<td>14.0</td>
<td>3.0</td>
<td>8.0</td>
<td>10.1</td>
<td>3.7</td>
</tr>
</tbody>
</table>

### Table 4.5: Summary of skidder operating conditions.

<table>
<thead>
<tr>
<th>Skidder Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat Orientation (degrees)</td>
<td>Greased every other day, oil changed every 500 hours</td>
<td>Greased each day, oil changed every 250 hours</td>
<td>Greased each day, oil changed every 176 Hours&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Greased each day, oil changed every 500 hours</td>
<td>Greased each day, oil changed every 200 hours</td>
<td>Greased that day, oil changed every 150-200 hours</td>
<td>Greased once a week, oil changed each month (every 60 Hours&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>Greased every other day, oil changed each month (every 160 Hours&lt;sup&gt;3&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Operator Reported Maintenance History</td>
<td>Greased every other day, oil changed every 500 hours</td>
<td>Greased each day, oil changed every 176 Hours&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Greased each day, oil changed every 250 hours</td>
<td>Greased each day, oil changed every 500 hours</td>
<td>Greased each day, oil changed every 200 hours</td>
<td>Greased that day, oil changed every 150-200 hours</td>
<td>Greased once a week, oil changed each month (every 60 Hours&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>Greased every other day, oil changed each month (every 160 Hours&lt;sup&gt;3&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Operator Reported Tire Pressure (psi)</td>
<td>35</td>
<td>45</td>
<td>33.5</td>
<td>25</td>
<td>33.5</td>
<td>45</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Landscape</td>
<td>Large Hills</td>
<td>Large Hills</td>
<td>Flood bed with small rolling hills</td>
<td>Steep rolling hills</td>
<td>Steep rolling hills</td>
<td>Steep rolling hills</td>
<td>Small rock outcrops on small rolling hills</td>
<td>Small rock outcrops on steep rolling hills</td>
</tr>
<tr>
<td>Terrain Description</td>
<td>Rocky with loose loam soil</td>
<td>Rocky with loose loam soil</td>
<td>Sand/loam mixed soil</td>
<td>Gravel with sand soil</td>
<td>Gravel with sand soil</td>
<td>Gravel with sand soil</td>
<td>Rocky with sand/loam mix soil</td>
<td>Clay soil with gravel and large rocks</td>
</tr>
<tr>
<td>Travel path</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>Most trees remained standing</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>No cleared trees</td>
<td>Most trees cleared</td>
</tr>
<tr>
<td>Forestation</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>Most trees remained standing</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>No cleared trees</td>
<td>Most trees cleared</td>
</tr>
</tbody>
</table>

<sup>3</sup> Estimated based on a 4 day work week with the reported hours/day worked in Table 4.2. If the hours worked were less than 10 hrs a day then a 5 day work week was assumed.
axis), pitch (rotation about Y-axis) and yaw (rotation about Z-axis). The 6-DOF seat-pad transducer was fitted with two ADXL320EB (Analog Devices Inc., MA, USA) dual axis accelerometers and three ADXRS150EB (Analog Devices Inc., MA, USA) rate gyroscopes orthogonally aligned in a Delrin™ plastic casing with a soft rubber shell to minimize pressure points and discomfort (refer to Cation \textit{et al.} (2008) for a complete description of the transducer).

While conducting their normal skidding job tasks, the skidder operators sat on the 6-DOF seat-pad transducer as raw accelerometer and rate gyroscope voltages were collected with a 12-bit SOMAT™ 2100 Field Computer System (nCode, Urbana, Illinois, USA) at a sampling rate of 500Hz. Five operating conditions were observed and monitored; driving with a load (DL), driving without a load (DUL), picking up a load (PUAL), dropping off a load (DOAL), and ploughing logs (refer to Table 4.6 for a full break down of the task operating times). A digital video camera (Sony DCR-PC 109, Shinagawa, Tokyo, Japan) mounted in the skidder cab was used to determine when the skidder operator was performing each of the aforementioned tasks. The video camera filmed the operators as well as the rear implements of the skidders.

4.2.2 Data analysis

Video data were collected in the field in conjunction with an audible beep and simultaneous voltage spike recorded by a Biometrics Ltd. P98 data logger (Gwent, UK). The beep and corresponding voltage spike were used to time stamp the data. The second data logger was required because all available input channels of the SOMAT™ 2100 Field Computer System were utilized. The Biometrics Ltd. data logger and SOMAT™ 2100 Field Computer time histories were aligned using a multiple resolution cross correlation procedure described in Jack \textit{et al.} (2008b – Appendix B). The WBV data were then divided into the various skidder operating conditions for analysis.

The raw accelerometer voltages collected were converted to translational accelerations while the rate gyroscope voltages were converted to angular velocities using the equations found in Table 4.7 (refer to Cation (2007) for a complete description of the 6-DOF seat-pad transducer calibration). Following conversion of the raw voltage data, the time histories were then band-pass filtered between 0.4Hz and 40Hz. The rotational velocity time histories were then converted from °/s to rad/s, and a 4-point differentiation equation was used to determine the rotational
### Table 4.6: Average and total data collection times for the five operating conditions monitored during field data collection.

<table>
<thead>
<tr>
<th>Operator</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Total operating time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving Loaded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.88</td>
</tr>
<tr>
<td>Number of trials</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>10</td>
<td>19</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>116.65</td>
</tr>
<tr>
<td>Average trial time (min)</td>
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<td>0.83</td>
<td>1.75</td>
<td>0.98</td>
<td>1.08</td>
<td>3.50</td>
<td>5.22</td>
<td>4.07</td>
<td>-</td>
</tr>
<tr>
<td>Standard deviation (min)</td>
<td>0.43</td>
<td>0.71</td>
<td>1.33</td>
<td>0.20</td>
<td>0.86</td>
<td>1.57</td>
<td>2.97</td>
<td>2.23</td>
<td>-</td>
</tr>
<tr>
<td>Total operating time (min)</td>
<td>5.55</td>
<td>1.67</td>
<td>10.50</td>
<td>9.78</td>
<td>20.57</td>
<td>21.00</td>
<td>31.30</td>
<td>16.28</td>
<td>116.65</td>
</tr>
<tr>
<td>Driving Unloaded</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.36</td>
</tr>
<tr>
<td>Number of trials</td>
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<td>3</td>
<td>5</td>
<td>11</td>
<td>11</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>3.85</td>
</tr>
<tr>
<td>Average trial time (min)</td>
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<td>1.22</td>
<td>3.29</td>
<td>0.96</td>
<td>1.22</td>
<td>3.49</td>
<td>3.37</td>
<td>4.54</td>
<td>-</td>
</tr>
<tr>
<td>Standard deviation (min)</td>
<td>1.05</td>
<td>0.94</td>
<td>1.64</td>
<td>0.29</td>
<td>0.80</td>
<td>1.56</td>
<td>3.58</td>
<td>2.94</td>
<td>-</td>
</tr>
<tr>
<td>Total operating time (min)</td>
<td>11.98</td>
<td>3.65</td>
<td>16.43</td>
<td>10.57</td>
<td>13.37</td>
<td>20.93</td>
<td>20.23</td>
<td>13.62</td>
<td>110.78</td>
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<tr>
<td>Dropping Off a Load</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31.66</td>
</tr>
<tr>
<td>Number of trials</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>8</td>
<td>14</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>7.48</td>
</tr>
<tr>
<td>Average trial time (min)</td>
<td>0.38</td>
<td>0.12</td>
<td>0.11</td>
<td>0.15</td>
<td>0.12</td>
<td>0.27</td>
<td>-</td>
<td>0.18</td>
<td>-</td>
</tr>
<tr>
<td>Standard deviation (min)</td>
<td>0.53</td>
<td>0.12</td>
<td>0.06</td>
<td>0.10</td>
<td>0.06</td>
<td>0.31</td>
<td>-</td>
<td>0.09</td>
<td>-</td>
</tr>
<tr>
<td>Total operating time (min)</td>
<td>1.13</td>
<td>0.23</td>
<td>0.33</td>
<td>2.73</td>
<td>1.15</td>
<td>1.35</td>
<td>-</td>
<td>0.55</td>
<td>7.48</td>
</tr>
<tr>
<td>Picking Up a Load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29.17</td>
</tr>
<tr>
<td>Number of trials</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>9</td>
<td>14</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>17.45</td>
</tr>
<tr>
<td>Average trial time (min)</td>
<td>0.41</td>
<td>0.41</td>
<td>0.54</td>
<td>0.24</td>
<td>0.41</td>
<td>0.67</td>
<td>-</td>
<td>0.18</td>
<td>-</td>
</tr>
<tr>
<td>Standard deviation (min)</td>
<td>0.09</td>
<td>0.25</td>
<td>0.66</td>
<td>0.15</td>
<td>0.32</td>
<td>0.20</td>
<td>-</td>
<td>0.06</td>
<td>-</td>
</tr>
<tr>
<td>Total operating time (min)</td>
<td>1.22</td>
<td>0.82</td>
<td>3.23</td>
<td>2.12</td>
<td>5.77</td>
<td>3.33</td>
<td>0.42</td>
<td>0.55</td>
<td>17.45</td>
</tr>
<tr>
<td>Ploughing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>53.80</td>
</tr>
<tr>
<td>Number of trials</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>6</td>
<td>5</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>31.00</td>
</tr>
<tr>
<td>Average trial time (min)</td>
<td>-</td>
<td>-</td>
<td>0.66</td>
<td>0.83</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Standard deviation (min)</td>
<td>-</td>
<td>-</td>
<td>0.27</td>
<td>0.28</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total operating time (min)</td>
<td>-</td>
<td>-</td>
<td>1.17</td>
<td>3.97</td>
<td>4.13</td>
<td>1.85</td>
<td>-</td>
<td>-</td>
<td>263.48</td>
</tr>
</tbody>
</table>

**Total operating time (min) = 263.48**

### Table 4.7: 6-DOF seat-pad transducer calibration information.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Sensitivity</th>
<th>r²-values Are All Greater Than a</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-52.02 (m/s)/V</td>
<td>0.99</td>
</tr>
<tr>
<td>Y</td>
<td>-52.18 (m/s)/V</td>
<td>0.99</td>
</tr>
<tr>
<td>Z</td>
<td>51.13 (m/s)/V</td>
<td>0.99</td>
</tr>
<tr>
<td>Roll</td>
<td>81.47 (°/s)/V</td>
<td>0.99</td>
</tr>
<tr>
<td>Pitch</td>
<td>-84.34 (°/s)/V</td>
<td>0.99</td>
</tr>
<tr>
<td>Yaw</td>
<td>79.22 (°/s)/V</td>
<td>0.99</td>
</tr>
</tbody>
</table>

*aValues represent the minimum r²-value from all calibration equations determined.*
accelerations (rad/s² - Burden and Faires 1989). Once the acceleration data were obtained, ISO 2631-1:1997 health weightings were applied to the data using the Vibratools™ software package (Axiom EduTech, Ljusterö, Sweden) within a custom MatLab™ (Mathworks Inc., MA, USA) program.

The weighted and unweighted peak accelerations, root-mean-squared (RMS) average accelerations, crest factors (CF), and the dominant 1/3-octave band exposure frequencies with the three greatest percentages of occurrence were determined for each exposure axis and operating condition. Peak accelerations were determined by full wave rectifying the data and selecting the largest recorded acceleration value. The RMS average accelerations were determined using Equation 1 and the CFs were determined by taking the ratio of the peak acceleration for each individual exposure measurement by the RMS average acceleration for that same measurement. Several CFs exceeded the ISO 2631-1:1997 limit of 9. As a result, and in accordance with ISO 2631-1:1997, running RMS average accelerations using 1-second sliding window averaging with a 90% overlap (Equation 2) were determined for each axis and operating condition (ISO 1997).

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

Where $a$ is the weighted or unweighted RMS average acceleration, $a(t)$ is the weighted or unweighted acceleration as a function of time ($t$) and $T$ is the measurement duration (i.e. the duration of the individual recorded trial).

$$ a(t_0) = \left[ \frac{1}{\tau} \int_{t_0-\tau}^{t_0} \left( \int_{t_0-\tau}^{t_0} a(t) dt \right)^2 dt \right]^{\frac{1}{2}} $$ (2)

Where $a(t_0)$ is the weighted or unweighted running RMS average acceleration, $a(t)$ is the instantaneous weighted or unweighted acceleration as a function of time ($t$), $\tau$ is the integration time for the running average, and $t_0$ is the time of observation.

Vibration total values (VTV) were calculated for the translational axes (Equation 3) and used to determine potential health risks in accordance with the ISO 2631-1:1997 health guidance.
caution zones. The amount of exposure time with which the translational running RMS VTV would exceed the lower and upper limits of the ISO 2631-1:1997 health caution zones was determined with Equations 4 and 5. These equations were created by fitting polynomial curves to the ISO 2631-1:1997 lower and upper health caution zone acceleration limit values (using a digitized version of Figure B.1 of the standard) for the durations between 10-minutes and 24-hours. Least squares fit polynomials to predict the time to exceed the lower (Equation 4) and upper (Equation 5) health caution zone limit for a given exposure acceleration were then determined (both Equations 4 and 5 had $r^2$ values of one). Only accelerations between $0.25\text{m/s}^2$ and $3.27\text{m/s}^2$ should be used for the time to the lower exposure limit equation. An acceleration less than $0.25\text{m/s}^2$ would exceed the lower health caution zone acceleration limit in greater than 24-hours, while an acceleration of $3.27\text{m/s}^2$ or more would exceed the lower health caution zone acceleration limits within 10-minutes. In addition, accelerations between $0.45\text{m/s}^2$ and $5.85\text{m/s}^2$ should be used for the time to the upper exposure limit equation. An acceleration less than $0.45\text{m/s}^2$ would exceed the upper health caution zone acceleration limit in greater than 24-hours, while an acceleration in excess of $5.85\text{m/s}^2$ would exceed the upper health caution zone acceleration limits within 10-minutes.

$$a_v = \left[k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2\right]^\frac{1}{2} \quad (3)$$

Where $a_v$ is the VTV, $a_w$ is the weighted RMS average acceleration in the X, Y and Z axes, and $k$ is the axis multiplying factor.

$$T_{lower} = \frac{1}{\left[-0.0422x^5 + 0.3337x^4 - 0.8704x^3 + 1.4146x^2 - 0.3312x + 0.049\right]} \quad (4)$$

$$T_{upper} = \frac{1}{\left[-0.0023x^5 + 0.0324x^4 - 0.1514x^3 + 0.4408x^2 - 0.1849x + 0.049\right]} \quad (5)$$

Where $T$ is the time in hours to exceed the ISO 2631-1 lower or upper exposure limit, and $x$ is the weighted RMS average acceleration or VTV in m/s$^2$.

When quantifying the VTV for health effects, $k_x = k_y = 1.4$ and $k_z = 1.0$. VTVs were also calculated for the translational axes using the ISO 2631-1:1997 comfort multiplying factors ($k = 1$ for all translational axes). The translational comfort VTVs were then expanded to include all 6-
DOF (Equation 6) where \( k_{rx}=0.63 \text{ m/rad} \), \( k_{ry}=0.4 \text{ m/rad} \) and \( k_{rz}=0.2 \text{ m/rad} \) (note that the rotational k-values are for comfort assessments; ISO 2631-1:1997 does not provide any health multiplying factors for the rotational accelerations and therefore the rotational exposures were not used in the health analysis). The predicted comfort ratings for the OSI were then determined from the translational and 6-DOF VTVs using the ISO 2631-1:1997 guidelines.

\[
a_v = \left[ k_x a_{wx}^2 + k_y a_{wy}^2 + k_z a_{wz}^2 + k_{rx} a_{wrx}^2 + k_{ry} a_{wry}^2 + k_{rz} a_{wrz}^2 \right]^\frac{1}{2}
\]  

(6)

Where \( a_v \) is the VTV, \( a_w \) is the weighted RMS average acceleration in the X, Y, Z, roll (rx), pitch (ry) and yaw (rz) axes, and \( k \) is the axis multiplying factor.

4.3 RESULTS

4.3.1 Health survey

Table 4.3 provides a summary of the musculoskeletal health survey results. Musculoskeletal complaints were reported for every body region except the shoulder. Although the operators didn’t necessarily associate their neck and back pain with vibration exposure, all of the symptoms were associated to some aspect of the driving tasks (only one complaint of low-back pain and one complaint of neck pain were associated with vibration exposure). Also of note, one operator (Operator 6) identified that his knees and ankles/feet experienced moderate discomfort and pain from having to stabilize his body while driving. Although Operator 6 did not directly attribute this discomfort/pain to WBV, the vibration exposure causing the stabilization response was the underlying source of the complaint. In addition, as shown in Table 4.3, the operators associated awkward postures and long durations of sitting with their musculoskeletal complaints.

4.3.2 Whole-body vibration exposures

The average ISO 2631-1:1997 weighted and unweighted WBV exposure values pooled across driving conditions are presented in Tables 4.8 and 4.9 respectively. The mean translational
Table 4.8: Average ISO 2631-1:1997 weighted WBV exposure values.

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driving</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Loaded</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS</td>
<td>0.69</td>
<td>0.91</td>
<td>0.65</td>
<td>0.71</td>
<td>0.52</td>
<td>0.33</td>
</tr>
<tr>
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<td>4.37</td>
<td>5.29</td>
<td>3.71</td>
<td>3.21</td>
<td>1.91</td>
</tr>
<tr>
<td>CF</td>
<td>5.27</td>
<td>4.90</td>
<td>8.29</td>
<td>5.40</td>
<td>6.24</td>
<td>5.87</td>
</tr>
<tr>
<td>Running RMS</td>
<td>0.62</td>
<td>0.82</td>
<td>0.59</td>
<td>0.64</td>
<td>0.46</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Unloaded</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS</td>
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<td>1.04</td>
<td>0.69</td>
<td>0.78</td>
<td>0.63</td>
<td>0.34</td>
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<tr>
<td>Peak</td>
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<td>4.94</td>
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<td>CF</td>
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<td>7.86</td>
<td>5.11</td>
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<td>5.73</td>
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<td>0.94</td>
<td>0.63</td>
<td>0.71</td>
<td>0.56</td>
<td>0.30</td>
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<tr>
<td><strong>Dropping off a load</strong></td>
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</tr>
<tr>
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<td>0.61</td>
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<td>0.49</td>
<td>0.42</td>
<td>0.22</td>
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<tr>
<td>Peak</td>
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<td>2.59</td>
<td>1.84</td>
<td>1.62</td>
<td>0.87</td>
</tr>
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<td>3.61</td>
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<td>0.43</td>
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<td>0.32</td>
<td>0.16</td>
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</tbody>
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<p>| Dominant Exposure Frequencies | | | | | | |</p>
<table>
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<tr>
<th>RMS</th>
<th>Peak</th>
<th>CF</th>
<th>Running RMS</th>
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<tr>
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<td></td>
</tr>
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<td></td>
</tr>
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<td>2Hz (55.4%)</td>
</tr>
<tr>
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<td>1.25Hz (26.8%)</td>
<td>1.25Hz (21.4%)</td>
<td>2.5Hz (19.6%)</td>
</tr>
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<td>1.6Hz (17.9%)</td>
<td>0.8Hz (19.6%)</td>
<td>1.6Hz (7.1%)</td>
</tr>
<tr>
<td></td>
<td>10Hz (7.1%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unloaded</td>
<td>1Hz (57.1%)</td>
<td>2Hz (55.1%)</td>
<td>1Hz (59.1%)</td>
</tr>
<tr>
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<td>1.25Hz (20.4%)</td>
<td>2.5Hz (30.6%)</td>
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<tr>
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<td>0.8Hz (16.3%)</td>
<td>3.15Hz (4.1%)</td>
<td>1.6Hz (6.8%)</td>
</tr>
<tr>
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<td>1.6Hz (10.2%)</td>
<td>4Hz (4.1%)</td>
<td>2.5Hz (14.3%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8Hz (4.1%)</td>
<td>1Hz (10.2%)</td>
</tr>
</tbody>
</table>

<p>| <strong>Dropping off a load</strong> |      |      |      |      |       |      |
| Dominant Exposure Frequencies | | | | | | |</p>
<table>
<thead>
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<th>Peak</th>
<th>CF</th>
<th>Running RMS</th>
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</thead>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.6Hz (23.5%)</td>
<td>1Hz (23.5%)</td>
<td>2Hz (14.7%)</td>
<td>1.6Hz (34.5%)</td>
</tr>
<tr>
<td>0.8Hz (20.6%)</td>
<td>0.8Hz (17.7%)</td>
<td>2.5Hz (14.7%)</td>
<td>1Hz (17.2%)</td>
</tr>
<tr>
<td>1.25Hz (20.6%)</td>
<td>1.25Hz (14.7%)</td>
<td>3.15Hz (11.8%)</td>
<td>0.8Hz (13.8%)</td>
</tr>
<tr>
<td>1Hz (17.7%)</td>
<td></td>
<td>4Hz (11.8%)</td>
<td>1.25Hz (13.8%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.3Hz (11.8%)</td>
<td>2Hz (13.8%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5Hz (8.8%)</td>
<td>3.15Hz (5.9%)</td>
</tr>
</tbody>
</table>

Note: RMS, peak, and running RMS data are in m/s² for the translational axes, and rad/s² for the rotational axes. The bracketed numbers next to the dominant exposure frequencies represent the percentage of trials within the driving condition with which that frequency was the dominant frequency.
### Table 4.8 Continued: Average ISO 2631-1:1997 weighted WBV exposure values.

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RMS</strong></td>
<td>0.48 ± 0.20</td>
<td>0.44 ± 0.22</td>
<td>0.50 ± 0.25</td>
<td>0.47 ± 0.28</td>
<td>0.38 ± 0.14</td>
<td>0.17 ± 0.09</td>
</tr>
<tr>
<td><strong>Peak</strong></td>
<td>2.29 ± 0.82</td>
<td>2.15 ± 0.87</td>
<td>3.58 ± 1.40</td>
<td>2.83 ± 1.87</td>
<td>2.09 ± 0.97</td>
<td>0.94 ± 0.48</td>
</tr>
<tr>
<td><strong>CF</strong></td>
<td>4.89 ± 0.74</td>
<td>4.99 ± 0.82</td>
<td>7.53 ± 1.70</td>
<td>5.93 ± 2.40</td>
<td>5.50 ± 1.07</td>
<td>5.51 ± 0.93</td>
</tr>
<tr>
<td><strong>Rolling RMS</strong></td>
<td>0.39 ± 0.19</td>
<td>0.36 ± 0.20</td>
<td>0.43 ± 0.23</td>
<td>0.40 ± 0.25</td>
<td>0.32 ± 0.12</td>
<td>0.14 ± 0.08</td>
</tr>
<tr>
<td><strong>Dominant Exposure</strong></td>
<td>1.25Hz (30.2%)</td>
<td>1Hz (25.6%)</td>
<td>6.3Hz (18.6%)</td>
<td>1.6Hz (43.2%)</td>
<td>1.6Hz (20.9%)</td>
<td>1Hz (23.3%)</td>
</tr>
<tr>
<td><strong>Exposure Frequencies</strong></td>
<td>0.8Hz (14.0%)</td>
<td>0.8Hz (16.3%)</td>
<td>10Hz (14.0%)</td>
<td>1.25Hz (13.5%)</td>
<td>1.25Hz (16.3%)</td>
<td>1.25Hz (16.3%)</td>
</tr>
<tr>
<td></td>
<td>1Hz (14.0%)</td>
<td>8Hz (11.6%)</td>
<td>2Hz (14.0%)</td>
<td>12.5Hz (11.6%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Peak</strong></td>
<td>3.86 ± 0.94</td>
<td>4.43 ± 0.86</td>
<td>4.26 ± 0.70</td>
<td>3.69 ± 0.76</td>
<td>3.34 ± 0.78</td>
<td>2.02 ± 0.21</td>
</tr>
<tr>
<td><strong>CF</strong></td>
<td>4.54 ± 0.76</td>
<td>5.11 ± 0.63</td>
<td>6.50 ± 0.80</td>
<td>5.03 ± 0.56</td>
<td>5.40 ± 0.65</td>
<td>5.75 ± 1.12</td>
</tr>
<tr>
<td><strong>Rolling RMS</strong></td>
<td>0.76 ± 0.13</td>
<td>0.80 ± 0.23</td>
<td>0.61 ± 0.11</td>
<td>0.67 ± 0.20</td>
<td>0.56 ± 0.18</td>
<td>0.33 ± 0.08</td>
</tr>
<tr>
<td><strong>Dominant Exposure</strong></td>
<td>1Hz (53.9%)</td>
<td>1Hz (46.2%)</td>
<td>2.5Hz (38.5%)</td>
<td>1Hz (33.3%)</td>
<td>1.25Hz (30.8%)</td>
<td>2Hz (38.5%)</td>
</tr>
<tr>
<td><strong>Exposure Frequencies</strong></td>
<td>0.8Hz (38.5%)</td>
<td>1Hz (23.1%)</td>
<td>1.25Hz (23.1%)</td>
<td>1.25Hz (15.4%)</td>
<td>1.25Hz (15.4%)</td>
<td>1.25Hz (15.4%)</td>
</tr>
<tr>
<td></td>
<td>1.6Hz (7.7%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: RMS, peak, and running RMS data are in m/s² for the translational axes, and rad/s² for the rotational axes. The bracketed numbers next to the dominant exposure frequencies represent the percentage of trials within the driving condition with which that frequency was the dominant frequency.
Table 4.9: Average ISO 2631-1:1997 unweighted WBV exposure values.

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X  Y  Z  Roll  Pitch Yaw</strong></td>
<td>RMS</td>
<td>Peak</td>
<td>Crest Factor</td>
<td>Running RMS</td>
<td>Dominant Exposure Frequencies</td>
<td></td>
</tr>
<tr>
<td><strong>Driving Loaded</strong></td>
<td>0.92 ± 0.22</td>
<td>1.23 ± 0.28</td>
<td>1.06 ± 0.34</td>
<td>1.67 ± 0.66</td>
<td>1.52 ± 0.44</td>
<td>1.11 ± 0.40</td>
</tr>
<tr>
<td>Peak</td>
<td>7.51 ± 3.29</td>
<td>8.18 ± 2.03</td>
<td>7.36 ± 2.28</td>
<td>17.63 ± 5.59</td>
<td>15.96 ± 5.86</td>
<td>16.07 ± 7.28</td>
</tr>
<tr>
<td>Crest Factor</td>
<td>7.90 ± 1.60</td>
<td>6.65 ± 0.82</td>
<td>7.01 ± 1.00</td>
<td>11.41 ± 4.86</td>
<td>10.39 ± 1.62</td>
<td>14.87 ± 5.40</td>
</tr>
<tr>
<td>Driving</td>
<td>0.85 ± 0.21</td>
<td>1.15 ± 0.26</td>
<td>0.94 ± 0.30</td>
<td>1.56 ± 0.60</td>
<td>1.39 ± 0.39</td>
<td>1.02 ± 0.34</td>
</tr>
<tr>
<td>1Hz (26.8%)</td>
<td>1Hz (30.4%)</td>
<td>2Hz (62.5%)</td>
<td>2.5Hz (38%)</td>
<td>3.15Hz (37.7%)</td>
<td>8Hz (26.8%)</td>
<td></td>
</tr>
<tr>
<td>1.25Hz (16.1%)</td>
<td>0.8Hz (12.5%)</td>
<td>1.6Hz (26.8%)</td>
<td>3.15Hz (24%)</td>
<td>4Hz (32.1%)</td>
<td>31.5Hz (19.6%)</td>
<td></td>
</tr>
<tr>
<td>0.8Hz (10.7%)</td>
<td>1.25Hz (8.9%)</td>
<td>2.5Hz (8.9%)</td>
<td>10Hz (12%)</td>
<td>2.5Hz (5.4%)</td>
<td>16Hz (17.9%)</td>
<td></td>
</tr>
<tr>
<td>25Hz (10.7%)</td>
<td>31.5Hz (8.9%)</td>
<td>5Hz (12.2%)</td>
<td>16Hz (14.3%)</td>
<td>16Hz (17.9%)</td>
<td>16Hz (14.3%)</td>
<td></td>
</tr>
<tr>
<td><strong>Driving Unloaded</strong></td>
<td>1.06 ± 0.23</td>
<td>1.34 ± 0.27</td>
<td>1.09 ± 0.40</td>
<td>1.77 ± 0.59</td>
<td>1.74 ± 0.38</td>
<td>1.18 ± 0.40</td>
</tr>
<tr>
<td>Peak</td>
<td>8.42 ± 2.03</td>
<td>9.65 ± 2.29</td>
<td>7.16 ± 1.96</td>
<td>18.84 ± 9.75</td>
<td>18.88 ± 3.59</td>
<td>16.99 ± 7.99</td>
</tr>
<tr>
<td>Crest Factor</td>
<td>7.93 ± 1.31</td>
<td>7.10 ± 1.06</td>
<td>6.63 ± 1.58</td>
<td>9.95 ± 2.27</td>
<td>10.98 ± 0.79</td>
<td>14.33 ± 5.74</td>
</tr>
<tr>
<td>Driving</td>
<td>0.97 ± 0.21</td>
<td>1.24 ± 0.25</td>
<td>0.99 ± 0.27</td>
<td>1.64 ± 0.52</td>
<td>1.60 ± 0.34</td>
<td>1.09 ± 0.34</td>
</tr>
<tr>
<td>1.25Hz (34.7%)</td>
<td>1Hz (49.0%)</td>
<td>2Hz (59.2%)</td>
<td>2.5Hz (31.8%)</td>
<td>2.5Hz (28.6%)</td>
<td>8Hz (24.5%)</td>
<td></td>
</tr>
<tr>
<td>1Hz (24.5%)</td>
<td>0.8Hz (16.3%)</td>
<td>2.5Hz (28.6%)</td>
<td>8Hz (22.7%)</td>
<td>3.15Hz (16.3%)</td>
<td>31.5Hz (24.5%)</td>
<td></td>
</tr>
<tr>
<td>1.6Hz (12.2%)</td>
<td>1.25Hz (16.3%)</td>
<td>1.6Hz (8.2%)</td>
<td>3.15Hz (13.6%)</td>
<td>5Hz (12.2%)</td>
<td>16Hz (14.3%)</td>
<td></td>
</tr>
<tr>
<td>31.5Hz (10.2%)</td>
<td>31.5Hz (8.9%)</td>
<td>5Hz (12.2%)</td>
<td>16Hz (14.3%)</td>
<td>16Hz (14.3%)</td>
<td>16Hz (14.3%)</td>
<td></td>
</tr>
<tr>
<td><strong>Dropping off a load</strong></td>
<td>0.83 ± 0.34</td>
<td>1.01 ± 0.28</td>
<td>0.76 ± 0.35</td>
<td>1.59 ± 0.50</td>
<td>1.46 ± 0.51</td>
<td>1.02 ± 0.31</td>
</tr>
<tr>
<td>Peak</td>
<td>4.38 ± 1.55</td>
<td>4.45 ± 1.76</td>
<td>3.77 ± 1.97</td>
<td>11.94 ± 6.23</td>
<td>10.61 ± 4.46</td>
<td>10.55 ± 6.59</td>
</tr>
<tr>
<td>Crest Factor</td>
<td>5.35 ± 0.83</td>
<td>4.40 ± 1.10</td>
<td>4.67 ± 0.70</td>
<td>7.25 ± 3.64</td>
<td>6.87 ± 1.49</td>
<td>9.39 ± 4.17</td>
</tr>
<tr>
<td>Running RMS</td>
<td>0.64 ± 0.31</td>
<td>0.79 ± 0.30</td>
<td>0.60 ± 0.28</td>
<td>1.11 ± 0.38</td>
<td>1.12 ± 0.31</td>
<td>0.76 ± 0.27</td>
</tr>
<tr>
<td>1.6Hz (17.7%)</td>
<td>1Hz (20.6%)</td>
<td>2Hz (32.4%)</td>
<td>8Hz (20.7%)</td>
<td>2.5Hz (17.7%)</td>
<td>25Hz (17.7%)</td>
<td></td>
</tr>
<tr>
<td>0.8Hz (14.7%)</td>
<td>0.63Hz (11.8%)</td>
<td>2.5Hz (20.6%)</td>
<td>2Hz (13.8%)</td>
<td>4Hz (17.7%)</td>
<td>31.5Hz (17.7%)</td>
<td></td>
</tr>
<tr>
<td>25Hz (14.7%)</td>
<td>0.8Hz (8.8%)</td>
<td>3.15Hz (14.7%)</td>
<td>2.5Hz (13.8%)</td>
<td>16Hz (11.8%)</td>
<td>8Hz (14.7%)</td>
<td></td>
</tr>
<tr>
<td>12.5Hz (11.8%)</td>
<td>1.25Hz (8.8%)</td>
<td>3.15Hz (13.8%)</td>
<td>5Hz (8.8%)</td>
<td>10Hz (14.7%)</td>
<td>16Hz (11.8%)</td>
<td></td>
</tr>
<tr>
<td>1.6Hz (8.8%)</td>
<td>10Hz (13.8%)</td>
<td>6.3Hz (8.8%)</td>
<td>16Hz (11.8%)</td>
<td>16Hz (11.8%)</td>
<td>16Hz (11.8%)</td>
<td></td>
</tr>
<tr>
<td>2.5Hz (8.8%)</td>
<td>25Hz (8.8%)</td>
<td>31.5Hz (10.3%)</td>
<td>31.5Hz (8.8%)</td>
<td>31.5Hz (8.8%)</td>
<td>31.5Hz (8.8%)</td>
<td></td>
</tr>
<tr>
<td><strong>Dominant Exposure Frequencies</strong></td>
<td>31.5Hz (8.8%)</td>
<td>31.5Hz (8.8%)</td>
<td>31.5Hz (8.8%)</td>
<td>31.5Hz (8.8%)</td>
<td>31.5Hz (8.8%)</td>
<td>31.5Hz (8.8%)</td>
</tr>
</tbody>
</table>

Note: RMS, peak, and running RMS data are in m/s² for the translational axes, and rad/s² for the rotational axes. The bracketed numbers next to the dominant exposure frequencies represent the percentage of trials within the driving condition with which that frequency was the dominant frequency.
### Table 4.9 Continued: Average ISO 2631-1:1997 unweighted WBV exposure values.

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Picking up a load</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS</td>
<td>0.75 ± 0.27</td>
<td>0.81 ± 0.28</td>
<td>0.65 ± 0.28</td>
<td>1.96 ± 1.72</td>
<td>1.71 ± 1.08</td>
<td>0.92 ± 0.28</td>
</tr>
<tr>
<td>Peak</td>
<td>5.50 ± 2.17</td>
<td>5.00 ± 1.89</td>
<td>4.41 ± 1.69</td>
<td>19.25 ± 14.29</td>
<td>14.54 ± 11.15</td>
<td>10.44 ± 6.48</td>
</tr>
<tr>
<td>Crest Factor</td>
<td>7.35 ± 1.60</td>
<td>6.42 ± 2.32</td>
<td>7.01 ± 1.72</td>
<td>10.43 ± 6.43</td>
<td>8.19 ± 1.81</td>
<td>10.45 ± 4.06</td>
</tr>
<tr>
<td>Running RMS</td>
<td>0.65 ± 0.27</td>
<td>0.73 ± 0.29</td>
<td>0.57 ± 0.27</td>
<td>1.66 ± 1.41</td>
<td>1.49 ± 0.84</td>
<td>0.84 ± 0.21</td>
</tr>
<tr>
<td></td>
<td>1.25Hz (18.6%)</td>
<td>8Hz (23.3%)</td>
<td>2Hz (23.3%)</td>
<td>3.15Hz (16.2%)</td>
<td>3.15Hz (21.0%)</td>
<td>16Hz (23.3%)</td>
</tr>
<tr>
<td>Dominant Exposure</td>
<td>25Hz (14.0%)</td>
<td>0.8Hz (11.6%)</td>
<td>3.15Hz (21.0%)</td>
<td>10Hz (16.2%)</td>
<td>6.3Hz (18.6%)</td>
<td>31.5Hz (21.0%)</td>
</tr>
<tr>
<td>Exposure Frequencies</td>
<td>0.8Hz (11.6%)</td>
<td>1Hz (11.6%)</td>
<td>2.5Hz (14.0%)</td>
<td>2.5Hz (13.5%)</td>
<td>4Hz (11.6%)</td>
<td>25Hz (14.0%)</td>
</tr>
<tr>
<td></td>
<td>31.5Hz (11.6%)</td>
<td>1.6Hz (7.0%)</td>
<td>8Hz (13.5%)</td>
<td>12.5Hz (10.8%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Running RMS</strong></td>
<td>1.16 ± 0.14</td>
<td>1.33 ± 0.14</td>
<td>1.00 ± 0.15</td>
<td>1.82 ± 0.50</td>
<td>1.90 ± 0.39</td>
<td>1.36 ± 0.13</td>
</tr>
<tr>
<td>Peak</td>
<td>8.13 ± 2.43</td>
<td>10.65 ± 2.56</td>
<td>6.76 ± 1.48</td>
<td>16.19 ± 4.76</td>
<td>15.21 ± 1.02</td>
<td>19.45 ± 7.43</td>
</tr>
<tr>
<td>Crest Factor</td>
<td>6.91 ± 1.73</td>
<td>7.84 ± 1.05</td>
<td>6.93 ± 2.24</td>
<td>9.12 ± 3.04</td>
<td>8.23 ± 1.89</td>
<td>14.01 ± 4.63</td>
</tr>
<tr>
<td>Running RMS</td>
<td>1.08 ± 0.14</td>
<td>1.23 ± 0.14</td>
<td>0.92 ± 0.17</td>
<td>1.67 ± 0.44</td>
<td>1.77 ± 0.36</td>
<td>1.24 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>1Hz (38.5%)</td>
<td>1Hz (38.5%)</td>
<td>2Hz (61.5%)</td>
<td>8Hz (33.3%)</td>
<td>25Hz (30.8%)</td>
<td>8Hz (38.5%)</td>
</tr>
<tr>
<td>Dominant Exposure</td>
<td>1.25Hz (23.1%)</td>
<td>0.8Hz (30.8%)</td>
<td>2.5Hz (30.8%)</td>
<td>2Hz (25%)</td>
<td>3.15Hz (15.4%)</td>
<td>12.5Hz (23.1%)</td>
</tr>
<tr>
<td>Exposure Frequencies</td>
<td>25Hz (23.1%)</td>
<td>2Hz (15.4%)</td>
<td>1.6Hz (7.7%)</td>
<td>2.5Hz (25%)</td>
<td>5Hz (15.4%)</td>
<td>10Hz (15.4%)</td>
</tr>
<tr>
<td></td>
<td>1.6Hz (15.4%)</td>
<td>25Hz (15.4%)</td>
<td>3.15Hz (8.3%)</td>
<td>10Hz (8.3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ploughing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: RMS, peak, and running RMS data are in m/s² for the translational axes, and rad/s² for the rotational axes. The bracketed numbers next to the dominant exposure frequencies represent the percentage of trials within the driving condition with which that frequency was the dominant frequency.
running RMS weighted and unweighted accelerations were all in excess of 0.36 m/s² and 0.57 m/s², with the greatest average accelerations occurring while driving unloaded. With respect to the rotational accelerations, running RMS weighted and unweighted accelerations all exceeded 0.14 rad/s² and 0.76 rad/s² respectively. Here, the greatest average weighted rotational accelerations occurred while driving unloaded, but the greatest average unweighted rotational accelerations occurred while ploughing. Note that no roll data were available for Skidder 2 while DOAL, and for all Skidder 3 driving conditions due to an inadequate sensor cable connection.

When evaluating the driving conditions (driving loaded and driving unloaded), the greatest running RMS exposures occurred in the Y-axis for translational exposures and roll for the rotational exposures (both weighted and unweighted). This running RMS axis pattern remained consistent while ploughing logs and DOAL or PUAL. The exceptions included the weighted X-axis which was greatest while DOAL, the weighted Z-axis which was greatest while PUAL and the unweighted pitch axis was greatest while DOAL and ploughing.

The dominant 1/3-octave band exposure frequencies with three greatest percentages of occurrence for each driving condition are reported in Tables 4.8 and 4.9. When driving, the dominant weighted exposure frequencies ranged between 0.8-2.5Hz, although some of the driving unloaded trials had higher dominant frequencies (4Hz and 8Hz). It is interesting to see that although the dominant unweighted exposure frequencies remained in a similar frequency range as the weighted driving exposures, several trials had dominant unweighted exposure frequencies that exceeded 25Hz. DOAL and PUAL displayed a similar pattern of dominant weighted and unweighted exposure frequencies, but it should be noted that the dominant weighted exposure frequencies had several trials with high dominant frequencies, (even higher than those found while driving). This is likely due to the fact that the vehicles are stationary and the higher frequency engine vibrations become more prominent than when the vehicle is driving.

Tables 4.8 and 4.9 report average running RMS and peak exposure values; however, since these are average values they are not indicative of the upper limit of the accelerations experienced by the skidder operators. Tables 4.10 and 4.11 report the greatest running RMS and peak acceleration levels, along with the associated exposure axis for each skidder and operating condition. Typically, the Y-axis had the greatest weighted and unweighted running RMS acceleration across all operating conditions. However, the greatest peak acceleration axes (Tables 4.10 and 4.11) were more varied with the Z- and X- axes commonly being the greatest
exposure axes when weighted and the X-axis when unweighted. Considering rotational axes exposures, roll was the axis most often to have the greatest weighted running RMS accelerations; pitch was slightly more prevalent when unweighted. The greatest weighted rotational peak

<table>
<thead>
<tr>
<th>Table 4.10: Greatest translational and rotational weighted accelerations.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Greatest Weighted Translational Acceleration</strong></td>
</tr>
<tr>
<td>Running RMS</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td><strong>Skidder 1</strong></td>
</tr>
<tr>
<td>Driving Loaded</td>
</tr>
<tr>
<td>Driving Unloaded</td>
</tr>
<tr>
<td>Dropping off a Load</td>
</tr>
<tr>
<td>Picking up a Load</td>
</tr>
<tr>
<td>Ploughing</td>
</tr>
<tr>
<td><strong>Skidder 2</strong></td>
</tr>
<tr>
<td>Driving Loaded</td>
</tr>
<tr>
<td>Driving Unloaded</td>
</tr>
<tr>
<td>Dropping off a Load</td>
</tr>
<tr>
<td>Picking up a Load</td>
</tr>
<tr>
<td>Ploughing</td>
</tr>
<tr>
<td><strong>Skidder 3</strong></td>
</tr>
<tr>
<td>Driving Loaded</td>
</tr>
<tr>
<td>Driving Unloaded</td>
</tr>
<tr>
<td>Dropping off a Load</td>
</tr>
<tr>
<td>Picking up a Load</td>
</tr>
<tr>
<td>Ploughing</td>
</tr>
<tr>
<td><strong>Skidder 4</strong></td>
</tr>
<tr>
<td>Driving Loaded</td>
</tr>
<tr>
<td>Driving Unloaded</td>
</tr>
<tr>
<td>Dropping off a Load</td>
</tr>
<tr>
<td>Picking up a Load</td>
</tr>
<tr>
<td>Ploughing</td>
</tr>
<tr>
<td><strong>Skidder 5</strong></td>
</tr>
<tr>
<td>Driving Loaded</td>
</tr>
<tr>
<td>Driving Unloaded</td>
</tr>
<tr>
<td>Dropping off a Load</td>
</tr>
<tr>
<td>Picking up a Load</td>
</tr>
<tr>
<td>Ploughing</td>
</tr>
<tr>
<td><strong>Skidder 6</strong></td>
</tr>
<tr>
<td>Driving Loaded</td>
</tr>
<tr>
<td>Driving Unloaded</td>
</tr>
<tr>
<td>Dropping off a Load</td>
</tr>
<tr>
<td>Picking up a Load</td>
</tr>
<tr>
<td>Ploughing</td>
</tr>
<tr>
<td><strong>Skidder 7</strong></td>
</tr>
<tr>
<td>Driving Loaded</td>
</tr>
<tr>
<td>Driving Unloaded</td>
</tr>
<tr>
<td>Dropping off a Load</td>
</tr>
<tr>
<td>Picking up a Load</td>
</tr>
<tr>
<td>Ploughing</td>
</tr>
<tr>
<td><strong>Skidder 8</strong></td>
</tr>
<tr>
<td>Driving Loaded</td>
</tr>
<tr>
<td>Driving Unloaded</td>
</tr>
<tr>
<td>Dropping off a Load</td>
</tr>
<tr>
<td>Picking up a Load</td>
</tr>
<tr>
<td>Ploughing</td>
</tr>
</tbody>
</table>

Note: peak and running RMS data are in m/s² for the translational axes, and rad/s² for the rotational axes.
Accelerations were frequently in the roll axis and occasionally in the pitch axis. However, the greatest unweighted rotational peak accelerations were more evenly spread between roll and pitch, with yaw being the greatest exposure in several instances.

Table 4.11: Greatest translational and rotational unweighted accelerations.

<table>
<thead>
<tr>
<th>Skidder</th>
<th>Driving Loaded</th>
<th>Driving Unloaded</th>
<th>Dropping off a Load</th>
<th>Picking up a Load</th>
<th>Ploughing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Running RMS</td>
<td>Peak Axis</td>
<td>Running RMS</td>
<td>Peak Axis</td>
<td>Running RMS</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Driving Loaded</td>
<td>1.26 Z</td>
<td>9.33 Z</td>
<td>1.38 Roll</td>
<td>39.46 Roll</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>1.25 Z</td>
<td>15.97 Z</td>
<td>1.51 Roll</td>
<td>25.24 Roll</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>1.37 Z</td>
<td>9.91 Z</td>
<td>1.53 Roll</td>
<td>11.98 Pitch</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>0.67 X</td>
<td>11.06 X</td>
<td>1.12 Pitch</td>
<td>16.48 Pitch</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>- - - -</td>
<td>- - - -</td>
<td>- - - -</td>
<td>- - - -</td>
</tr>
<tr>
<td>2</td>
<td>Driving Loaded</td>
<td>1.19 Y</td>
<td>6.73 Y</td>
<td>2.31 Roll</td>
<td>30.70 Yaw</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>1.16 Y</td>
<td>10.65 X</td>
<td>2.28 Roll</td>
<td>70.00 Roll</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>0.69 Y</td>
<td>4.85 X</td>
<td>* * * *</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>0.86 Z</td>
<td>9.01 Y</td>
<td>5.27 Roll</td>
<td>50.33 Roll</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>- - - -</td>
<td>- - - -</td>
<td>- - - -</td>
<td>- - - -</td>
</tr>
<tr>
<td>3</td>
<td>Driving Loaded</td>
<td>1.17 Z</td>
<td>10.21 Y</td>
<td>* * * *</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>1.24 Z</td>
<td>13.23 Y</td>
<td>* * * *</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>1.11 X</td>
<td>5.12 X</td>
<td>* * * *</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>1.31 Z</td>
<td>9.11 X</td>
<td>* * * *</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>1.21 Y</td>
<td>9.53 Y</td>
<td>* * * *</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Driving Loaded</td>
<td>1.89 Y</td>
<td>31.94 X</td>
<td>2.91 Roll</td>
<td>62.28 Pitch</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>2.14 Y</td>
<td>24.04 X</td>
<td>3.28 Roll</td>
<td>65.49 Roll</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>1.94 Y</td>
<td>15.29 X</td>
<td>3.38 Pitch</td>
<td>56.08 Yaw</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>1.34 Y</td>
<td>22.55 X</td>
<td>2.27 Pitch</td>
<td>75.32 Yaw</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>1.64 Y</td>
<td>17.29 X</td>
<td>2.98 Roll</td>
<td>29.68 Yaw</td>
</tr>
<tr>
<td>5</td>
<td>Driving Loaded</td>
<td>1.75 Y</td>
<td>16.52 X</td>
<td>2.03 Roll</td>
<td>49.70 Roll</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>1.99 Y</td>
<td>18.55 Y</td>
<td>2.34 Yaw</td>
<td>44.05 Yaw</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>1.62 Z</td>
<td>9.43 Y</td>
<td>1.92 Roll</td>
<td>44.61 Yaw</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>1.65 X</td>
<td>18.99 Y</td>
<td>2.27 Pitch</td>
<td>65.70 Roll</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>1.52 Y</td>
<td>37.41 Y</td>
<td>1.65 Roll</td>
<td>39.67 Roll</td>
</tr>
<tr>
<td>6</td>
<td>Driving Loaded</td>
<td>1.20 Y, Z</td>
<td>18.39 Z</td>
<td>1.49 Roll</td>
<td>33.51 Roll</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>1.50 Y</td>
<td>14.42 Y</td>
<td>1.79 Roll</td>
<td>45.64 Yaw</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>1.05 X</td>
<td>9.28 X</td>
<td>1.86 Roll</td>
<td>30.76 Roll</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>0.66 Y</td>
<td>6.22 X</td>
<td>0.97 Roll</td>
<td>22.64 Yaw</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>- - - -</td>
<td>- - - -</td>
<td>- - - -</td>
<td>- - - -</td>
</tr>
<tr>
<td>7</td>
<td>Driving Loaded</td>
<td>1.36 Y</td>
<td>9.29 Y</td>
<td>1.47 Pitch</td>
<td>20.40 Roll</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>1.32 Y</td>
<td>9.13 Y</td>
<td>1.50 Pitch</td>
<td>30.87 Pitch</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>- - - -</td>
<td>- - - -</td>
<td>- - - -</td>
<td>- - - -</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>0.66 Y</td>
<td>2.75 Y</td>
<td>1.57 Pitch</td>
<td>35.83 Roll</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>1.07 Y</td>
<td>8.72 Y</td>
<td>1.73 Pitch</td>
<td>14.04 Pitch</td>
</tr>
<tr>
<td>8</td>
<td>Driving Loaded</td>
<td>1.10 Y, Z</td>
<td>9.30 Y</td>
<td>1.12 Pitch</td>
<td>19.70 Pitch</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>1.28 Y</td>
<td>11.54 Y</td>
<td>1.33 Pitch</td>
<td>20.88 Pitch</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>1.22 Y</td>
<td>4.87 Z</td>
<td>1.29 Roll</td>
<td>5.00 Pitch</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>1.32 Y</td>
<td>6.15 Z</td>
<td>1.47 Roll</td>
<td>6.04 Pitch</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>- - - -</td>
<td>- - - -</td>
<td>- - - -</td>
<td>- - - -</td>
</tr>
</tbody>
</table>

Note: peak and running RMS data are in m/s² for the translational axes, and rad/s² for the rotational axes.
Finally, the vibration total values (VTV) calculated for both the 3-DOF translational axes and the 6-DOF axes combination are presented in Table 4.12. Based upon the translational VTVs, it would take on average 2.8-hours to exceed the upper limit of the ISO 2631-1:1997 health guidance caution zone while DL, and 2.3-hours while DUL or ploughing. The time to exceed the upper limit when DOAL or PUAL was varied, ranging from 1.6-hours to >24-hours. Although ISO 2631-1 affords the use of VTVs for health analyses (particularly when the exposure levels of each measurement axes are comparable), the accelerations from the dominant exposure axis are typically used. As a result, the running RMS average accelerations of the dominant axes from Table 4.8 were also used with Equations 5 and 6 to determine the time it would take to exceed the upper and lower limits of the ISO 2631-1:1997 health guidance caution zone for each driving condition. It was found that when DL, DUL, DOAL and ploughing, the dominant running RMS acceleration occurred in the Y-axis with exposures of 0.91m/s², 1.04m/s², 0.61m/s² and 0.89m/s² respectively. PUAL on the other hand had a dominant running RMS acceleration of 0.50m/s² in the Z-axis. Using these dominant running RMS accelerations it would take 2.1-hours to exceed the lower limit of the ISO 2631-1:1997 health guidance caution zone while DL, 1.7-hours while DUL, 4.6-hours while DOAL, 6.8 hours while PUAL, and 2.2-hours while ploughing. When considering the upper limit of the ISO 2631-1:1997 health guidance caution zone, those same dominant running RMS accelerations would exceed that upper limit in 6.6-hours while DL, 5.0-hours while DUL, 14.3-hours while DOAL, 20.1-hours while PUAL, and 6.7-hours while ploughing. If the exposure times presented in Table 4.6 are extrapolated to the average 10-hour work day reported in Table 4.4, only the driving conditions would surpass the times to exceed the ISO 2631-1:1997 health guidance caution zone lower limit listed above. Finally, when utilizing the ISO 2631-1:1997 expected comfort ratings, rarely would any of the 6-DOF VTVs be considered anything less than uncomfortable in all driving conditions.

4.4 DISCUSSION

This study reports rotational data for the OSI in the form of peak and running RMS accelerations, as well as crest factors. With the exception of a study by Cation et al. (2008), the authors of this paper have not found any studies which report rotational exposures at the OSI in
Table 4.12: Vibration total values (VTV) calculated for both health and comfort analyses.

<table>
<thead>
<tr>
<th></th>
<th>Average Running RMS VTV Using Health Analysis Axis Multiplying Factors</th>
<th>Average Running RMS VTV Using Comfort Analysis Axis Multiplying Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Translational (m/s²)</td>
<td>Poses a Potential Health Risk After a</td>
</tr>
<tr>
<td>Skidder 1</td>
<td>Driving Loaded</td>
<td>1.41 ± 0.26</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>1.57 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>1.29 ± 0.45</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>0.83 ± 0.10</td>
</tr>
<tr>
<td>Skidder 2</td>
<td>Driving Loaded</td>
<td>1.42 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>1.45 ± 0.39</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>0.73 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>0.95 ± 0.11</td>
</tr>
<tr>
<td>Skidder 3</td>
<td>Driving Loaded</td>
<td>1.32 ± 0.25</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>1.72 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>1.11 ± 0.30</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>0.89 ± 0.42</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>1.78</td>
</tr>
<tr>
<td>Skidder 4</td>
<td>Driving Loaded</td>
<td>2.46 ± 0.23</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>2.39 ± 0.70</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>1.89 ± 0.66</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>1.08 ± 0.35</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>1.88 ± 0.29</td>
</tr>
</tbody>
</table>

a Indicates the amount of exposure time with which the translational running RMS VTV would exceed the lower limit of the ISO 2631-1:1997 health caution zone placing the operator at a potential health risk.

b Indicates the amount of exposure time with which the translational running RMS VTV would exceed the upper limit of the ISO 2631-1:1997 health caution zone placing the operator at a likely health risk.

c Indicates the level of comfort expected for the 6-DOF running RMS VTV presented, using the likely comfort reactions outlined in ISO 2631-1:1997. If no 6-DOF data was available, the translational running RMS VTV was used.
Table 4.12 Continued: Vibration total values (VTV) calculated for both health and comfort analyses.

<table>
<thead>
<tr>
<th>Skidder</th>
<th>Average Running RMS VTV Using Health Analysis Axis Multiplying Factors</th>
<th>Average Running RMS VTV Using Comfort Analysis Axis Multiplying Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Translational (m/s²)</td>
<td>Poses a Potential Health Risk After &lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Driving Loaded</td>
<td>1.73 ± 0.30</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>2.28 ± 0.43</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>1.46 ± 0.21</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>1.70 ± 0.27</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>1.85 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>Driving Loaded</td>
<td>1.65 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>2.09 ± 0.39</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>1.26 ± 0.21</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>0.79 ± 0.15</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Driving Loaded</td>
<td>0.96 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>0.99 ± 0.27</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Ploughing</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>Driving Loaded</td>
<td>1.51 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>Driving Unloaded</td>
<td>1.85 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>Dropping off a Load</td>
<td>0.23 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>Picking up a Load</td>
<td>0.33 ± 0.12</td>
</tr>
</tbody>
</table>

<sup>a</sup> Indicates the amount of exposure time with which the translational running RMS VTV would exceed the lower limit of the ISO 2631-1:1997 health caution zone placing the operator at a potential health risk.

<sup>b</sup> Indicates the amount of exposure time with which the translational running RMS VTV would exceed the upper limit of the ISO 2631-1:1997 health caution zone placing the operator at a likely health risk.

<sup>c</sup> Indicates the level of comfort expected for the 6-DOF running RMS VTV presented, using the likely comfort reactions outlined in ISO 2631-1:1997. If no 6-DOF data was available, the translational running RMS VTV was used.
these formats. As a result of this gap in the literature there are no additional articles or healthy exposure limits with which to gauge our results. We can say that the 6-DOF vibration exposures determined here will likely be rated somewhere between uncomfortable and extremely uncomfortable (Table 4.12). The translational accelerations levels reported in this study, however, can be compared to other exposures found in the literature. Here, the weighted running RMS and RMS accelerations presented in Table 4.8 represent some of the higher exposures found in industry (Table 4.1) and in particular, the forestry industry (Table 4.2).

This study reports unweighted exposure data in addition to weighted data. This too is uncommon in the literature. Weightings are designed to attenuate the high frequency content of the exposure signal to emphasize the frequency ranges that are important for health. This is evident in the differences seen between the weighted and unweighted dominant frequencies (Tables 4.8 and 4.9). These frequency weightings are responsible for lowering the weighted acceleration values and may alter the dominant axis of vibration. This study found that weighting the data shifted the average running RMS exposures from the Y-axis to the X-axis while DOAL, from the Y-axis to the Z-axis while PUAL, and from pitch to roll while DOAL and ploughing.

It is also important to collect field data during normal operating conditions. There are several studies that investigate exposures while driving on ISO 5008 test tracks (Sherwin et al. 2004a; Sherwin et al. 2004b; Scarlett et al. 2005; Scarlett et al. 2007). These test tracks are meant to improve the repeatability of vibration exposures for seat and vehicle suspension performance testing. The vibration exposures measured on these test tracks do not necessarily represent actual field exposures. Scarlett et al. (2007) and Scarlett et al. (2005) have shown that exposures measured on ISO 5008 test tracks overestimate those found during field tasks. On the other hand, one should be aware that studies tracking exposures over an entire work cycle may underestimate the acceleration levels for specific work tasks. This is due to the different vibration exposures for the individual work tasks as well as the fact that periods where the vehicle is stationary are often incorporated into the exposure average.

This study was conducted to obtain representative 6-DOF field exposure data to be used as vibration exposure inputs during subsequent laboratory investigations into the biodynamic responses of seated individuals. Although limited in its sample size, this study did explore potential connections between the musculoskeletal health complaints of the skidder operators studied and the vibration exposures they experienced. As indicated in Table 4.12, Northern
Ontario skidder operators are exposed to WBV acceleration levels that would place them at both a potential and likely health risk. Bovenzi (1996) found a significant association between WBV and low back complaints with an estimated odds ratio for low back pain (LBP) varying from 1.6 to 2.0 when weighted vector sum accelerations range between 0.7 and 0.9 m/s². This investigation found that skidder operators were typically exposed to acceleration levels within this range, however, only one operator reported LBP in this investigation. A greater number of operators in the current investigation may have revealed a greater incidence of LBP complaints. Much of the remaining musculoskeletal complaints were attributed to posture by the operators. Jack et al. (2008a – Chapter 3) describe the postures adopted for the same operating trials reported here. It was interesting to note that the operators in this study who reported low-back and neck pain were not exposed to the greatest exposure accelerations, but they were the operators who adopted the greatest lateral trunk bending and forward flexion for the greatest percentage of time. It is also worth noting that Operator 4, who complained of neck pain as a result of twisting to see the rear of the vehicle while PUAL and DOAL, also experienced some of the highest translational and rotational vibration exposures during those operating conditions. Village, Morrison and Leong (1989), Bovenzi and Betta (1994), Bovenzi (1996), NIOSH (1997) and Jack and Oliver (2008 – Chapter 2), all caution that posture is a contributing factor to the WBV complaints experienced by operators. Bovenzi and Betta (1994) reported that vibration dose and postural load combined to increase the odds of LBP. Village, Morrison and Leong (1989) reported a high incidence of neck pain in load-haul-dump operators who have to rotate their trunk towards the direction of travel relative to other workers who face the direction of travel. When consolidating the data presented here with the findings of Jack et al. (2008a – Chapter 3) it is evident that the lower acceleration exposures experienced while ploughing or DOAL and PUAL are associated with the postures furthest away from neutral. On the other hand the highest acceleration levels experienced by the operators occurred while driving, a condition which presented the most neutral postures (Jack et al. 2008a – Chapter 3). How these postural and vibration exposures interact to affect the body’s response to those exposures should be investigated and will be the focus of future studies.
CHAPTER 4: Field Exposure Levels

4.5 CONCLUSION

Northern Ontario skidder operators are exposed to high levels of vibration. These exposure levels have been associated with adverse health outcomes, including reports of low-back and neck pain. Furthermore, 6-DOF exposure investigations are becoming more feasible and should be conducted to provide representative field exposure data for use as exposure inputs in laboratory investigations.

REFERENCES


CHAPTER 4: Field Exposure Levels


CHAPTER 5

CHARACTERIZATION OF 6-DEGREE-OF-FREEDOM WHOLE-BODY VIBRATION EXPOSURE SPECTRA DURING FORESTRY SKIDDER FIELD OPERATION

5.1 INTRODUCTION

Investigations into the biodynamic response of the human body to whole-body vibration (WBV) frequently use exposures which do not reflect actual WBV exposures found in the field. A review of 83 studies (published between 1974 and 2008 – refer to Table 5.1) investigating the effects of seated vibration exposure on input impedance, absorbed power, apparent mass, transmissibility, muscle activity, fatigue, reading, writing, response time, perceived comfort and annoyance revealed that random vibration and sine waves are typically used as exposures during biodynamic studies. Studies by Holmlund (1999), Holmlund and Lundstrom (2001), and Jonsson and Johansson (2005) have exposed subjects to real vibrations in the field, while others such as Dupuis et al. (1991), Boileau and Rakheja (1998), Bluthner, Seidel and Hinz (2001), Bluthner, Seidel and Hinz (2002), Rakheja et al. (2002), Rakheja et al. (2006), Schust et al. (2006), and Jack and Eger (2008) have attempted to simulate field exposures in the laboratory. The field studies exposed individuals to complex field exposures but often field instrumentation was limited to three or fewer degrees-of-freedom (DOF). Similarly, the laboratory studies which attempted to simulate field exposures were typically limited in the number of DOF simulated. The vibration exposures were often limited to 1-DOF. Some studies have utilized combinations of axes, but those combinations are still limited to 2- or 3-DOF (Griffin and Whitham 1977; Mansfield and Lundstrom, 1999; Demic et al. 2002; Hinz et al. 2006; Mansfield and Maeda 2006; Matsumoto et al. 2006; Schust et al. 2006; Mansfield and Maeda 2007; Jack and Eger 2008). In the field, operators are exposed to complex 6-DOF WBV spectra (Cation et al. 2008; Dickey, Eger and 2010; Jack et al. 2010 – Chapter 4) which are not reflected in the sine wave or random noise exposures of isolated axes.
Table 5.1: Biodynamic studies reviewed.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Frequency Spectra</th>
<th>Exposure Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barnes &amp; Rance 1974</td>
<td>Jang &amp; Griffin 2000</td>
<td>Matsumoto et al. 2006</td>
</tr>
<tr>
<td>Bluthner et al. 2002</td>
<td>Kim et al. 2005</td>
<td>Nawayseh &amp; Griffin 2003</td>
</tr>
<tr>
<td>Boileau &amp; Rakheja 1998</td>
<td>Kitazaki and Griffin 1998</td>
<td>Nawayseh &amp; Griffin 2004</td>
</tr>
<tr>
<td>Demic et al. 2002</td>
<td>Kjellberg &amp; Wikstrom 1985</td>
<td>Nawayseh &amp; Griffin 2005</td>
</tr>
<tr>
<td>Donati &amp; Bonthoux 1983</td>
<td>Lewis &amp; Griffin 1979</td>
<td>Paddock &amp; Griffin 1988a</td>
</tr>
<tr>
<td>Dupis et al. 1991</td>
<td>Lewis &amp; Griffin 1980</td>
<td>Paddock &amp; Griffin 1988b</td>
</tr>
<tr>
<td>El-Khatib et al. 1998</td>
<td>Ljungberg et al. 2004</td>
<td>Paddock &amp; Griffin 1994</td>
</tr>
<tr>
<td>Fairley &amp; Griffin 1989</td>
<td>Lundstrom &amp; Holmstrom 1998</td>
<td>Paddock &amp; Griffin 2000</td>
</tr>
<tr>
<td>Fleury &amp; Mistrot 2006</td>
<td>Lundstrom et al. 1998</td>
<td>Parsons &amp; Griffin 1978</td>
</tr>
<tr>
<td>Griffin &amp; Whitham 1976</td>
<td>Mandapuram et al. 2005</td>
<td>Pope et al. 1989</td>
</tr>
<tr>
<td>Griffin &amp; Whitham 1977</td>
<td>Mansfield &amp; Griffin 1998</td>
<td>Pope et al. 1990</td>
</tr>
<tr>
<td>Griffin &amp; Whitham 1978</td>
<td>Mansfield &amp; Griffin 2000</td>
<td>Pope et al. 1998</td>
</tr>
<tr>
<td>Griffin and Hayward 1994</td>
<td>Mansfield &amp; Griffin 2002</td>
<td>Rakehja et al. 2002</td>
</tr>
<tr>
<td>Hinz et al. 2001</td>
<td>Mansfield &amp; Maeda 2005a</td>
<td>Schust et al. 2006</td>
</tr>
<tr>
<td>Hinz et al. 2006a</td>
<td>Mansfield &amp; Maeda 2005b</td>
<td>Seidel et al. 1980</td>
</tr>
<tr>
<td>Hinz et al. 2006b</td>
<td>Mansfield &amp; Maeda 2006</td>
<td>Seroussi et al. 1989</td>
</tr>
<tr>
<td>Holmlund 1999</td>
<td>Mansfield et al. 2001</td>
<td>Wang et al. 2008</td>
</tr>
<tr>
<td>Holmlund et al. 2000</td>
<td>Mansfield et al. 2006</td>
<td>Whitham &amp; Griffin 1978</td>
</tr>
<tr>
<td>Howarth &amp; Griffin 1988</td>
<td>Matsumoto &amp; Griffin 2005</td>
<td>Wilder et al. 1982</td>
</tr>
<tr>
<td>Huang &amp; Griffin 2006</td>
<td>Matsumoto &amp; Griffin 1998</td>
<td>Wilder et al. 1994</td>
</tr>
<tr>
<td>Ishitake et al. 2002</td>
<td>Matsumoto &amp; Griffin 2000</td>
<td>Zimmerman and Cook 1997</td>
</tr>
<tr>
<td>Jack &amp; Eger 2008</td>
<td>Matsumoto &amp; Griffin 2002a</td>
<td>Zimmerman et al. 1993</td>
</tr>
<tr>
<td>Jang &amp; Griffin 1999</td>
<td>Matsumoto &amp; Griffin 2002b</td>
<td></td>
</tr>
</tbody>
</table>

As affordable technologies to reproduce field 6-DOF exposures in a laboratory become available, realistic 6-DOF input data for such experiments will be required. These inputs should reflect the vibrations to which the operators are exposed. Thus, exposures at the operator/seat interface (OSI) are particularly important when conducting biodynamic investigations because those are the exposures operators are subjected to in the field. Unfortunately, there are few studies which report vibration exposures in the form of frequency spectra, and even fewer which report this data at the OSI. An extensive literature search uncovered nearly 50 research articles that reported vibration exposures in some form, but less than half of those articles provided any sort of frequency data, and even fewer reported that data for multiple axes at the OSI (Table 5.2).

In order to address the limitations present in the biodynamic response literature, it is important to first quantify complex 6-DOF exposure spectra and exposure levels at the OSI, so that they can be utilized as input parameters in laboratory investigations. The findings of these 6-DOF exposure investigations can then be incorporated into current exposure criteria which are
Table 5.2: A summary of the spectral exposure data measured during field operating tasks.

<table>
<thead>
<tr>
<th>Study</th>
<th>Measurement Site</th>
<th>Spectral Type</th>
<th>Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boileau et al., 2006</td>
<td>Chassis PSD</td>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>Wegsheid, 1994</td>
<td>Chassis PSD</td>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>Els, 2005</td>
<td>OSI PSD</td>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>Paddan &amp; Griffin, 2002</td>
<td>OSI PSD</td>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>Lewis &amp; Griffin, 1998</td>
<td>OSI PSD</td>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>Johanning et al., 2002</td>
<td>OSI &amp; Chassis PSD</td>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>Malchaire et al., 1996</td>
<td>OSI &amp; Chassis 1/3-octave band</td>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>Kumar et al., 2001</td>
<td>OSI 1/3-octave band</td>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>Boileau &amp; Rakheja, 1990</td>
<td>Chassis 1/3-octave band</td>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>Kumar et al., 1999</td>
<td>Chassis PSD</td>
<td></td>
<td>X Y Z</td>
</tr>
<tr>
<td>Qui &amp; Griffin, 2003</td>
<td>OSI &amp; Chassis PSD</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Fleury &amp; Mistrot, 2006</td>
<td>Chassis PSD</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Holmlund, 1999</td>
<td>OSI PSD</td>
<td></td>
<td>X Y Z</td>
</tr>
<tr>
<td>Burstrom et al., 2006</td>
<td>OSI 1/3-octave band</td>
<td></td>
<td>X Y Z</td>
</tr>
<tr>
<td>Village et al., 1989</td>
<td>OSI 1/3-octave band</td>
<td></td>
<td>X Y Z</td>
</tr>
<tr>
<td>Bovenzi, 1996</td>
<td>OSI 1/3-octave band</td>
<td></td>
<td>X Y Z</td>
</tr>
<tr>
<td>Melo &amp; Miguel, 2000</td>
<td>OSI 1/3-octave band</td>
<td></td>
<td>X Y Z</td>
</tr>
<tr>
<td>Rehn et al., 2005</td>
<td>OSI 1/3-octave band</td>
<td></td>
<td>X Y Z</td>
</tr>
<tr>
<td>Marsili et al., 1998</td>
<td>OSI 1/3-octave band</td>
<td></td>
<td>X Y Z</td>
</tr>
<tr>
<td>Zinck, 1998</td>
<td>OSI 1/3-octave band</td>
<td></td>
<td>X Y Z</td>
</tr>
<tr>
<td>Sherwin et al., 2004</td>
<td>OSI &amp; Chassis 1/3-octave band</td>
<td></td>
<td>X Y Z</td>
</tr>
<tr>
<td>Boileau et al., 2002</td>
<td>Chassis PSD</td>
<td></td>
<td>X Y Z rx ry</td>
</tr>
<tr>
<td>Parsons et al., 1979</td>
<td>OSI &amp; Chassis PSD</td>
<td></td>
<td>X Y Z rx ry z</td>
</tr>
<tr>
<td>Cation et al., 2008</td>
<td>OSI &amp; Chassis 1/3-octave band</td>
<td></td>
<td>X Y Z rx ry z</td>
</tr>
</tbody>
</table>

Note: rx indicates rotation about the X-axis or Roll, ry indicates rotation about the Y-axis or Pitch, and rz indicates rotation about the Z-axis or Yaw. Also, PSD indicates a power spectral density, and OSI indicated the operator/seat interface.

Based on laboratory and field data that do not include these more complete exposure datasets. The goal of this study was to characterize field measured 6-DOF WBV exposures at the OSI of Northern Ontario forestry skidders as distinct spectral profiles for use as vibration inputs during investigations of the human response to WBV. The prevalence of each exposure spectra for the X, Y, Z, Roll, Pitch and Yaw axes, and the conditions under which they occur will be reported. Spectral profile combinations (3-DOF translational and rotational axis combinations and 6-DOF axis combinations) which occur in the field will also be determined. This will be done to shed light on which profile combinations occur together in the field. The prevalence and conditions under which each spectral profile combination occurred will also be reported.
5.2 METHODS

5.2.1 Field data collection

Translational and rotational whole-body vibration (WBV) exposures at the operator/seat interface (OSI) were determined for eight male Northern Ontario skidder operators under field operating conditions (refer to Table 5.3 for a summary of operator characteristics and Table 5.4 for a summary of the operating conditions). A custom made 6-degree-of-freedom (DOF) seat-pad transducer (Figure 5.1) was placed on the skidder seat beneath the operator’s ischial tuberosities with a basicentric orientation (as outlined in ISO 2631-1 (1997)). The 6-DOF seat-pad transducer was comprised of two ADXL320EB (Analog Devices Inc., MA, USA) dual axis accelerometers to determine translational accelerations in the X-, Y- and Z-axes; and three ADXRS150EB (Analog Devices Inc., MA, USA) rate gyroscopes to determine angular velocities in Roll (rotation about X-axis), Pitch (rotation about Y-axis) and Yaw (rotation about Z-axis). All of the aforementioned components were orthogonally aligned in a Delrin™ plastic casing. The seat-pad transducer was also fitted with a soft rubber shell to minimize pressure points and discomfort. Refer to Cation et al. (2008) for a complete description of the transducer.

![Figure 5.1](image)

**Figure 5.1**: 6-DOF seat-pad transducer placed on the skidder seat with a basicentric orientation.
Table 5.3: Summary of operator characteristics and driving experience.

<table>
<thead>
<tr>
<th>Operator</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>39</td>
<td>32</td>
<td>33</td>
<td>28</td>
<td>45</td>
<td>50</td>
<td>50</td>
<td>56</td>
<td>41.6</td>
<td>10.1</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>145.2</td>
<td>61.2</td>
<td>86.2</td>
<td>83.9</td>
<td>108.9</td>
<td>72.6</td>
<td>97.5</td>
<td>94.7</td>
<td>25.8</td>
<td></td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.80</td>
<td>1.73</td>
<td>1.91</td>
<td>1.78</td>
<td>1.80</td>
<td>1.73</td>
<td>1.75</td>
<td>1.80</td>
<td>1.79</td>
<td>0.06</td>
</tr>
<tr>
<td>Years operating mobile equipment</td>
<td>20.0</td>
<td>11.0</td>
<td>13.0</td>
<td>5.0</td>
<td>31.0</td>
<td>33.0</td>
<td>15.0</td>
<td>35.0</td>
<td>20.4</td>
<td>11.3</td>
</tr>
<tr>
<td>Years operating a skidder</td>
<td>20.0</td>
<td>5.0</td>
<td>13.0</td>
<td>0.1</td>
<td>31.0</td>
<td>33.0</td>
<td>12.0</td>
<td>35.0</td>
<td>18.6</td>
<td>13.3</td>
</tr>
<tr>
<td>Average hours/day operating a skidder</td>
<td>11.0</td>
<td>11.0</td>
<td>8.0</td>
<td>14.0</td>
<td>12.0</td>
<td>14.0</td>
<td>3.0</td>
<td>8.0</td>
<td>10.1</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Table 5.4: Summary of skidder operating conditions.

<table>
<thead>
<tr>
<th>Skidder Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat Orientation, °</td>
<td>0</td>
<td>25</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Operator Reported Maintenance History</td>
<td>Greased every other day, oil changed every 500 hours</td>
<td>Greased every other day, oil changed every 250 hours</td>
<td>Greased each day, oil changed each month (every 176 Hours)</td>
<td>Greased each day, oil changed every 500 hours</td>
<td>Greased each day, oil changed every 200 hours</td>
<td>Greased that day, oil changed every 150-200 hours</td>
<td>Greased once a week, oil changed each month (every 60 Hours)</td>
<td>Greased every other day, oil changed each month (every 160 Hours)</td>
</tr>
<tr>
<td>Operator Reported Tire Pressure, psi</td>
<td>35</td>
<td>45</td>
<td>33.5</td>
<td>25</td>
<td>33.5</td>
<td>45</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Landscape</td>
<td>Large Hills</td>
<td>Large Hills</td>
<td>Flood bed with small Rolling hills</td>
<td>Steep Rolling hills</td>
<td>Steep Rolling hills</td>
<td>Steep Rolling hills</td>
<td>Small rock outcrops on small Rolling hills</td>
<td>Small rock outcrops on steep Rolling hills</td>
</tr>
<tr>
<td>Terrain Description</td>
<td>Rocky with loose loam soil</td>
<td>Rocky with loose loam soil</td>
<td>Sand/loam mixed soil</td>
<td>Gravel with sand soil</td>
<td>Gravel with sand soil</td>
<td>Gravel with sand soil</td>
<td>Clay soil with gravel and large rocks</td>
<td></td>
</tr>
<tr>
<td>Travel path</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>Most trees remained standing</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>No cleared trees</td>
<td>Most trees cleared</td>
</tr>
<tr>
<td>Forestation</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>Most trees cleared</td>
<td>No cleared trees</td>
<td>Most trees cleared</td>
</tr>
</tbody>
</table>

† Estimated based on a 4 day work week with the reported hours/day worked in Table 5.3. If the hours worked were less than 10 hrs a day then a 5 day work week was assumed.
Raw accelerometer and rate gyroscope voltages were recorded with a 12-bit SOMAT™ 2100 Field Computer System (nCode, Urbana, Illinois, USA) at a sampling rate of 500 Hz, while the operators performed their normal driving duties. Five operating conditions were observed and monitored; driving with a load (DL), driving without a load (DUL), picking up a load (PUAL), dropping off a load (DOAL), and ploughing logs (refer to Table 5.5 for a full breakdown of the task operating times). A digital video camera (Sony DCR-PC 109, Shinagawa, Tokyo, Japan) mounted in the skidder cab was used to determine when the skidder operator performed each of the aforementioned tasks. The video camera filmed the operators as well as the rear implements of the skidders. The video data in conjunction with an audible beep and simultaneous voltage spike recorded by a Biometrics Ltd. P98 data logger (Gwent, UK) were used to time stamp the data. The second data logger was required for the time stamp because all available input channels of the SOMAT™ 2100 Field Computer System were utilized. The Biometrics Ltd. data logger and SOMAT™ 2100 Field Computer time histories were aligned using a multiple resolution cross correlation procedure (Jack et al. 2008 – Appendix B). The WBV data were then divided into the various skidder operating conditions for analysis.

5.2.2 Data analysis

Following the conversion of the raw voltage data to appropriate units (Cation et al. 2007; Jack et al. 2010 – Chapter 4), the time histories were then band-pass filtered with the high-pass and low-pass cutoff frequencies set to 0.4 Hz and 40 Hz respectively. The rotational velocity time histories were then converted from °/s to rad/sec, and a 4-point differentiation equation (Burden and Faires 1989) was used to calculate rotational accelerations.

Unweighted 1/3-octave band running root-mean-squared (RMS) average accelerations (Equation 1) using center frequencies ranging from 0.5-31.5 Hz were calculated using the Vibratools™ software package (Axiom EduTech, Ljusterö, Sweden) in conjunction with a custom MatLab™ (The Mathworks Inc., MA, USA) program. The running RMS average accelerations for each 1/3-octave band were determined using 1-second sliding window averaging with a 90% overlap. In addition to 1/3-octave bandwidth running RMS average acceleration spectra, Discrete Fourier Time Series (DFT) power spectra were also determined using a 1-second Hanning window with the same 90% overlap as the 1/3-octave band running
## Table 5.5: Average and total data collection times for the five operating conditions monitored during field data collection.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Driving Loaded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of trials</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>10</td>
<td>19</td>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Average trial time (min)</td>
<td>1.85</td>
<td>0.83</td>
<td>1.75</td>
<td>0.98</td>
<td>1.08</td>
<td>3.50</td>
<td>5.22</td>
<td>4.07</td>
</tr>
<tr>
<td>Standard deviation (min)</td>
<td>0.43</td>
<td>0.71</td>
<td>1.33</td>
<td>0.20</td>
<td>0.86</td>
<td>1.57</td>
<td>2.97</td>
<td>2.23</td>
</tr>
<tr>
<td>Total operating time (min)</td>
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<td>1.67</td>
<td>10.50</td>
<td>9.78</td>
<td>20.57</td>
<td>21.00</td>
<td>31.30</td>
<td>16.28</td>
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<td>11</td>
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<td>Average trial time (min)</td>
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<td>3.29</td>
<td>0.96</td>
<td>1.22</td>
<td>3.49</td>
<td>3.37</td>
<td>4.54</td>
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<tr>
<td>Standard deviation (min)</td>
<td>1.05</td>
<td>0.94</td>
<td>1.64</td>
<td>0.29</td>
<td>0.80</td>
<td>1.56</td>
<td>3.58</td>
<td>2.94</td>
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<td>Total operating time (min)</td>
<td>11.98</td>
<td>3.65</td>
<td>16.43</td>
<td>10.57</td>
<td>13.37</td>
<td>20.93</td>
<td>20.23</td>
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<td>Dropping Off a Load</td>
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<td>8</td>
<td>10</td>
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<td>Average trial time (min)</td>
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<td>0.12</td>
<td>0.11</td>
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<td>0.12</td>
<td>0.27</td>
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<td>0.18</td>
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<tr>
<td>Standard deviation (min)</td>
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<td>0.12</td>
<td>0.06</td>
<td>0.10</td>
<td>0.06</td>
<td>0.31</td>
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<td>0.09</td>
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<td>Total operating time (min)</td>
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<td>0.23</td>
<td>0.33</td>
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<td>1.15</td>
<td>1.35</td>
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<td>9</td>
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<td>0.41</td>
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<tr>
<td>Standard deviation (min)</td>
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<td>0.25</td>
<td>0.66</td>
<td>0.15</td>
<td>0.32</td>
<td>0.20</td>
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<td>0.06</td>
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<td>Total operating time (min)</td>
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<td>3.23</td>
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<td>5.77</td>
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<td>Ploughing</td>
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<td>-</td>
<td>1</td>
<td>6</td>
<td>5</td>
<td>-</td>
<td>1</td>
<td>-</td>
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<tr>
<td>Average trial time (min)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.66</td>
<td>0.83</td>
<td>-</td>
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<tr>
<td>Standard deviation (min)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.27</td>
<td>0.28</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total operating time (min)</td>
<td>-</td>
<td>-</td>
<td>1.17</td>
<td>3.97</td>
<td>4.13</td>
<td>-</td>
<td>1.85</td>
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<tr>
<td>Total operating time (min)</td>
<td>19.88</td>
<td>6.36</td>
<td>31.66</td>
<td>29.17</td>
<td>44.99</td>
<td>46.62</td>
<td>53.80</td>
<td>31.00</td>
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</table>
$a(t_0) = \left[ \frac{1}{\tau} \int_{t_0-\tau}^{t_0} (a(t))^2 \, dt \right]^{1/2}$  \hspace{1cm} (1)

Where $a(t_0)$ is the weighted or unweighted running RMS average acceleration, $a(t)$ is the instantaneous weighted or unweighted acceleration as a function of time $(t)$, $\tau$ is the integration time for the running average, and $t_0$ is the time of observation.

RMS average acceleration analysis. The aforementioned variables were determined in accordance with ISO 2631-1 (1997) for all skidders, in all 6-DOF, and for all driving conditions.

Unweighted vibration exposure trials which displayed similar 1/3-octave bandwidth running RMS average acceleration spectra peak and trough amplitudes were then grouped together for each axis and ensemble averages were determined. These ensemble averages provided a spectral profile representing each grouping of similar trials. Once the unique spectral profiles were established, the 6-DOF and 3-DOF (translational and rotational axes grouped together) combinations of those axes profiles which occurred in the field were then determined.

5.3 RESULTS

Using the 1/3-octave band running RMS average spectra, nine unique spectral profiles were established for the X-axis, thirteen for the Y-axis, six for the Z-axis, eight for Roll, seven for Pitch, and seven for Yaw. The ensemble average for each of the aforementioned spectral profiles is presented in Figures 5.2 through 5.7. An alphabetical naming convention was developed to distinguish between profiles (Roll-A was the first spectral profile in Roll, etc). These ensemble averages are presented in both 1/3-octave band running RMS average spectra, and DFT spectra for the reader’s convenience. Both methods provide the same spectral information, however, it is presented in two commonly used scales. The 1/3-octave band spectral profiles often displayed similar low frequency acceleration patterns; however, the higher frequency 1/3-octave band accelerations typically possessed unique acceleration patterns. Often it was the distinct high frequency acceleration pattern which determined which spectral profile, but the entire 1/3-octave band was used to establish spectral profiles. Note that no roll data were available for Skidder 2 while DOAL, and for all Skidder 3 driving conditions due to an inadequate sensor cable connection.
Figure 5.2: Unweighted X-axis spectral profiles for the nine (A through I) unique X-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.
Figure 5.2 Continued: Unweighted X-axis spectral profiles for the nine (A through I) unique X-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.

Figure 5.3: Unweighted Y-axis spectral profiles for the thirteen (A through M) unique Y-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.
Figure 5.3 Continued: Unweighted Y-axis spectral profiles for the thirteen (A through M) unique Y-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.
**Figure 5.3 Continued:** Unweighted Y-axis spectral profiles for the thirteen (A through M) unique Y-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.

**Figure 5.4:** Unweighted Z-axis spectral profiles for the six (A through F) unique Z-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.
Figure 5.5: Unweighted Roll-axis spectral profiles for the eight (A through H) unique Roll-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.
Figure 5.5 Continued: Unweighted Roll-axis spectral profiles for the eight (A through H) unique Roll-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.

Figure 5.6: Unweighted Pitch-axis spectral profiles for the seven (A through G) unique Pitch-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.
Figure 5.6 Continued: Unweighted Pitch-axis spectral profiles for the seven (A through G) unique Pitch-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.

Figure 5.7: Unweighted Yaw-axis spectral profiles for the seven (A through G) unique Yaw-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.
Figure 5.7 Continued: Unweighted Yaw-axis spectral profiles for the seven (A through G) unique Yaw-axis acceleration patterns. The solid line indicates the mean and the dashed line indicates ±1 standard deviation.

The 1/3-octave band spectral profiles often displayed similar low frequency acceleration patterns; however, the higher frequency 1/3-octave band accelerations typically possessed unique acceleration patterns. Often it was the distinct high frequency acceleration pattern which determined which spectral profile, but the entire 1/3-octave band was used to establish spectral profiles.

Considering the translational DFT spectral profiles, low frequency vibration typically dominated the exposures with peaks at 1Hz and little signal above 10Hz. The rotational spectral profiles however, tended to have a more gradual reduction in signal power (up to 30Hz) with peaks at 2Hz. There were some translational profiles with considerable signal power at frequencies up to 20Hz, often containing secondary peaks (for example, X-H, Z-B and Y-A). There were also profiles which displayed the typical low frequency dominance, but also possessed a distinct rise in signal power at high frequencies (for example, Y-B, Roll-C, Pitch-B, Pitch-E and Yaw-B). Some spectral profiles were dominated by high frequency accelerations (>34Hz; for example, Z-F, Y-L, Roll- H and Yaw-F). Finally, some spectral profiles had neither a low nor high frequency dominance, with the majority of their signal power between 2Hz-14Hz (for example, Z-C and Roll-D), and 8Hz-18Hz (Pitch-F).

Tables 5.6 through 5.11 identify the specific skidders for the individual spectral profiles and the corresponding operating conditions. Each of the skidders contributed to many of the individual spectral profiles. It was also apparent that some profiles were associated with more than one skidder. The Z-D, Pitch-A and Yaw-C profiles all appeared in seven of the eight skidders tested; Z-E showed up in six skidders; and X-E, Roll-A, Roll-B, Pitch-B and Pitch-C appeared in five of eight skidders. Although individual spectral profiles appeared in a number of skidders, they tended to appear under similar operating conditions across those skidders, i.e. while DL, DUL and Ploughing, or while DOAL and PUAL. It is interesting to note that the
Table 5.6: Summary of the X-axis profile occurrences and vibration exposure data associated with the X-axis ensemble averages presented in Figure 5.2.

<table>
<thead>
<tr>
<th>Vibration Spectral Profile</th>
<th>Skidders the Profile Occurred In</th>
<th>Driving Conditions the Profile Occurred In (Number of Trials)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-A</td>
<td>Skidder 3</td>
<td>DUL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 5</td>
<td>DL(19), DUL(9), Ploughing(5), PUAL(10)</td>
</tr>
<tr>
<td>X-B</td>
<td>Skidder 7</td>
<td>DL(6), DUL(5)</td>
</tr>
<tr>
<td>X-C</td>
<td>Skidder 2</td>
<td>DL(2), DUL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 6</td>
<td>DL(5), DUL(5), DOAL(2), PUAL(4)</td>
</tr>
<tr>
<td>X-D</td>
<td>Skidder 2</td>
<td>DL(3), DUL(4), DOAL(1), PUAL(2)</td>
</tr>
<tr>
<td></td>
<td>Skidder 3</td>
<td>DL(3), DUL(1), DOAL(1), PUAL(2)</td>
</tr>
<tr>
<td></td>
<td>Skidder 4</td>
<td>DUL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 5</td>
<td>DUL(1), PUAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 6</td>
<td>DL(4), DUL(3)</td>
</tr>
<tr>
<td></td>
<td>Skidder 7</td>
<td>DUL(1), DOAL(8), PUAL(1)</td>
</tr>
<tr>
<td>X-G</td>
<td>Skidder 3</td>
<td>PUAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 7</td>
<td>PUAL(1)</td>
</tr>
<tr>
<td>X-H</td>
<td>Skidder 2</td>
<td>PUAL(2)</td>
</tr>
<tr>
<td></td>
<td>Skidder 4</td>
<td>PUAL(5)</td>
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<td>DL(1), DOAL(2), PUAL(1)</td>
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Table 5.7: Summary of the Y-axis profile occurrences and vibration exposure data associated with the Y-axis ensemble averages presented in Figure 5.3.

<table>
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<th>Vibration Spectral Profile</th>
<th>Skidders the Profile Occurred In</th>
<th>Driving Conditions the Profile Occurred In (Number of Trials)</th>
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<td>Y-A</td>
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</tr>
<tr>
<td></td>
<td>Skidder 6</td>
<td>DOAL(1)</td>
</tr>
<tr>
<td>Y-B</td>
<td>Skidder 7</td>
<td>DL(6), DUL(6), Ploughing(1), PUAL(1)</td>
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<tr>
<td>Y-C</td>
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<td>Y-D</td>
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<td>Y-E</td>
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<tr>
<td>Y-F</td>
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<td>Skidder 2</td>
<td>DL(2), DUL(1)</td>
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<td>Skidder 4</td>
<td>DOAL(3), Ploughing(3), PUAL(6)</td>
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<td>Skidder 6</td>
<td>DOAL(2), PUAL(3)</td>
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<td></td>
<td>Skidder 4</td>
<td>DUL(3), DOAL(1), Ploughing(3)</td>
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<td>Skidder 6</td>
<td>DL(6), DUL(5), DOAL(2), PUAL(2)</td>
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<td>Y-J</td>
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<td>Y-L</td>
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<td>DOAL(3), PUAL(3)</td>
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<td>Y-M</td>
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Table 5.8: Summary of the Z-axis profile occurrences and vibration exposure data associated with the Z-axis ensemble averages presented in Figure 5.4.

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<th>Vibration Spectral Profile</th>
<th>Skidders the Profile Occurred In</th>
<th>Driving Conditions the Profile Occurred In (Number of Trials)</th>
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<td>Z-C</td>
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<td>PUAL(2)</td>
</tr>
<tr>
<td>Z-D</td>
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<td>DL(3), DUL(4), PUAL(1)</td>
</tr>
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<td>DL(2), DUL(3), DOAL(1)</td>
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<td>DL(6), DUL(5), DOAL(1), Ploughing(1), PUAL(2)</td>
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</tr>
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<td>Skidder 8</td>
<td>DL(4), DUL(3)</td>
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<td>Skidder 4</td>
<td>DOAL(1), PUAL(5)</td>
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<td>Skidder 6</td>
<td>DOAL(1), PUAL(5)</td>
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<td>Skidder 7</td>
<td>PUAL(1)</td>
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<tr>
<td>Z-F</td>
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Table 5.9: Summary of the Roll profile occurrences and vibration exposure data associated with the Roll ensemble averages presented in Figure 5.5.

<table>
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<th>Vibration Spectral Profile</th>
<th>Skidders the Profile Occurred In</th>
<th>Driving Conditions the Profile Occurred In (Number of Trials)</th>
</tr>
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<td>Roll-A</td>
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<td>Skidder 2</td>
<td>DL(1), DUL(3)</td>
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<tr>
<td></td>
<td>Skidder 4</td>
<td>DL(10), DUL(10), DOAL(4), Ploughing(5), PUAL(3)</td>
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<td>Skidder 5</td>
<td>DL(19), DUL(9), DOAL(6), Ploughing(5), PUAL(8)</td>
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<td>Skidder 6</td>
<td>DOAL(1)</td>
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<tr>
<td></td>
<td>Skidder 1</td>
<td>DUL(4), DOAL(2), PUAL(3)</td>
</tr>
<tr>
<td></td>
<td>Skidder 4</td>
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<td></td>
<td>Skidder 5</td>
<td>DOAL(1), PUAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 6</td>
<td>DL(6), DUL(6), DOAL(4), PUAL(5)</td>
</tr>
<tr>
<td></td>
<td>Skidder 7</td>
<td>PUAL(1)</td>
</tr>
<tr>
<td>Roll-B</td>
<td>Skidder 7</td>
<td>DL(6), DUL(6), Ploughing(1)</td>
</tr>
<tr>
<td>Roll-C</td>
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<td>PUAL(2)</td>
</tr>
<tr>
<td>Roll-D</td>
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</tr>
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<td>Roll-E</td>
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<tr>
<td>Roll-F</td>
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<td>PUAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 5</td>
<td>DUL(1), PUAL(4)</td>
</tr>
<tr>
<td>Roll-G</td>
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<td>DUL(1), DOAL(3), Ploughing(1), PUAL(1)</td>
</tr>
<tr>
<td>Roll-H</td>
<td>Skidder 8</td>
<td>DOAL(3), PUAL(3)</td>
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</table>
### Table 5.10: Summary of the Pitch profile occurrences and vibration exposure data associated with the Pitch ensemble averages presented in Figure 5.6.

<table>
<thead>
<tr>
<th>Vibration Spectral Profile</th>
<th>Profile Occurrence Summary</th>
<th>Driving Conditions the Profile Occurred In (Number of Trials)</th>
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<td></td>
<td>Skidders the Profile Occurred In</td>
<td></td>
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<td><strong>Pitch-A</strong></td>
<td>Skidder 1</td>
<td>DOAL(1), PUAL(1)</td>
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<td></td>
<td>Skidder 2</td>
<td>DL(2), DUL(3)</td>
</tr>
<tr>
<td></td>
<td>Skidder 3</td>
<td>DL(6), DUL(4, DOAL(3), PUAL(5)</td>
</tr>
<tr>
<td></td>
<td>Skidder 4</td>
<td>DOAL(2), PUAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 5</td>
<td>DL(4), DOAL(3), PUAL(5)</td>
</tr>
<tr>
<td></td>
<td>Skidder 6</td>
<td>DOAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 8</td>
<td>DUL(1)</td>
</tr>
<tr>
<td><strong>Pitch-B</strong></td>
<td>Skidder 1</td>
<td>DOAL(1, PUAL(2)</td>
</tr>
<tr>
<td></td>
<td>Skidder 5</td>
<td>DOAL(1, PUAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 6</td>
<td>DOAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 7</td>
<td>DUL(1), PUAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 8</td>
<td>DOAL(3), PUAL(3)</td>
</tr>
<tr>
<td><strong>Pitch-C</strong></td>
<td>Skidder 1</td>
<td>DL(3), DUL(4), DOAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 2</td>
<td>DOAL(2)</td>
</tr>
<tr>
<td></td>
<td>Skidder 3</td>
<td>PUAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 5</td>
<td>DL(15), DUL(7), DOAL(4), Ploughing(5), PUAL(6)</td>
</tr>
<tr>
<td></td>
<td>Skidder 6</td>
<td>DUL(4), DOAL(2), PUAL(5)</td>
</tr>
<tr>
<td></td>
<td>Skidder 3</td>
<td>DUL(1), Ploughing(1)</td>
</tr>
<tr>
<td><strong>Pitch-D</strong></td>
<td>Skidder 4</td>
<td>DL(10), DUL(11), DOAL(3), Ploughing(6), PUAL(8)</td>
</tr>
<tr>
<td></td>
<td>Skidder 5</td>
<td>DUL(4), DOAL(1), PUAL(2)</td>
</tr>
<tr>
<td></td>
<td>Skidder 6</td>
<td>DUL(2)</td>
</tr>
<tr>
<td><strong>Pitch-E</strong></td>
<td>Skidder 7</td>
<td>DL(6), DUL(5), Ploughing(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 8</td>
<td>DL(4), DUL(2)</td>
</tr>
<tr>
<td><strong>Pitch-F</strong></td>
<td>Skidder 2</td>
<td>PUAL(2)</td>
</tr>
<tr>
<td><strong>Pitch-G</strong></td>
<td>Skidder 6</td>
<td>DL(6)</td>
</tr>
</tbody>
</table>

The majority of profiles that contained more dominant high frequency signal in either the 1/3-octave band or DFT spectra (X-F, X-H, Y-A, Y-H, Y-L, Z-B, Z-C, Z-F, Roll-B, Roll-D, Roll-H, Pitch-B, Pitch-F, Yaw-C and Yaw-F) occurred almost exclusively while DOAL and PUAL. This is likely the result of prominent higher frequency engine vibration while the vehicle is stationary during those tasks. The loading conditions (DOAL and PUAL) also include driving elements and as a result there were a number of profiles which occurred under both the loading and driving tasks (DL, DUL, Ploughing). The driving tasks were still dominated by low frequency accelerations, but they also had profiles with higher frequency 1/3-octave band or DFT accelerations (X-A, X-B, Y-B, Roll-B, Roll-C, Roll-E, Pitch-E, Pitch-G, Yaw-A and Yaw-B).

Upon determining the profiles for each individual axis, combinations of those profiles which occurred in the field were established. Several 6-DOF combinations of the individual axes profiles occurred in the field (Table 5.12), however, these 6-DOF profile combinations were unique to individual skidders. When considering only translational axes, again, several
Table 5.11: Summary of the Yaw profile occurrences and vibration exposure data associated with the Yaw ensemble averages presented in Figure 5.7.

<table>
<thead>
<tr>
<th>Vibration Spectral Profile</th>
<th>Skidders the Profile Occurred In</th>
<th>Profile Occurrence Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Driving Conditions the Profile Occurred In (Number of Trials)</td>
</tr>
<tr>
<td>Yaw-A</td>
<td>Skidder 1</td>
<td>DL(2), DUL(4), DOAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 4</td>
<td>DOAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 5</td>
<td>DL(18), DUL(10), DOAL(3), Ploughing(5), PUAL(9)</td>
</tr>
<tr>
<td></td>
<td>Skidder 6</td>
<td>DL(1), DUL(1)</td>
</tr>
<tr>
<td>Yaw-B</td>
<td>Skidder 1</td>
<td>DL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 7</td>
<td>DL(6), DUL(5), Ploughing(1), PUAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 8</td>
<td>DL(4), DUL(3)</td>
</tr>
<tr>
<td>Yaw-C</td>
<td>Skidder 1</td>
<td>DOAL(2), PUAL(3)</td>
</tr>
<tr>
<td></td>
<td>Skidder 2</td>
<td>DUL(1), DOAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 3</td>
<td>DOAL(3), PUAL(4)</td>
</tr>
<tr>
<td></td>
<td>Skidder 4</td>
<td>DOAL(1), PUAL(6)</td>
</tr>
<tr>
<td></td>
<td>Skidder 5</td>
<td>DUL(1), DOAL(2), PUAL(4)</td>
</tr>
<tr>
<td></td>
<td>Skidder 6</td>
<td>DOAL(5), PUAL(5)</td>
</tr>
<tr>
<td></td>
<td>Skidder 7</td>
<td>DUL(1)</td>
</tr>
<tr>
<td>Yaw-D</td>
<td>Skidder 2</td>
<td>PUAL(2)</td>
</tr>
<tr>
<td></td>
<td>Skidder 3</td>
<td>DL(6), DUL(5), Ploughing(1), PUAL(2)</td>
</tr>
<tr>
<td>Yaw-E</td>
<td>Skidder 2</td>
<td>DL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 4</td>
<td>DL(10), DUL(11), DOAL(4), Ploughing(6), PUAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 5</td>
<td>DL(1), DOAL(1)</td>
</tr>
<tr>
<td></td>
<td>Skidder 6</td>
<td>DL(5), DUL(5)</td>
</tr>
<tr>
<td>Yaw-F</td>
<td>Skidder 8</td>
<td>DOAL(3), PUAL(3)</td>
</tr>
<tr>
<td>Yaw-G</td>
<td>Skidder 2</td>
<td>DL(1), DUL(2)</td>
</tr>
</tbody>
</table>

combinations of the individual axes profiles occurred in the field (Table 5.12), but only one of those combinations occurred in more than one skidder (Table 5.13). With respect to rotational axes, numerous combinations of the individual axes profiles occurred in the field data (Table 5.12), and five of those combinations occurred in more than one skidder (Table 5.13).

5.4 DISCUSSION

There is a limited amount of complex 6-DOF exposure data available (amplitudes and spectra) for vibrations measured at the OSI. To our knowledge, Parsons et al. (1979) is the only other study which evaluates field exposures at the OSI to the same extent of the present study. However, the Parsons et al. (1979) report on standard automobiles is unlikely to be representative of industrial vehicles. Boileau et al. (2002) conducted a comprehensive study as well, but their data were recorded at the chassis of snow ploughs. Chassis exposures are required as inputs in laboratory testing of seat dynamics, so that seats can be tuned for the environments
CHAPTER 5: Field Exposure Spectra

Table 5.12: Spectral profile combinations found in the field.

<table>
<thead>
<tr>
<th>6-DOF Axes Combinations</th>
<th>3-DOF Translational Axes Combinations</th>
<th>3-DOF Rotational Axes Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X, Y, Z, rx, ry, rz)</td>
<td>(X, Y, Z)</td>
<td>(rx, ry, rz)</td>
</tr>
<tr>
<td>ACAACA</td>
<td>CFEBCC</td>
<td>EFDGDE</td>
</tr>
<tr>
<td>ACAADA</td>
<td>CGDBBC</td>
<td>EGDAAG</td>
</tr>
<tr>
<td>ACAFCA</td>
<td>CGDBCC</td>
<td>EGDADE</td>
</tr>
<tr>
<td>AHAAAA</td>
<td>CGDBCE</td>
<td>EGDGDE</td>
</tr>
<tr>
<td>AHAACA</td>
<td>CGDBDE</td>
<td>EGEEAE</td>
</tr>
<tr>
<td>AHAADA</td>
<td>CGDBGE</td>
<td>EMDADE</td>
</tr>
<tr>
<td>AHAADC</td>
<td>CGECBC</td>
<td>FHHAAA</td>
</tr>
<tr>
<td>AKAAAA</td>
<td>DFDBAC</td>
<td>FHBADA</td>
</tr>
<tr>
<td>AKAAAE</td>
<td>DFEBBC</td>
<td>FKAACA</td>
</tr>
<tr>
<td>AKAAACA</td>
<td>DJDACA</td>
<td>FKABBC</td>
</tr>
<tr>
<td>AKAAD A</td>
<td>DJDACB</td>
<td>GBEBBB</td>
</tr>
<tr>
<td>AKAFCA</td>
<td>DJDBCA</td>
<td>HFEBAC</td>
</tr>
<tr>
<td>AKAFCC</td>
<td>EAAAAA</td>
<td>HFEBDC</td>
</tr>
<tr>
<td>BBDC EB</td>
<td>ECAFCA</td>
<td>IFDBAC</td>
</tr>
<tr>
<td>CFDAAC</td>
<td>EDEEAB</td>
<td>IFEACC</td>
</tr>
<tr>
<td>CFDAAE</td>
<td>EDEEB</td>
<td>IGDBG A</td>
</tr>
<tr>
<td>CFDFAG</td>
<td>EFDADE</td>
<td>IGBECC</td>
</tr>
</tbody>
</table>

Note: the letter combinations presented above represent X, Y, Z, rx, ry, rz axes combinations. For example, ACAACA indicates a combination of the X-A, Y-C, Z-A, Roll-A, Pitch-C and Yaw-A spectral profiles.

they will be used in. However, the vibration attenuation and amplification characteristics of a seat mean that operators in the field are not actually exposed to the frequencies or levels found at the chassis. Parsons et al. (1979), Malchaire et al. (1996), Johanning et al. (2002), Qui & Griffin (2003), Sherwin et al. (2004), and Cation et al. (2008) all report dominant frequency shifts and amplitude changes between chassis and OSI field vibration exposures. Typically, human biodynamic studies are conducted with individuals sitting on rigid instrumented seats. These rigid seats need to be accelerated similarly to the OSI in the field so that the vibration exposures are same, and the results are transferable to industry. This makes the use of chassis inputs inappropriate for these types of human response studies.

Current vibration exposure guidelines indicate that the human response to vibration is dependent on vibration exposure frequency (BS 6841:1987; ISO 2631-1, 1997; EU Directive 2002/44/EC). Griffin (1998) has indicated that the pattern of frequency dependence used by these guidelines is based on the subjective and biodynamic response of individuals exposed to vibration. These forms of data are obtained from laboratory studies, and as indicated earlier, are often limited in the exposure axes and spectra utilized. Furthermore, these laboratory studies are
Table 5.13: 3-DOF spectral profile combinations found in the field which occurred in more than one skidder.

<table>
<thead>
<tr>
<th>Spectral Profile Combination</th>
<th>Profile Occurrence Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-DOF Translational Axes Combinations (X, Y, Z)</td>
<td>Skidders the Profile Occurred In</td>
</tr>
<tr>
<td>EGD</td>
<td>Skidder 2, Skidder 4</td>
</tr>
<tr>
<td>AAE</td>
<td>Skidder 2, Skidder 4, Skidder 5</td>
</tr>
<tr>
<td>ACA</td>
<td>Skidder 1, Skidder 5, Skidder 5</td>
</tr>
<tr>
<td>ADC</td>
<td>Skidder 4, Skidder 5</td>
</tr>
<tr>
<td>BAC</td>
<td>Skidder 1, Skidder 4, Skidder 5, Skidder 6</td>
</tr>
<tr>
<td>BBC</td>
<td>Skidder 1, Skidder 5, Skidder 6</td>
</tr>
</tbody>
</table>

Note: the letter combinations presented above represent X, Y, Z or rx, ry, rz axes combinations. For example, the translational EGD combination indicates X-E, Y-G and Z-D spectral profiles. The rotational AAE combination indicates Roll-A, Pitch-A and Yaw-E spectral profiles.

not directly linked to injury outcomes. This study has shown that skidder operators are exposed to a set of different spectral profiles, in a number of different combinations of axes, depending on the specific vehicle and the operating task. How those various profile combinations interact to affect health is not yet known. Therefore, it is important to begin looking at complex vibration exposures, and relate them to health outcomes, so that knowledge gaps can be filled and appropriate guidance can be provided. The current study administered a musculoskeletal survey to its skidder operators. However, with such a large number of profiles and such a small sample of operators, no patterns of exposure profile and musculoskeletal health complaint were found.

It was interesting to note that the spectral profiles comprised primarily of DOAL and PUAL trials often demonstrated higher dominance vibration exposure frequencies (>5 Hz with dominant peaks typically between 8Hz and 31.5Hz) for translational axes. Conversely, the DL and DUL driving conditions are often dominated by low frequency acceleration (<5 Hz with dominant peaks typically between 0.8Hz and 2Hz). There were also a number of DOAL and PUAL profiles with some large accelerations at lower frequencies. As the DOAL and PUAL
conditions often have driving elements (particularly when DOAL with a grapple skidder), it is likely that the lower frequency signal is due to that driving component. This also explains why a number of profiles are comprised of the DL, DUL, DOAL and PUAL conditions, as driving conditions with higher frequency accelerations had similar profiles to DOAL and PUAL conditions that included more driving. Rotational accelerations (Roll and Pitch) on the other hand, had much more prevalent accelerations below 5Hz when DOAL and PUAL. The driving conditions, however, had dominant rotational accelerations at higher frequencies (typically between 2.5Hz and 4Hz) in the Roll and Pitch. Rocking motions induced by the grappling and release of logs are likely responsible for the low frequency rotations observed during loading and unloading tasks. The higher frequency rotations while driving are likely induced by the combination of terrain and driving speed. Again there was some overlap between the driving and loading conditions, but in Roll and Pitch, this typically occurred in profiles that had a gradual rise to >4Hz and then a relatively flat plateau at higher frequencies. Yaw accelerations were dominated by higher frequencies (>4Hz) in all conditions. Although some interesting trends were found, it is important to acknowledge that despite the large number of measurements performed, only a small sample size of vehicles were investigated while operating in a few Northern Ontario locations during the summer months. An expanded dataset with more vehicles and operating environments is desired for the future. It is also important to note that the individual 1/3-octave band spectra were grouped together at the discretion of the authors and although the similar profiles were easily established, their grouping was not based on any statistical method. Using a principal component analysis to identify patterns within 6-DOF exposure spectra may help streamline the process in the future, as well as, identify important signal components which were not identified in the current study.

5.5 CONCLUSION

A number of distinct spectral exposure profiles occur during the field operation of forestry skidders. These profiles vary between vehicles and operating tasks. Several 3-DOF translational and rotational spectral profile combinations occurred in more than one skidder; however, the 6-DOF profile combinations were unique to individual skidders. This means that some 3-DOF translational and rotational spectral profile combinations can be generalizable, but
the 6-DOF spectral profile combinations presented here are not. Further 6-DOF spectral analyses adding to the current sample of eight machines and driving environments should be conducted to identify the full range of 6-DOF spectral profiles that occur in the field.

REFERENCES


Schust, M., Bluthner, R. and Seidel, H., 2006. Examination of perceptions (intensity, seat comfort, effort) and reaction times (brake and accelerator) during low-frequency vibration in x- or y-direction and biaxial (xy-) vibration of driver seats with activated and deactivated suspension. *Journal of Sound and Vibration*, 298, 606-626.


CHAPTER 6

BIODYNAMIC TRENDS ATTRIBUTABLE TO FIELD MEASURED 6-DOF FORESTRY SKIDDER VIBRATION EXPOSURES AND TRI-PLANAR TRUNK POSTURES

6.1 INTRODUCTION

With the industrialization of the workforce in the twentieth century, many employees are exposed to mechanical whole-body vibration (WBV). This exposure to WBV has been identified as a possible risk factor for low-back pain and pathological changes to the spine (Bovenzi 1996; El-Khatib et al. 1998; Kitazaki and Griffin 1998; Koda et al. 2000; Pope and Novotny 1993; Thalheimer 1996). In addition, nervous, circulatory, and digestive system problems have been associated with WBV; as well as noise induced hearing loss, disturbances to pregnancies, and disorders of the female reproductive organs (Seidel et al. 1980; Bovenzi 1996; Thalheimer 1996). As a result, vibration exposure guidelines (ANSI S3.18:1979, BS 6841:1987, ISO 2631-1:1997, 2001 ACGIH TLV, EU Directive 2002/44/EC, EN 14253:2003) have been developed to help determine hazardous exposures to WBV. Unfortunately, despite greater awareness and ergonomic improvements, the current literature indicates that vehicle operators are still being injured. This is partly the result of gaps in the literature and subsequent standard limitations.

Currently, field studies monitoring WBV exposures at the operator seat interface (OSI) are limited in their exposure measurements. This includes many epidemiological studies relating those exposures to low-back pain/injury (Boshuizen, Bongers and Hulshof 1990; Boshuizen, Bongers and Hulshof 1992; Bovenzi and Betta 1994; Bovenzi 1996; Schwarze et al. 1998; Bovenzi, Pinto and Stacchini 2002; Palmer et al. 2003; Bovenzi et al. 2006; Okunribido, Magnusson and Pope 2006a; Okunribido, Magnusson and Pope 2006b; Okunribido, Magnusson and Pope 2008; Tiemessen, Hulshof and Frings-Dresen 2008). These studies are often limited to a few degrees-of-freedom (DOF), with minimal spectral data and virtually no rotational data.
available. To date, only a few studies have collected 6-DOF exposures at the OSI (Parsons, Whitham and Griffin 1979; Cation et al. 2008; Jack et al. 2010 - Chapter 4; Chapter 5). Neck pain/injury has also been related to WBV exposure (Village, Morrison and Leong 1989; Axelsson and Ponten 1990; Hagen, Magnus and Vetlesen 1998; Ariens et al. 2001; Hagberg et al. 2006; Jensen et al. 2008), but of the 12 articles located that reported that relationship, 6 conducted the same limited vibration exposure measurements seen in the low-back pain studies mentioned above (Johanning 1991; Magnusson et al. 1996; Rehn et al. 2002; Rehn, Nilsson and Jarvholm 2004; Johanning et al. 2006; Eger et al. 2008). In all cases, the relationship between WBV and neck pain is based on the fact that the operators drive vehicles and therefore are exposed to vibration, as no connections between measured exposures and neck pain/injury are made. As a result, the effects of varying levels and patterns of measured vibration exposures on neck pain are not known. Much of the literature relating low-back pain/injury to WBV exposure also use the fact that operators drive vehicles and not measured vibration exposures to establish that relationship. As a result, guidelines presently used to establish vibration exposure limits do not consider rotational vibrations, and the frequency weightings and exposure thresholds that they do utilize may be inaccurate.

Furthermore, operator postures have also been linked to musculoskeletal complaints in the low-back (Village, Morrison and Leong 1989; Toren 2001; Bovenzi and Betta 1994; Bovenzi, Pinto and Stacchini 2002; Hoy et al. 2005; Bovenzi et al. 2006; Okunribido, Magnusson and Pope 2006a; Okunribido, Magnusson and Pope 2006b; Eger et al. 2008; Jack et al. 2008a – Chapter 3; Okunribido, Magnusson and Pope 2008) and neck (Village, Morrison and Leong 1989; Eger et al. 2008; Jack et al. 2008a – Chapter 3). While there are studies which describe operator postures as they operate their machines (i.e. flexed, extended, bent, twisted), few studies quantified postures (Kittusamy and Buchholz 2001; Rehn et al. 2005; Bovenzi et al. 2006; Eger et al. 2008) and even fewer studies have directly measured operator postures (Eklund et al. 1994; Gellerstedt 1998; Hermanns et al. 2008; Jack et al. 2008a – Chapter 3). Similar limitations also appear in laboratory studies investigating the effects of vibration exposure on a number of human responses (Table 6.1 through Table 6.6). These laboratory studies are often limited to a few DOF, with limited spectral exposures and only a few single plane of motion postures investigated. Moreover, the postures and vibration exposures used in these laboratory studies typically are not based on field data.
Table 6.1: A summary of operator/seat interface vibration exposures and seated trunk postures utilized in laboratory studies investigating discomfort or annoyance.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Input Type</th>
<th>Input Axis</th>
<th>RMS Input Acceleration (m/s² or rad/s²)</th>
<th>Trunk Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matsumoto et al. 2006</td>
<td>Sinusoidal (2.5, 3.15, 4, 5, 6.3, 8Hz)</td>
<td>X, Z, XZ</td>
<td>0.7</td>
<td>Unspecified sitting</td>
</tr>
<tr>
<td>Morioka &amp; Griffin 2006</td>
<td>Sinusoidal Isolated 1/3-Octave Band Vibration (2-315Hz)</td>
<td>X, Y, Z</td>
<td>X: 1.21, 0.99, 1.74, 1.40, 2.47, 2.03</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Schust et al. 2006</td>
<td>Simulated Tractor</td>
<td>X, Y, Z</td>
<td>Y: 0.83, 0.66, 1.20, 0.94, 1.70, 1.31</td>
<td>Driving posture with a backrest (angle not specified)</td>
</tr>
<tr>
<td>Matsumoto &amp; Griffin 2005</td>
<td>Sinusoidal (3.15, 4, 5, 6.3, 8Hz), Shock (3.15, 4, 5, 6.3, 8Hz)</td>
<td>Z</td>
<td>0.5</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Ljungberg et al. 2004</td>
<td>Sinusoidal (16Hz)</td>
<td>Z</td>
<td>1.0, 1.6, 2.5</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Demic et al. 2002</td>
<td>Random Isolated 1/3-Octave Band Vibration (0.63-16Hz)</td>
<td>X, Z, XZ</td>
<td>Equivalent response for 2.5, 4, 8-hour exposures</td>
<td>Driving posture with a backrest at an angle of 0˚ and 14˚</td>
</tr>
<tr>
<td>Jang &amp; Griffin 2000</td>
<td>Sinusoidal (2.5, 3.15, 4, 5, 6.3Hz)</td>
<td>Z</td>
<td>0.25, .04, 0.63, 1.0, 1.6</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Mansfield et al. 2000</td>
<td>White Noise (2-20Hz), Random Shocks, White Noise &amp; Shocks</td>
<td>Z</td>
<td>0.5, 1.0, 1.5</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Jang &amp; Griffin 1999</td>
<td>Sinusoidal (4Hz)</td>
<td>Z</td>
<td>0.25, 0.4, 0.63, 1.0, 1.6</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Wilder et al. 1994</td>
<td>Simulated Truck</td>
<td>Z</td>
<td>Input Spectra Provided</td>
<td>Upright facing forward, Flexed (angle not specified), Facing forward with a backrest (angle not specified)</td>
</tr>
<tr>
<td>Howarth &amp; Griffin 1988</td>
<td>Sinusoidal Isolated 1/2-Octave Band Vibration (4-63Hz)</td>
<td>Y, Z</td>
<td>0.04, 0.06, 0.1, 0.16, 0.25, 0.4</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Kjellberg &amp; Wikstrom 1985</td>
<td>Sinusoidal (6.3, 31.5Hz)</td>
<td>Z</td>
<td>1.1, 2.3</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Griffin &amp; Whitham 1978</td>
<td>Sinusoidal (4, 16Hz)</td>
<td>Z</td>
<td>0.41, 0.55, 0.74, 1.0, 1.35, 1.82, 2.46</td>
<td>Unspecified sitting</td>
</tr>
<tr>
<td>Parsons &amp; Griffin 1978</td>
<td>Sinusoidal (1.6, 2, 4, 8, 16, 31.5Hz)</td>
<td>Rx, Ry</td>
<td>Not Reported</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Whitham &amp; Griffin 1978</td>
<td>Sinusoidal (2, 4, 8, 16, 32, 64Hz)</td>
<td>X, Y, Z</td>
<td>X: 1.0</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Griffin &amp; Whitham 1977</td>
<td>Sinusoidal (3.15Hz)</td>
<td>Y</td>
<td>Y: 0.4, 0.52, 0.7, 1.0, 1.4, 2.1, 2.5</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Griffin &amp; Whitham 1976</td>
<td>Sinusoidal (4,16Hz)</td>
<td>Z</td>
<td>0.75</td>
<td>Upright facing forward</td>
</tr>
</tbody>
</table>

Note: Postures reported are without a back rest unless specified. All angles are relative to the vertical. All trunk postures are relative to the hip unless specified. Input axes are in accordance with ISO 2631-1:1997.
Table 6.2: A summary of operator/seat interface vibration exposures and seated postures utilized in laboratory studies investigating mechanical impedance.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Input Type</th>
<th>Input Axis</th>
<th>RMS Input Acceleration (m/s² or rad/s²)</th>
<th>Trunk Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matsumoto &amp; Griffin 2005</td>
<td>Sinusoidal (3.15, 4, 5, 6.3, 8Hz)</td>
<td>Z</td>
<td>0.5, 1.0, 2.0</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td></td>
<td>Shock (3.15, 4, 5, 6.3, 8Hz)</td>
<td></td>
<td>0.7, 1.4, 2.8 p</td>
<td></td>
</tr>
<tr>
<td>Holmlund &amp; Lundstrom 2001</td>
<td>Sinusoidal Sweep (2-100Hz)</td>
<td>Z</td>
<td>0.5, 0.7, 1.0, 1.4</td>
<td>Upright facing forward while erect and relaxed</td>
</tr>
<tr>
<td></td>
<td>Sinusoidal Sweep (1.13-80Hz)</td>
<td>X, Y</td>
<td>0.25, 0.35, 0.5, 0.7, 1.0, 1.4</td>
<td></td>
</tr>
<tr>
<td>Holmlund et al. 2000</td>
<td>Sinusoidal Sweep (2-100Hz)</td>
<td>Z</td>
<td>0.5, 0.7, 1.0, 1.4</td>
<td>Upright facing forward while erect and relaxed</td>
</tr>
<tr>
<td>Holmlund 1999</td>
<td>Sinusoidal Sweep (1.13-100Hz)</td>
<td>Z</td>
<td>0.5</td>
<td>Upright facing forward while erect and relaxed</td>
</tr>
<tr>
<td></td>
<td>X, Y</td>
<td></td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Boileau &amp; Rakheja 1998</td>
<td>Random (0.625-10Hz), Sinusoidal Sweep (0.625-10Hz), ISO 7096:1982 Class I &amp; II, ISO 5007:1982 ISO 1 &amp; 2</td>
<td>Z</td>
<td>1.0, 1.5, 2.0</td>
<td>Upright facing forward while erect with the low back in contact with backrest, while erect with the whole back in contact with backrest, and while slouched with the low back in contact with backrest</td>
</tr>
<tr>
<td>Holmlund &amp; Lundstrom 1998</td>
<td>Sinusoidal Sweep (1.13-80)</td>
<td>X, Y</td>
<td>0.25, 0.35, 0.5, 0.7, 1.0, 1.4</td>
<td>Upright facing forward while erect and relaxed</td>
</tr>
<tr>
<td>Donati &amp; Bonthoux 1983</td>
<td>Sinusoidal Sweep, Gaussian (1-10Hz)</td>
<td>Z</td>
<td>1.6</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Seidel et al. 1980</td>
<td>Sinusoidal (4,8Hz)</td>
<td>Z</td>
<td>1.0</td>
<td>Unspecified sitting</td>
</tr>
</tbody>
</table>

Note: Sinusoidal Sweep indicates that the subjects were exposed to individual sine waves which were increased in frequency incrementally. This may or may not have occurred within a single exposure trial. Postures reported are without a back rest unless specified. All angles are relative to the vertical. All trunk postures are relative to the hip unless specified. Input axes are in accordance with ISO 2631-1:1997.
Table 6.3: A summary of operator/seat interface vibration exposures and seated postures utilized in laboratory studies investigating apparent mass.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Input Type</th>
<th>Input Axis</th>
<th>RMS Input Acceleration (m/s² or rad/s²)</th>
<th>Trunk Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wang <em>et al.</em> 2008</td>
<td>White Noise (0.5-15Hz)</td>
<td>Z</td>
<td>0.25, 0.5, 1.0</td>
<td>Driving posture, Driving posture with a backrest at an angle of 0° and 24°</td>
</tr>
<tr>
<td>Fleury &amp; Mistrot 2006</td>
<td>Random (0.5-8Hz)</td>
<td>X</td>
<td>1.2</td>
<td>Driving posture, Driving posture with a backrest at an angle of 0° and 10°</td>
</tr>
<tr>
<td>Hinz <em>et al.</em> 2006b</td>
<td>Random (0.3-20Hz)</td>
<td>Z</td>
<td>0.23, 0.26, 0.76, 0.83, 1.37, 1.57</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Huang &amp; Griffin 2006</td>
<td>White Noise (0.5-20Hz)</td>
<td>Z</td>
<td>0.25, 2.0</td>
<td>Upright facing forward while erect and relaxed, Flexed and extended (angles not specified)</td>
</tr>
<tr>
<td>Mansfield <em>et al.</em> 2006</td>
<td>Random (2-20Hz), Mixed Amplitude Random (2-7Hz &amp; 7-20Hz), Mixed Sinusoidal (~10Hz) &amp; Random (2-20Hz)</td>
<td>Z</td>
<td>0.5, 1.0, 1.5</td>
<td>Upright facing forward while erect and relaxed</td>
</tr>
<tr>
<td>Rakheja <em>et al.</em> 2006</td>
<td>White Noise (0.5-40Hz)</td>
<td>Z</td>
<td>0.25, 0.5, 1.0</td>
<td>Driving posture with a backrest at an angle of 24°</td>
</tr>
<tr>
<td>Kim <em>et al.</em> 2005</td>
<td>Random (1-50Hz)</td>
<td>Z</td>
<td>1.0</td>
<td>Upright facing forward while erect and relaxed</td>
</tr>
<tr>
<td>Mansfield &amp; Maeda 2005a</td>
<td>White Noise (1-40Hz), Sinusoidal (1,2,4,8,16,32Hz)</td>
<td>Z</td>
<td>0.1</td>
<td>Unspecified sitting</td>
</tr>
<tr>
<td>Mansfield &amp; Maeda 2005b</td>
<td>White Noise (1-20Hz)</td>
<td>Z</td>
<td>0.4</td>
<td>Upright facing forward, Upright with a trunk twist at an angle of 45°, Facing forward with a backrest at an angle of 0°</td>
</tr>
<tr>
<td>Matsumoto &amp; Griffin 2005</td>
<td>Sinusoidal (3.15, 4, 5, 6.3, 8Hz)</td>
<td>Z</td>
<td>0.5, 1.0, 2.0</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Nawayseh &amp; Griffin 2005</td>
<td>White Noise (0.25-20Hz)</td>
<td>X</td>
<td>0.125, 0.25, 0.625, 1.25</td>
<td>Upright facing forward</td>
</tr>
</tbody>
</table>

*Indicated the input data is reported in the form of a weighted acceleration.

‡Peak value reported.

Calculated from data presented by the authors.

Note: Postures reported are without a backrest unless specified. All angles are relative to the vertical. All trunk postures are relative to the hip unless specified. Input axes are in accordance with ISO 2631-1:1997.
<table>
<thead>
<tr>
<th>Authors</th>
<th>Input Type</th>
<th>Input Axis</th>
<th>RMS Input Acceleration (m/s² or rad/s²)</th>
<th>Trunk Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mansfield &amp; Maeda 2007</td>
<td>White Noise (1-20Hz)</td>
<td>X, Y, Z, XYZ</td>
<td>0.4, 0.8</td>
<td>Upright facing forward, Facing forward with a backrest at an angle of 0°</td>
</tr>
<tr>
<td>Hinz et al. 2006a</td>
<td>White Noise (0.25-30Hz)</td>
<td>X, Y, Z, XY,YZ</td>
<td>~0.25, ~0.9, ~1.8</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Mansfield &amp; Maeda 2006</td>
<td>White Noise (1-20Hz)</td>
<td>X, Y, Z, XY, XYZ, YZ</td>
<td>0.4</td>
<td>Upright facing forward, Facing forward with a backrest at an angle of 0°</td>
</tr>
<tr>
<td>Mandapuram et al. 2005</td>
<td>Random (0.5-10Hz)</td>
<td>X, Y</td>
<td>0.25, 0.5, 1.0</td>
<td>Upright facing forward, Facing forward with a backrest at an angle of 0° and 12.5°</td>
</tr>
<tr>
<td>Nawayseh &amp; Griffin 2004</td>
<td>White Noise (0.25-20Hz)</td>
<td>Z</td>
<td>0.125, 0.25, 0.625, 1.25</td>
<td>Upright facing forward with a backrest at an angle of 0°</td>
</tr>
<tr>
<td>Nawayseh &amp; Griffin 2003</td>
<td>White Noise (0.25-25Hz)</td>
<td>Z</td>
<td>0.125, 0.25, 0.625, 1.25</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Mansfield &amp; Griffin 2002</td>
<td>Gausian (1-20Hz)</td>
<td>Z</td>
<td>0.2, 1.0, 2.0</td>
<td>Upright facing forward, Flexed and extended at an angle of 10°, Slouched, Facing forward with a backrest at an angle of 0°</td>
</tr>
<tr>
<td>Matsumoto &amp; Griffin 2002a</td>
<td>Random (2-20Hz), Sinusoidal (3.15, 4, 5, 6.3, 8Hz)</td>
<td>Z</td>
<td>0.35, 0.5, 0.7, 1.0, 1.4</td>
<td>Upright facing forward while erect and relaxed</td>
</tr>
<tr>
<td>Matsumoto &amp; Griffin 2002b</td>
<td>Gausian (0.5-20Hz)</td>
<td>Z</td>
<td>0.125, 0.25, 0.5, 1.0, 2.0</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Rakheja et al. 2002</td>
<td>White Noise (0.5-40Hz)</td>
<td>Z</td>
<td>0.25, 0.5, 1.0</td>
<td>Driving posture with a backrest at an angle of 24°</td>
</tr>
<tr>
<td>Mansfield et al. 2001</td>
<td>White Noise (2-20Hz), Random Shocks, White Noise&amp; Shocks</td>
<td>Z</td>
<td>0.5, 1.0, 1.5</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Mansfield &amp; Griffin 2000</td>
<td>White Noise (0.2-20Hz)</td>
<td>Z</td>
<td>0.25, 0.5, 1, 1.5, 2.0, 2.5</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Matsumoto &amp; Griffin 2000</td>
<td>Random (0.5-20Hz)</td>
<td>Z</td>
<td>1.0</td>
<td>Upright facing forward</td>
</tr>
</tbody>
</table>

*a* Indicated the input data is reported in the form of a weighted acceleration.

*b* Peak value reported.

*c* Calculated from data presented by the authors.

Note: Postures reported are without a back rest unless specified. All angles are relative to the vertical. All trunk postures are relative to the hip unless specified. Input axes are in accordance with ISO 2631-1:1997.

Table 6.3 Continued: A summary of operator/seat interface vibration exposures and seated postures utilized in laboratory studies investigating apparent mass.
Table 6.3 Continued: A summary of operator/seat interface vibration exposures and seated postures utilized in laboratory studies investigating apparent mass.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Input Type</th>
<th>Input Axis</th>
<th>RMS Input Acceleration (m/s² or rad/s²)</th>
<th>Trunk Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mansfield &amp; Lundstrom 1999</td>
<td>Random (1.5-20Hz)</td>
<td>X, Y, XY</td>
<td>0.1, 0.18, 0.19, 0.23, 0.25, 0.35, 0.38, 0.46, 0.5, 0.71, 0.92, 1.0 c</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Kitazaki and Griffin 1998</td>
<td>White Noise (0.5-35Hz)</td>
<td>Z</td>
<td>1.7</td>
<td>Flexed and extended (angles not specified), Slouched with the thoracic and cervical spine inclined forward 25˚ from the normal position</td>
</tr>
<tr>
<td>Matsumoto &amp; Griffin 1998</td>
<td>White Noise (0.5-20Hz)</td>
<td>Z</td>
<td>1.0</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Fairley &amp; Griffin 1989</td>
<td>White Noise (0.25-20Hz)</td>
<td>Z</td>
<td>0.25, 0.5, 1.0, 2.0</td>
<td>Upright facing forward while erect and relaxed</td>
</tr>
</tbody>
</table>

* Indicated the input data is reported in the form of a weighted acceleration.
* Peak value reported.
* Calculated from data presented by the authors.

Note: Postures reported are without a back rest unless specified. All angles are relative to the vertical. All trunk postures are relative to the hip unless specified. Input axes are in accordance with ISO 2631-1:1997.
Table 6.4: A summary of operator/seat interface vibration exposures and seated postures utilized in laboratory studies investigating muscle activity and fatigue.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Input Type</th>
<th>Input Axis</th>
<th>RMS Input Acceleration (m/s² or rad/s²)</th>
<th>Trunk Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jiao et al. 2004</td>
<td>Sinusoidal (1.8, 6Hz)</td>
<td>Z</td>
<td>0.05g</td>
<td>Driving posture</td>
</tr>
<tr>
<td>Bluthner et al. 2002</td>
<td>Simulated Tracked Hydraulic</td>
<td>Z</td>
<td>0.7, 1.0, 1.4 *</td>
<td>Upright facing forward while erect and relaxed,</td>
</tr>
<tr>
<td></td>
<td>Excavator</td>
<td></td>
<td></td>
<td>Flexed (angle not specified)</td>
</tr>
<tr>
<td>Bluthner et al. 2001</td>
<td>Simulated Tracked Hydraulic</td>
<td>Z</td>
<td>0.7, 1.0, 1.4 *</td>
<td>Upright facing forward while erect,</td>
</tr>
<tr>
<td></td>
<td>Excavator</td>
<td></td>
<td></td>
<td>Driving posture, Flexed (angle not specified)</td>
</tr>
<tr>
<td>Pope et al. 1998</td>
<td>Sinusoidal Isolated Vibration</td>
<td>Z</td>
<td>Not Reported</td>
<td>Slightly lordotic facing forward,</td>
</tr>
<tr>
<td>(3-10Hz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zimmerman and Cook 1997</td>
<td>Sinusoidal (4.5, 5, 6, 8, 10, 12, 16Hz)</td>
<td>Z</td>
<td>1.0</td>
<td>Upright facing forward, Upright facing forward</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>with an anterior and posterior pelvic tilt at an</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>angle of 10°</td>
</tr>
<tr>
<td>Wilder et al. 1994</td>
<td>Simulated Truck</td>
<td>Z</td>
<td>Input Spectra Provided</td>
<td>Upright facing forward, Flexed (angle not specified), Facing forward with a backrest (angle not specified)</td>
</tr>
<tr>
<td>Bluthner et al. 1993</td>
<td>Sinusoidal Shocks (Symmetrical &amp; Asymmetrical)</td>
<td>Z</td>
<td>2.7 †</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Zimmerman et al. 1993</td>
<td>Sinusoidal (4.5Hz)</td>
<td>Z</td>
<td>6.21</td>
<td>Upright facing forward, Flexed at an angle of 30° at the T4 spinal level, Extended at an angle of 10°</td>
</tr>
<tr>
<td>Dupis et al. 1991</td>
<td>Simulated Earth-moving Machine (With &amp; Without Shocks)</td>
<td>Z</td>
<td>1.25</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Hansson et al 1991</td>
<td>Sinusoidal (5Hz)</td>
<td>Z</td>
<td>0.2g</td>
<td>Flexed at an angle of 20°</td>
</tr>
<tr>
<td>Seroussi et al 1989</td>
<td>Sinusoidal Sweep (3-10Hz)</td>
<td>Z</td>
<td>0.1g</td>
<td>Flexed at an angle of 10-16° with a slight lordosis</td>
</tr>
</tbody>
</table>

*Indicated the input data is reported in the form of a weighted acceleration.
† Peak value reported.

Note: Sinusoidal Sweep indicates that the subjects were exposed to individual sine waves which were increased in frequency incrementally. This may or may not have occurred within a single exposure trial. Postures reported are without a back rest unless specified. All angles are relative to the vertical. All trunk postures are relative to the hip unless specified. Input axes are in accordance with ISO 2631-1:1997. If a g is beside the input acceleration value that indicates that the acceleration is actually in the unit g.
Table 6.4 Continued: A summary of operator/seat interface vibration exposures and seated postures utilized in laboratory studies investigating muscle activity and fatigue.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Input Type</th>
<th>Input Axis</th>
<th>RMS Input Acceleration (m/s² or rad/s²)</th>
<th>Trunk Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilder et al. 1982</td>
<td>Sinusoidal Sweep(1-16Hz)</td>
<td>Z</td>
<td>Not Reported</td>
<td>Upright facing forward while relaxed and performing a Valsalva maneuver, Flexed and extended at an angle of 5°, Laterally bent at an angle of 5°, Maximally twisted</td>
</tr>
<tr>
<td>Seidel et al. 1980</td>
<td>Sinusoidal (4.8Hz)</td>
<td>Z</td>
<td>1.0</td>
<td>Unspecified sitting</td>
</tr>
</tbody>
</table>

* Indicated the input data is reported in the form of a weighted acceleration.

p Peak value reported.

Note: Sinusoidal Sweep indicates that the subjects were exposed to individual sine waves which were increased in frequency incrementally. This may or may not have occurred within a single exposure trial. Postures reported are without a back rest unless specified. All angles are relative to the vertical. All trunk postures are relative to the hip unless specified. Input axes are in accordance with ISO 2631-1:1997. If a g is beside the input acceleration value that indicates that the acceleration is actually in the unit g.
Table 6.5: A summary of operator/seat interface vibration exposures and seated postures utilized in laboratory studies investigating absorbed power.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Input Type</th>
<th>Input Axis</th>
<th>RMS Input Acceleration (m/s$^2$ or rad/s$^2$)</th>
<th>Trunk Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wang <em>et al.</em> 2006</td>
<td>White Noise (0.5-40Hz)</td>
<td>Z</td>
<td>0.5, 1.0</td>
<td>Upright facing forward, Facing forward with a backrest at an angle of 0$^\circ$ and 12$^\circ$</td>
</tr>
<tr>
<td>Mansfield <em>et al.</em> 2001</td>
<td>White Noise (2-20Hz), Random Shocks, White Noise &amp; Shocks</td>
<td>Z</td>
<td>0.5, 1.0, 1.5</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Mansfield <em>et al.</em> 2000</td>
<td>White Noise (2-20Hz), Random Shocks, White Noise &amp; Shocks</td>
<td>Z</td>
<td>0.5, 1.0, 1.5</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Holmlund 1999</td>
<td>Sinusoidal Sweep (1.13-100Hz)</td>
<td>Z</td>
<td>0.5</td>
<td>Upright facing forward while erect and relaxed</td>
</tr>
<tr>
<td></td>
<td>X, Y</td>
<td></td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Lundstrom <em>et al.</em> 1998</td>
<td>Sinusoidal Sweep(2-100Hz)</td>
<td>Z</td>
<td>0.5, 0.7, 1.0, 1.4</td>
<td>Upright facing forward while erect and relaxed</td>
</tr>
<tr>
<td>Lundstrom &amp; Holmlund 1998</td>
<td>Sinusoidal Sweep(2-80Hz)</td>
<td>Z</td>
<td>0.5, 0.7, 1.0, 1.4</td>
<td>Upright facing forward while erect and relaxed</td>
</tr>
<tr>
<td></td>
<td>Sinusoidal Sweep(1.13-80Hz)</td>
<td>X, Y</td>
<td>0.25, 0.35, 0.5, 0.7, 1.0, 1.4</td>
<td></td>
</tr>
<tr>
<td>Mansfield &amp; Griffin 1998</td>
<td>Gaussian (0.2-20Hz)</td>
<td>Z</td>
<td>0.25, 0.5, 1.0, 1.5, 2.0, 2.5</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Donati &amp; Bonthoux 1983</td>
<td>Sinusoidal Sweep, Gaussian (1-10Hz)</td>
<td>Z</td>
<td>1.6</td>
<td>Upright facing forward</td>
</tr>
</tbody>
</table>

Note: Sinusoidal Sweep indicates that the subjects were exposed to individual sine waves which were increased in frequency incrementally. This may or may not have occurred within a single exposure trial. Postures reported are without a back rest unless specified. All angles are relative to the vertical. All trunk postures are relative to the hip unless specified. Input axes are in accordance with ISO 2631-1:1997.
Table 6.6: A summary of operator/seat interface vibration exposures and seated postures utilized in laboratory studies investigating transmissibility.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Input Type</th>
<th>Input Axis</th>
<th>RMS Input Acceleration (m/s² or rad/s²)</th>
<th>Trunk Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jack &amp; Eger 2008</td>
<td>Simulated Field Exposure</td>
<td>XYZ</td>
<td>Input Spectra Provided</td>
<td>Upright facing forward, Flexed and extended at an angle of 10° and 15°</td>
</tr>
<tr>
<td>Wang et al. 2008</td>
<td>White Noise (0.5-15Hz)</td>
<td>Z</td>
<td>0.25, 0.5, 1.0</td>
<td>Driving posture, Driving posture with a backrest at an angle of 0° and 24°</td>
</tr>
<tr>
<td>Matsumoto et al. 2006</td>
<td>Sinusoidal (2.5, 3.15, 4, 5, 6.3, 8Hz)</td>
<td>X, Z, XZ</td>
<td>0.7</td>
<td>Unspecified sitting</td>
</tr>
<tr>
<td>Kim et al. 2005</td>
<td>Random (1-50Hz)</td>
<td>Z</td>
<td>1.0</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Demic et al. 2002</td>
<td>Random (0.5-40Hz)</td>
<td>X, Z, XZ</td>
<td>0.55, 1.75, 2.25</td>
<td>Driving posture with a backrest at an angle of 0° and 14°</td>
</tr>
<tr>
<td>Mansfield &amp; Griffin 2002</td>
<td>Gaussian (1-20Hz)</td>
<td>Z</td>
<td>0.2, 1.0, 2.0</td>
<td>Upright facing forward, Flexed and extended at an angle of 10°, Slouched, Facing forward with a backrest at an angle of 0°</td>
</tr>
<tr>
<td>Matsumoto &amp; Griffin 2002b</td>
<td>Gaussian (0.5-20Hz)</td>
<td>Z</td>
<td>0.125, 0.25, 0.5, 1.0, 2.0</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Hinz et al. 2001</td>
<td>Random Low Frequency Dominant (0.8-20Hz)</td>
<td>Z</td>
<td>0.7, 1.0, 1.4 w</td>
<td>Upright facing forward, Upright facing forward with tense back muscles, Flexed with tense back muscles</td>
</tr>
<tr>
<td>Mansfield &amp; Griffin 2000</td>
<td>White Noise (0.2-20Hz)</td>
<td>Z</td>
<td>0.25, 0.5, 1.0, 1.5, 2.0, 2.5</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Matsumoto &amp; Griffin 2000</td>
<td>Random (0.5-20Hz)</td>
<td>Z</td>
<td>1.0</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Paddan &amp; Griffin 2000</td>
<td>White Noise (0-5Hz)</td>
<td>Rz</td>
<td>1.0</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>El-Khatib et al. 1998 c</td>
<td>White Noise (0.8-25Hz)</td>
<td>Z</td>
<td>1.5</td>
<td>Upright facing forward with and without lumbar support, Facing forward with a backrest at an angle of 25° with and without lumbar support</td>
</tr>
</tbody>
</table>

w Indicated the input data is reported in the form of a weighted acceleration.

Note: Sinusoidal Sweep indicates that the subjects were exposed to individual sine waves which were increased in frequency incrementally. This may or may not have occurred within a single exposure trial. Postures reported are without a backrest unless specified. All angles are relative to the vertical. All trunk postures are relative to the hip unless specified. Input axes are in accordance with ISO 2631-1:1997.
Table 6.6 Continued: A summary of operator/seat interface vibration exposures and seated postures utilized in laboratory studies investigating transmissibility.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Input Type</th>
<th>Input Axis</th>
<th>RMS Input Acceleration (m/s² or rad/s²)</th>
<th>Trunk Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitazaki and Griffin 1998</td>
<td>White Noise (0.5-35Hz)</td>
<td>Z</td>
<td>1.7</td>
<td>Flexed and extended (angles not specified), Slouched with the thoracic and cervical spine inclined forward 25˚ from the normal position</td>
</tr>
<tr>
<td>Matsumoto &amp; Griffin 1998</td>
<td>White Noise (0.5-20Hz)</td>
<td>Z</td>
<td>1.0</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Pope et al. 1998</td>
<td>Impulse (0-31Hz)</td>
<td>Z</td>
<td>Not Reported</td>
<td>Upright facing forward while erect, relaxed, and performing a Valsalva maneuver</td>
</tr>
<tr>
<td>Zimmerman and Cook 1997</td>
<td>Sinusoidal (4.5, 5, 6, 8, 10, 12, 16Hz)</td>
<td>Z</td>
<td>1.0</td>
<td>Upright facing forward, Upright facing forward with an anterior and posterior pelvic tilt at an angle of 10˚</td>
</tr>
<tr>
<td>Paddan &amp; Griffin 1994</td>
<td>Random (0-5Hz)</td>
<td>Rx, Ry</td>
<td>1.0</td>
<td>Upright facing forward, Facing forward with a backrest at an angle of 6˚</td>
</tr>
<tr>
<td>Wilder et al. 1994</td>
<td>Simulated Truck</td>
<td>Z</td>
<td>Input Spectra Provided</td>
<td>Upright facing forward, Flexed (angle not specified), Facing forward with a backrest (angle not specified)</td>
</tr>
<tr>
<td>Dupis et al. 1991</td>
<td>Simulated Earth-moving Machine (With &amp; Without Shocks)</td>
<td>Z</td>
<td>1.25</td>
<td>Upright facing forward</td>
</tr>
<tr>
<td>Pope et al. 1990</td>
<td>Impulse (0-32Hz)</td>
<td>Z</td>
<td>Not Reported</td>
<td>Upright facing forward while erect, relaxed, and performing a Valsalva maneuver</td>
</tr>
<tr>
<td>Pope et al. 1989</td>
<td>Impulse (0-30Hz)</td>
<td>Z</td>
<td>Not Reported</td>
<td>Upright facing forward while erect, relaxed, and performing a Valsalva maneuver</td>
</tr>
<tr>
<td>Paddan &amp; Griffin 1988a</td>
<td>Gaussian (0.2-31.5Hz)</td>
<td>Z</td>
<td>1.75</td>
<td>Upright facing forward, Facing forward with a backrest at an angle of 13˚</td>
</tr>
</tbody>
</table>

* Indicates the input data is reported in the form of a weighted acceleration.

Cadaver study

Note: Sinusoidal Sweep indicates that the subjects were exposed to individual sine waves which were increased in frequency incrementally. This may or may not have occurred within a single exposure trial. Postures reported are without a back rest unless specified. All angles are relative to the vertical. All trunk postures are relative to the hip unless specified. Input axes are in accordance with ISO 2631-1:1997.
Table 6.6 Continued: A summary of operator/seat interface vibration exposures and seated postures utilized in laboratory studies investigating transmissibility.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Input Type</th>
<th>Input Axis</th>
<th>RMS Input Acceleration (m/s² or rad/s²)</th>
<th>Trunk Posture</th>
</tr>
</thead>
</table>
| Paddan & Griffin 1988b| Gaussian (0.2-16Hz)                             | X, Y       | 1.75                                   | Upright facing forward,  
Facing forward with a backrest (angle not specified) |
| Donati & Bonthoux 1983 | Sinusoidal Sweep,  
Gaussian (1-10Hz)                           | Z          | 1.6                                    | Upright facing forward |
| Wilder et al. 1982     | Sinusoidal Sweep(1-16Hz)                        | Z          | Not Reported                           | Upright facing forward while relaxed  
and performing a Valsalva maneuver,  
Flexed and extended at an angle of 5°,  
Laterally bent at an angle of 5°,  
Maximally twisted |
| Seidel et al. 1980     | Sinusoidal (4,8Hz)                              | Z          | 1.0                                    | Unspecified sitting |
| Griffin & Whitham 1978 | Sinusoidal (4, 16Hz)                            | Z          | 0.41, 0.55, 0.74, 1.0, 1.35, 1.82,  
2.46                                   | Unspecified sitting |
| Barnes & Rance 1974    | Sinusoidal (16 unspecified  
frequencies between 0.5-20Hz)            | Rz         | 7.07                                   | Upright facing forward while erect |

w: Indicated the input data is reported in the form of a weighted acceleration.  
c: Cadaver study  
Note: Sinusoidal Sweep indicates that the subjects were exposed to individual sine waves which were increased in frequency incrementally. This may or may not have occurred within a single exposure trial. Postures reported are without a back rest unless specified. All angles are relative to the vertical. All trunk postures are relative to the hip unless specified. Input axes are in accordance with ISO 2631-1:1997.
Although limited, the literature has demonstrated that the magnitude, direction (axis), frequency, and duration of exposure to vibration along with the posture of the operator will influence the effects of vibration. How the interaction of these variables influences the human response to vibration in the field is still not clearly understood. This has led to vibration exposure guidelines which mention postural hazards but have no postural provisions. Our field investigation (Jack et al. 2008a – Chapter 3; Jack et al. 2010 – Chapter 4) has revealed that forestry skidder operators who reported low-back and neck pain were not exposed to the greatest exposure accelerations, but did adopt the greatest lateral bending and forward flexion postures for the greatest percentage of time. As well, these extreme postures were typically observed under operating conditions producing higher frequency vibration exposures (Chapter 5). The combination of more extreme trunk postures and higher frequency vibration accelerations has the potential to increase the transmission of vibration through the body (Jack and Oliver 2008 – Chapter 2). Conditions that increase the stiffness or rigidity of a structure will increase the transmission of vibration through that structure as well as increase its natural frequency (Piersol and Paez 2010). In the case of the human body, increased rigidity can be the result of axial trunk rotation, trunk flexion/extension, lateral bending of the trunk, and/or increased muscle activation. Spinal tissues become stiffer the more they are deformed (Adams 1995), leading to greater passive tissue resistance and muscle activity to sustain these bent and/or twisted postures (Bottoms and Barber 1978; Boden and Oberg 1998; Chaffin et al. 1999; Bluthner, Seidel and Hinz 2001; Toren 2001). The increased muscle force and joint compression associated with more extreme postures (bending or twisting) also act to increase the stiffness of the trunk (Cholewicki and McGill 1996; McGill and Cholewicki 2001). Vibration exposure has also been found to increase muscle activity (Seidel et al. 1980; Wilder et al. 1982; Damkot et al. 1984; Seroussi et al. 1989; Village, Morrison and Leong 1989; Pope, Wilder and Magnusson 1998). Furthermore, the spine becomes stiffer when exposed to greater load magnitudes (Cholewicki and McGill 1996; Panjabi 2003) and with increased loading frequencies (Simunic et al. 2001). Therefore, the way a person sits in a seat, and the characteristics of the WBV exposure they are subjected to, can affect the transmission of vibration through their body because of the influence those factors have on the stiffness of the spine (Wilson and Corlett 1990; Michida et al. 2001).

The increased transmission of vibration through the body may in part be responsible for the greater risk of operator low-back and/or neck pain associated with non-neutral operator
postures (Village, Morrison and Leong 1989; Bovenzi and Betta 1994; Magnusson and Pope 1998; Toren 2001; Bovenzi, Pinto and Stacchini 2002; Kittusamy and Buchholz 2004; Hoy et al. 2005; Bovenzi et al. 2006; Okunribido, Magnusson and Pope 2006a; Okunribido, Magnusson and Pope 2006b; Eger et al. 2008; Jack et al. 2008a – Chapter 3; Okunribido, Magnusson and Pope 2008) or greater exposure accelerations (Bovenzi and Betta 1994; Wilkstrom, Kjellberg and Landstrom 1994; Bovenzi 1996; Schwarze et al. 1998; Bovenzi, Pinto and Stacchini 2002; Bovenzi et al. 2006; Burdorf and Hulshof 2006). Both of these conditions increase the risk of injury as well as increase the stiffness of the spine. Moreover, a consolidation of findings from several studies in Table 6.6 revealed a general trend of higher compressive spinal loading, decreased lumbar lordosis (a flattening of the lower back curvature), increased muscle activity, and increased stiffness/stability conditions resulting in transmission peaks at higher frequencies and greater vibration transmission (Seidel et al. 1980; Wilder et al. 1982; Pope, Broman and Hansson 1990; Wilder et al. 1994; Zimmerman and Cook 1997; El-Khatib et al. 1998; Pope, Wilder and Magnusson 1998; Hinz et al. 2001; Jack and Eger 2008). Therefore, it appears that spine stiffness and vibration transmission may be mediating factors for WBV injuries, but investigations into this relationship have yet to be conducted. The goal of the present study is to address many of the literature gaps mentioned above by using field measured 6-DOF vibration exposures and tri-planar trunk postures as inputs in a comprehensive investigation of the biodynamic response of the seated operator.

6.2 METHODS

6.2.1 Subjects

Nine young healthy (non-sedentary) males with no occupational exposure to vibration, and rare recreational exposure to vibration (this is to minimize any improved physiological tolerances to vibration with exposure - Bovenzi and Betta 1994) volunteered for the study. The average height, mass, and age the subjects were 1.76±4.1m, 69.8±7.0kg, and 23.1±2.4 years respectively. Individuals who were currently suffering from or frequently suffered from back and/or neck pain, had a documented spinal disorder, or had more than 5 years of occupational exposure to vibration were excluded from the study. Furthermore, with the exception of Subject
3 who walked for an hour and Subject 6 who biked 20km prior to testing, no subject performed any exercise or physical labour prior to testing.

6.2.2 Electromyographic data collection and processing

Seven pairs of electrodes were placed bilaterally on the subject’s rectus abdominus (3cm lateral to the umbilicus), external oblique (approximately 15cm lateral to the umbilicus and sloping 45° downward from the superior lateral electrode to the inferior medial electrode), internal oblique (approximately midway between the anterior superior iliac spine and symphysis pubis, above inguinal ligament and sloping 20° upward from the inferior lateral electrode to the superior medial electrode), latissimus dorsi (lateral to T9 over the belly and sloping 55° downward from the superior lateral electrode to the inferior medial electrode), thoracic erector spinae (5cm lateral to T9 spinous process), lumbar erector spinae (3cm lateral to L3 spinous process), and multifidus (2cm lateral to L4-5 spinous processes) in accordance with McGill and Norman (1986), Cholewicki and McGill (1996) and Brown and Potvin (2005). Refer to Figure 6.1 for a depiction of the electrode placements. Prior to affixing the electromyography (EMG) electrodes, each subject’s skin was shaved, lightly abraded with sand paper, and then cleaned with rubbing alcohol.

The rectus abdominus, external oblique, and internal oblique EMG signals were collected with a Noraxon™ Telemyo telemetered EMG unit (10-500Hz bandwidth, 2000 fixed gain, >10MΩ input impedance, CMRR = >85 db) and Ag/AgCl electrodes (center-to-center distance of 2.5cm). The thoracic erector spinae, lumbar erector spinae, multifidus, and latissimus dorsi muscle activity was recorded with a Delsys™ Bagnoli EMG unit (20-450Hz bandwidth, 1000 selected gain, >1015Ω / 0.2pF input impedance, CMRR = >84 db) and DE-2.1 electrodes (fixed center-to-center distance of 1cm). All EMG data were collected with a sampling rate of 1000Hz using a VICON™ 460 data station.

All raw EMG signals were Butterworth band-pass filtered with lower and upper cut-off frequencies of 31.5Hz and 450Hz. This frequency range was selected because the WBV inputs were all below 31.5Hz, and the Bagnoli EMG unit has an internal band-pass filter with an upper cut-off frequency of 450Hz. Filtered EMG signals were then rectified and low-pass filtered at 6Hz to create a linear envelope in accordance with Cholewicki and McGill (1996). Cholewicki
Figure 6.1: Electromyographic (EMG) electrode placement locations. Note: each pair of solid black dots in a) represent the Delsys™ DE-2.1 and Noraxon™ Telemyo Ag/AgCl EMG electrode pairs seen in b) and c). The reference electrodes were placed over the medial tibial malleoli.
and McGill (1996) selected 6Hz as a low-pass cut-off frequency because it reflected muscle activation dynamics (i.e., calcium release and diffusion processes with a time constant of about 25ms). The linear envelope data were then averaged across the entire duration of the data time history to produce an average EMG value (AEMG).

A series of maximal voluntary reference contractions (MVCs) were conducted prior to testing using methods outlined in Brown and Potvin (2005) (refer to Table 6.7). Three 5-second duration attempts at a maximal contraction were conducted with a 2 minute break between each attempt. For each subject and muscle, the MVC trial with the greatest AEMG voltage produced was used as the reference contraction and that AEMG level was used for the normalization of all subsequent EMG data collected for that same subject and muscle (in accordance with Deluca 1997).

### Table 6.7: Maximal voluntary reference contraction descriptions.

<table>
<thead>
<tr>
<th>Muscles</th>
<th>Contraction Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumbar erector spinae</td>
<td>Isometric back extensions against resistance while lying prone with their hips and legs secured</td>
</tr>
<tr>
<td>Thoracic erector spinae</td>
<td></td>
</tr>
<tr>
<td>Multifidus</td>
<td></td>
</tr>
<tr>
<td>Rectus abdominus</td>
<td>Isometric trunk curls to the left, right, and directly anterior to the body against resistance while subjects sit with their feet flat, knees up, and their ankles secured</td>
</tr>
<tr>
<td>External oblique</td>
<td></td>
</tr>
<tr>
<td>Internal oblique</td>
<td></td>
</tr>
<tr>
<td>Latissimus dorsi</td>
<td>Subjects simultaneously pull inferiorly and posteriorly against resistance with their shoulder abducted 90° and the elbow flexed 90° as they stand</td>
</tr>
</tbody>
</table>

#### 6.2.3 Vibration data collection and processing

Marker triads (Figures 6.2 and 6.3) were placed on a rigid seat (Kistler™ 9281B force plate); on the skin over the T9 and C7 spinous processes; and the head (Occipital Crest). A
VICONTM 460 motion capture system (with six M²mcam cameras) recorded the 6-degree-of-freedom (DOF) basicentric motion of each marker triad with a sampling rate of 250Hz. The basicentric orientation used is described in ISO 2631-1:1997. Raw marker coordinate data were 4th order zero lag low-pass Butterworth filtered at 12.5Hz for linear data and 6.3Hz for rotational data. This cut-off frequency is 1/3 of an octave above the greatest translational and rotational
frequencies of interest (i.e., 10Hz and 5Hz respectively, in accordance with ISO 2631-1:1997). These cut-off frequencies were chosen as the upper frequency limit based on the findings of Jack, Oliver and Hayward (Appendix C) and some preliminary investigations that indicated that above this frequency the camera/marker set-up used could no longer measure the motion of the marker triads given the magnitude of the input accelerations used in this study.

The filtered marker coordinates were then used to calculate linear and rotational displacements at the seat, T9, C7 and the head. Rotational displacements were determined using matrix rotation calculations outlined in Hamill and Selbie (2004). Linear and rotational velocities and accelerations at the seat, T9, C7 and the head were also determined through single and double differentiation of the aforementioned displacement time histories with a 4-point equation (Burden and Faires 1989).

### 6.2.4 Kinetic data collection and processing

Raw voltages from a Kistler™ 9281B force plate were recorded with a sampling rate of 1000Hz by a VICON™ 460 data station during each test trial. These voltages were 4th order zero lag low-pass Butterworth filtered at 12.5Hz and then converted to reaction forces and moments using the manufacturer’s specifications. The plate was rigidly fixed to a 6-DOF PRSCO™ robot platform with an aluminum seat frame (Figure 6.4). Subjects sat directly on the force plate (with

![Figure 6.4: Kistler force plate and test seat set-up.](image)
the ischial tuberosities centered over the force plate origin) which provided a sitting height of 44.15cm relative to the robot platform for all subjects.

6.2.5 Vibration exposures

Subjects sat directly on a Kistler™ force plate rigidly fixed to a Parallel Robotic Systems Corporation (PRSCO) 6-DOF robotic platform which exposed the subjects to 6-DOF vibration. The 6-DOF vibration the robot produced conformed to the basicentric orientation described in ISO 2631-1:1997. The subjects were randomly exposed to three different 6-DOF vibration exposure profiles. The selected exposure profiles included a random broad-band spectrum and two unique spectral profiles found in the Northern Ontario forestry industry by Jack et al. (Chapter 5). The specific 6-DOF field profiles were selected because each individual axis spectral profile occurred in more than one skidder and differed between each axis of the two profiles. Furthermore, each 6-DOF profile occurred in the field. These criteria were applied in order to obtain 6-DOF exposures that would be representative of several skidders while allowing the use of unique profiles that were recorded during field operation. The aforementioned resulted in profile EGDADE and HFEBAC being selected from Jack et al. (Chapter 5). It is also worth noting that these two profiles occurred while driving a skidder (EGDADE) and while picking-up a load (HFEBAC), two very distinct job tasks.

The translational and rotational vibration exposure profiles which the subjects were exposed to were created by taking field acceleration time histories and deconstructing that data into 1/3-octave band time histories. A gain was applied to each individual 1/3-octave band such that the reconstructed profile of each exposure axis matched the desired spectral profile. To ensure that the PRSCO 6-DOF robot could reproduce the desired profiles, the low frequency displacements (i.e., accelerations after double differentiation) from each profile had to be reduced such that they did not exceed the physical limitations of the 6-DOF robot. Care was taken to ensure that these reductions had a minimal effect on the frequency pattern of each profile. Once the desired spectral profiles were obtained, an increasing or decreasing gain was applied to that profile in order to achieve the desired running RMS average acceleration exposure level for each exposure axis. A similar procedure was used in Jack et al. (2008b – Appendix B). This provided 6-DOF input accelerations with the exact 1/3-octave band spectra and overall
acceleration levels desired. The final acceleration time histories created were then double integrated to obtain displacement time histories required for the operation of the position feedback controlled robot.

For each of the three WBV exposure profiles, subjects were exposed to two acceleration levels found to occur during the operation of forestry skidders in Northern Ontario. The acceleration levels chosen represented a 20% reduction in the mean of the unweighted running RMS average acceleration while driving a skidder loaded (DL) and unloaded (DUL) as reported by Jack et al. (2010 – Chapter 4), and a 20% reduction in the mean unweighted running RMS average acceleration while picking-up (PUAL) and dropping-off (DOAL) a load. These mean acceleration reductions were also performed to ensure that the physical limitations of the 6-DOF robot were not exceeded and that all of the exposure profiles could be reproduced. The WBV accelerations utilized can be found in Table 6.8. Note that the energy-equivalent WBV exposure for the duration of subject testing was below the ISO 2631-1:1997 health caution zone minimizing the subject’s risk for injury. Also note that the reduced values are within one standard deviation from the original exposure means selected and that the low PUAL and DOAL average acceleration levels chosen were greater than one standard deviation away from the average accelerations while driving. The final testing profile spectra can be seen in Figure 6.5 through Figure 6.7.

| Table 6.8: Unweighted running RMS average acceleration WBV exposure levels that subjects were exposed to. |
|-------------------------------------------------|-----------------|-----------------|
| Axis                            | Running RMS average acceleration level | Low | High |
| X                               | 0.52            | 0.73            |
| Y                               | 0.61            | 0.96            |
| Z                               | 0.47            | 0.77            |
| Roll                            | 1.11            | 1.28            |
| Pitch                           | 1.04            | 1.20            |
| Yaw                             | 0.64            | 0.84            |
| Running RMS Average VTV         | Weighted for Health (Translational Axes Only) | 0.72 | 1.34 |
| Running RMS Average VTV         | Weighted for Comfort (6-DOF)             | 0.60 | 1.08 |

Note: running RMS data are unweighted and in m/s² for the translational axes, and rad/s² for the rotational axes. The VTV data is in m/s³ and was weighted in accordance with ISO 2631-1:1997.
6.2.6 Postural exposures

Subjects adopted combinations of axial trunk twisting (TWST; 0° or 15° to the right), lateral trunk bending (LTB; 0° or 15° to the right), and trunk flexion/extension (FLEX/EXT, 0° or 15° of flexion or extension). Note that the TWST, LTB, and FLEX/EXT postures adopted in this study corresponded to a neutral posture and a commonly adopted deviation from that neutral posture determined by Jack et al. (2008a – Chapter 3). The 15° TWST represents a common posture adopted by forestry skidder operators while DL, DUL, DOAL, PUAL, and Ploughing. With respect to LTB, a 15° angle was again selected. Jack et al. (2008a – Chapter 3) found that skidder operators spent large percentages of time adopting a deep supported LTB to one side. This posture was not acceptable for the present study because unsupported postures were desired. The LTB posture selected was, however, common in operators who did not adopt the supported laterally bent posture while they DL, DUL, DOAL PUAL and Ploughed. Similar to LTB, trunk EXT was typically performed with the trunk supported against a back rest. Therefore, the trunk EXT angle was a mirror of the 15° flexion angle. This flexion angle selected represented a common but end range posture seen in the field. Furthermore, all of the posture combinations were maintained with the trunk muscle activity level required by the subject to adopt that test posture (i.e. the normal muscle activity condition) and a voluntary increase in their trunk muscle activity (i.e. the voluntary muscle contraction condition). Specifically, the subjects were instructed to “Noticeably increase your trunk muscle contractions, without holding your breath or excessively straining yourself”. The voluntary trunk muscle contractions associate with this task would result in a stiffer trunk, ensuring a stiff trunk dataset for statistical analysis. The voluntary increase in trunk muscle activity was only performed during the random WBV profile exposures in order to maintain a reasonable duration for the laboratory testing session.

Figure 6.5: Low and high exposure acceleration level spectra for the random noise vibration inputs.
All of the postures were adopted with the aid of an LED laser and a series of laser targets. Refer to Figure 6.8 for a depiction of the LED laser and targets. The LED laser was mounted over the mid-sternum, mid-way between the xyphoid process and the suprasternal notch of each subject. During each data collection trial, subjects were instructed to shine the laser beam over a

Figure 6.6: Low and high exposure acceleration level spectra for the EGDADFE vibration inputs based on the mean 1/3-octave band spectra selected from Jack et al. (Chapter 5) (solid line).
target. Each target was positioned such that each subject would adopt a specific trunk posture combination when the LED laser was shone on it. To ensure that the subjects adopted the same posture, the targets were positioned using each subject’s own anthropometrics and a target placement aid. The target placement aid was designed to mimic the trunk FLEX/EXT and LTB

Figure 6.7: Low and high exposure acceleration level spectra for the HFEBAC vibration inputs based on the mean 1/3-octave band spectra selected from Jack et al. (Chapter 5)(solid line).
angles that one would measure with a hip mounted goniometer as well as the TWST that one would measure with a torsionmeter mounted over the lumbar spine. The mimicking of a goniometer/torsionmeter was done so that the positioning of the targets was in line with how the selected postures were determined in the field. Each subject’s seat-to-greater trochanter sitting height was used to adjust the location of the rigid model’s axis point relative to the subject/seat interface. The subject’s seat-to-mid-sternum sitting height was used to mount the LED laser at the same distance from that axis point as it would be if mounted on the subject. The rigid model was then twisted, flexed or extended, and laterally bent (in that order) into the desired posture. Once in this desired posture a laser target was placed where the laser shone on wall with which the subjects were facing during testing. This process was repeated for each posture combination. With the laser mounted on the subject’s mid-sternum, they twisted, flexed or extended, and laterally bent until the laser fell on the strategically placed laser target, thereby placing the subject in the desired posture. In addition, subjects held these postures with their feet on the robot platform; their arms relaxed at their sides with their hands held over (but not contacting) the thighs; and their trunk unsupported.

Figure 6.8: a) LED laser mounting over the mid-sternum. b) LED laser targets for postural control.
6.2.7 Experimental test protocol

Subjects were exposed to each randomly selected combination of vibration spectral profile, running RMS average exposure level, adopted posture and muscle activity for 10-seconds, followed by a 3-second break between exposures. After every three exposures, a 60 second rest break was provided, and a 120 second break was provided after every 9 exposures until all test combinations had been completed. The numerous breaks were provided to minimize subject fatigue and discomfort, and trial randomization helped control for the effects of spinal creep and physical activity. Camera, force plate, and EMG data were simultaneously collected during each test trial.

6.2.8 Biodynamic analyses

A 1/3-octave band-pass filter was applied to all acceleration data and running RMS acceleration values (Equation 1) for each 1/3-octave band ranging from 0.5Hz to 10Hz were determined for all three basicentric translational axes in accordance with ISO 2631-1:1997. Running RMS acceleration values for each 1/3-octave band ranging from 0.5Hz to 5Hz were determined for all three basicentric rotational axes. The overall running RMS average acceleration was then calculated for each basicentric axis in accordance with ISO 2631-1:1997 (Equation 2). The transmissibility of vibration for all 6-DOF was then obtained by dividing the

$$ rRMS_i = \left[ \frac{1}{\tau} \int_{t_0}^{t} a_i(t)^2 \, dt \right]^{\frac{1}{2}} \quad (1) $$

Where $rRMS_i$ is the running RMS average acceleration for the $i^{th}$ 1/3-octave band, $a_i(t)$ is the instantaneous acceleration for the $i^{th}$ 1/3-octave band, $\tau$ is the integration time for the moving average, t is the time, and $t_0$ is the time of observation.

$$ a = \left[ \sum_i rRMS_i^2 \right]^{\frac{1}{2}} \quad (2) $$

Where $a$ is the overall running RMS average obtained by combining a series of 1/3-octave band running RMS accelerations ($rRMS$) for a given axis, and $i$ indicates the $i^{th}$ 1/3-octave band.
overall running RMS accelerations measured at one spinal level (i.e. T9, C7 or the head) by the overall running RMS accelerations measured at the seat (Seidel et al. 1980).

The transfer functions were also calculated across the frequency ranges previously mentioned for all 6-DOF. The transfer functions were calculated using the cross-spectral density (CSD) method (Equation 3 - Griffin 1990; Smith 1999). From these Transfer functions the dominant transmission frequency (frequency with the greatest transfer function modulus magnitude) was determined for each translational and rotational axis at each level of the spine.

\[ T_{io}(f) = \frac{CSD_{io}(f)}{PSD_{ii}(f)} \]  

Where \( T_{io} \) is the complex transfer function between the seat input (ii) accelerations and the T9, C7 or the head output (oo) accelerations at frequency f. CSD\(_{io}\) indicates a cross-spectral density function between the seat input accelerations and accelerations for the output of interest. PSD\(_{ii}\) represents the power-spectral density of the seat input.

Finally, 6-DOF dynamic transfer stiffnesses were determined by calculating the complex ratio of the input force/moment and the translational/rotational displacement of the T9 marker triad (Equations 4 - Piersol and Paez 2010; Griffin 1990). This provided translational and rotational stiffness values for the trunk. Preliminary investigations found smaller displacements relative to the input forces as frequencies increased causing the dynamic stiffness values to increase exponentially with frequency. As a result the log of the stiffness value at each frequency was determined and the integral of that log scaled stiffness and frequency curve was used to obtain an overall stiffness value for comparisons (Equation 5). This allowed each frequency to have a similar influence on the overall stiffness value.

\[ S(f) = \frac{PSD_F(f)}{PSD_d(f)} \]  

Where \( S \) is the dynamic stiffness between the seat input force (F) and the L5 or the head output displacement (d) at frequency f. PSD\(_F\) indicates a spectral density function of the seat input force and PSD\(_d\) is the output displacement of interest.

\[ S_{overall} = \int_0^F Log[S(f)] \]  

Where \( S_{overall} \) is the total logged dynamic stiffness integrated from 0Hz to frequency F (5Hz or 10Hz, the maximum frequency for each rotational and translational axis investigated).
6.2.9 Statistical analysis

Preliminary statistical analysis revealed that the data were not normally distributed; therefore a non-parametric statistic was required. As a result, a series of exact binomial probability calculations (Hays 1973), with a \( b=0.05 \) cumulative probability cut-off were performed to see if any significant dependent variable trends occurred with the manipulation of an independent variable. Here, the dependent variables examined were the muscle activation level of the 14 muscles monitored, 6-DOF trunk stiffness (dynamic stiffness between the seat and T9 spinal level), 6-DOF transmissibility and 6-DOF dominant transmission frequency at the T9 and C7 spinal levels as well as the head. The independent variables included:

1) Trunk muscle activity with a voluntary contraction of the trunk muscles compared to its normal/relaxed counterpart for all possible posture and random vibration exposures (binomial \( n=216 \));

2) Exposure acceleration level with the high running RMS average acceleration exposure level compared to the low running RMS average acceleration exposure level for all three spectral profile exposures while the subject was in an upright posture (0˚ FLEX/EXT 0˚ LTB and 0˚TWST; binomial \( n=9 \));

3) Exposure spectral profile with the EDGADE and HFEBAC spectral profiles compared to the random spectral profile and then each other while exposed to the high running RMS average acceleration exposure level in the upright posture (binomial \( n=9 \));

4) Posture with a 15˚ flexed, 15˚ extended, 15˚ LTB, 15˚ TWST, 15˚ flexion/15˚ LTB/15˚ TWST and 15˚ extension/15˚ LTB/15˚ TWST tri-planar trunk posture combination compared to the upright posture while exposed to the high running RMS average acceleration exposure level EDGADE or HFEBAC spectral profiles (binomial \( n=9 \)).

The independent variables selected for comparison were chosen such that the analysis utilized datasets with the least potential for measurement error, as well as the least potential interaction from variables not evaluated at the time. In addition, the field exposures were utilized
whenever possible.

For each exact binomial probability calculation changes in the independent variables were considered to have a random effect (i.e., a $p=0.5$ probability of occurrence). The number of times that the independent variable increased or decreased the muscle activation level, trunk stiffness, transmissibility or dominant frequency was counted. The direction of the largest count was determined and the probability of seeing that many increases or decreases in a particular variable was calculated using Equation 9. Furthermore, the average change for the dominant trend was calculated. All signal processing and statistical analyses were conducted using custom MatLab™ 7.0.4 source code.

$$b(r \leq X \leq N; N, p) = \sum_{i=r}^{N} \binom{N}{i} p^i q^{N-i} \quad (9)$$

Where $b$ is the probability of observing $r$ occurrences or more in $N$ observations of random variable $X$ when the probability of an occurrence is equal to $p$. Here $q$ equals $1-p$.

### 6.3 RESULTS

Several significant trends in muscle activity, 6-DOF dynamic trunk stiffness, 6-DOF vibration transmissibility and 6-DOF dominant transmission frequency were found. In many instances, these significant trends were infrequent. This is a consequence of the low sample size where over 8 out of 9 participants must display the same trend for statistical significance to occur. In an attempt to uncover patterns in the human biodynamic responses measured, trends approaching significance ($p \leq 0.1$), i.e., the trend was seen in 7 out of 9 participants, were also included. The incorporation of these additional results helped reveal patterns in the data which otherwise would not have been seen.

#### 6.3.1 Biodynamic response trends related to a voluntary increase in trunk muscle activity

A significant proportion of increases in trunk muscle activity were found for 11 of 14 trunk muscles during the voluntary muscle contraction trials (Table 6.9). With this increase in muscle activity, significant increasing trends for trunk stiffness occurred in the Z, Roll and Yaw,
### Table 6.9: Effect of a voluntary trunk muscle contraction on 14 trunk muscles.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Mean Change in the Percentage of Maximum Voluntary Contraction Due to Voluntary Increased Trunk Muscle Activation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Rectus Abdominus</td>
<td>3.32*</td>
</tr>
<tr>
<td>Right Rectus Abdominus</td>
<td>3.11*</td>
</tr>
<tr>
<td>Left Internal Oblique</td>
<td>5.80*</td>
</tr>
<tr>
<td>Right Internal Oblique</td>
<td>9.75*</td>
</tr>
<tr>
<td>Left External Oblique</td>
<td>16.20*</td>
</tr>
<tr>
<td>Right External Oblique</td>
<td>14.83*</td>
</tr>
<tr>
<td>Left Thoracic Erector Spinae</td>
<td>-</td>
</tr>
<tr>
<td>Right Thoracic Erector Spinae</td>
<td>-</td>
</tr>
<tr>
<td>Left Lumbar Erector Spinae</td>
<td>6.21*</td>
</tr>
<tr>
<td>Right Lumbar Erector Spinae</td>
<td>8.17*</td>
</tr>
<tr>
<td>Left Multifidus</td>
<td>4.62*</td>
</tr>
<tr>
<td>Right Multifidus</td>
<td>9.83</td>
</tr>
<tr>
<td>Left Latissimus</td>
<td>4.84*</td>
</tr>
<tr>
<td>Right Latissimus</td>
<td>6.56*</td>
</tr>
</tbody>
</table>

Note: only \( p \leq 0.1 \) are reported. * indicates significance at \( p \leq 0.05 \).

### Table 6.10: Effect of a voluntary trunk muscle contraction on trunk stiffness, transmissibility, and dominant transmission frequency.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Mean Change Due to Voluntary Trunk Muscle Activation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trunk Stiffness</td>
</tr>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Z</td>
</tr>
<tr>
<td></td>
<td>Roll</td>
</tr>
<tr>
<td></td>
<td>Pitch</td>
</tr>
<tr>
<td></td>
<td>Yaw</td>
</tr>
</tbody>
</table>

Note: only \( p \leq 0.1 \) are reported. * indicates significance at \( p \leq 0.05 \). Translational trunk stiffness is reported in \( \log(N/m) \) and rotational stiffness is reported in \( \log(Nm/rad) \). Transmissibility is a unitless ratio. Dominant frequency is reported in Hz.
with an increasing stiffness trend approaching significance in Y. No stiffness trend was found for pitch, and in the X-axis there was a significant decreasing stiffness trend (Table 6.10). It can be seen in Table 6.10 that increasing stiffness trends coincided with a significant proportion of increases in dominant frequency when subjects voluntarily activated their trunk muscles.

Looking at Table 6.10 one can see that with the exception of the X-axis and the T9 level of the Z-axis, increasing trunk stiffness trends were associated with significant increasing vibration transmissibility trends. Decreases in trunk stiffness should therefore result in decreases in transmissibility, but the decreasing X-axis stiffness trend did not result in this pattern. Here, decreasing X-axis stiffness trend was accompanied by an increasing transmissibility trend. Thus, an interaction between axis, stiffness and transmissibility is present. It is also worth noting that the increases in transmissibility were larger at more superior measurement locations.

### 6.3.2 Biodynamic response trends related to exposure acceleration level

Muscle activity of the posterior muscles increased with increased random vibration exposure levels (Table 6.11). The increase in random vibration exposure acceleration level and subsequent posterior trunk muscle activity produced few changes in the biodynamic response (Table 6.12). Significant increasing trends in X and Y trunk stiffness were found, but no significant trends were found for transmissibility in those axes. There are some reduced

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Mean Change in the Percentage of Maximum Voluntary Contraction Due to Increased Exposure Acceleration Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Random</td>
</tr>
<tr>
<td>Left Rectus Abdominus</td>
<td>0.36*</td>
</tr>
<tr>
<td>Right Rectus Abdominus</td>
<td>0.19*</td>
</tr>
<tr>
<td>Left Internal Oblique</td>
<td>-</td>
</tr>
<tr>
<td>Right Internal Oblique</td>
<td>-</td>
</tr>
<tr>
<td>Left External Oblique</td>
<td>13.49*</td>
</tr>
<tr>
<td>Right External Oblique</td>
<td>19.98</td>
</tr>
<tr>
<td>Left Thoracic Erector Spinae</td>
<td>6.00</td>
</tr>
<tr>
<td>Right Thoracic Erector Spinae</td>
<td>5.02</td>
</tr>
<tr>
<td>Left Lumbar Erector Spinae</td>
<td>3.69*</td>
</tr>
<tr>
<td>Right Lumbar Erector Spinae</td>
<td>9.37</td>
</tr>
<tr>
<td>Left Multifidus</td>
<td>5.34*</td>
</tr>
<tr>
<td>Right Multifidus</td>
<td>6.85*</td>
</tr>
<tr>
<td>Left Latissimus</td>
<td>5.03*</td>
</tr>
<tr>
<td>Right Latissimus</td>
<td>5.99</td>
</tr>
</tbody>
</table>

Note: only $p \leq 0.1$ are reported. * indicates significance at $p \leq 0.05$. 

174
Table 6.12: Effect of increased exposure acceleration level on trunk stiffness, transmissibility, and dominant transmission frequency.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Axis</th>
<th>Trunk Stiffness</th>
<th>Mean Change Due to Increased Exposure Acceleration Level</th>
<th>Head</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T9</td>
<td>C7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stiffness</td>
<td>Transmissibility</td>
<td>Dominant Frequency</td>
</tr>
<tr>
<td>Random</td>
<td>X</td>
<td>1.26*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>6.67*</td>
<td>-0.47</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>0.08*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Roll</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Pitch</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Yaw</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.41</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>1.33*</td>
<td>-0.17*</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Roll</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Pitch</td>
<td>0.78</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Yaw</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EGDADE</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>2.86</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>1.13</td>
<td>-0.12*</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>-</td>
<td>-</td>
<td>-2.57*</td>
</tr>
<tr>
<td></td>
<td>Roll</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Pitch</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Yaw</td>
<td>-</td>
<td>-</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Note: only p ≤ 0.1 are reported. * indicates significance at p ≤ 0.05. Translational trunk stiffness is reported in log(N/m) and rotational stiffness is reported in log(Nm/rad). Transmissibility is a unitless ratio. Dominant frequency is reported in Hz.
transmission trends approaching significance for X and Y though. Furthermore, the dominant transmission frequency had a decreasing trend in Y with an increased trunk stiffness tendency. A significant decrease in Pitch dominant transmission frequency was observed as well. Finally, a significant increasing Z-axis transmissibility trend was also found at the T9 spinal level, but the average increase in transmissibility was only 0.08 making it a relatively small effect on transmissibility.

The change in muscle activity with an increase in exposure acceleration level was different for the EGDADEx and HFEBAC profiles, indicating that there was an interaction between profile and exposure level. Increasing the exposure acceleration level of the EGDADEx profile resulted in a significant number of subjects having increased rectus abdominus and external oblique muscle activation (Table 6.11). Meanwhile, the HFEBAC profile showed no significant trends in muscle activity. The increased anterior trunk muscle activity with the EGDADEx profile was accompanied by a significant trend towards increased stiffness in the Y-axis (Table 6.12). The increase in Y stiffness was again associated with decreasing transmissibility tendencies at all measurement levels. Although only approaching significance, the X-axis also showed an increase in trunk stiffness and a decrease in the head transmissibility. Significant increasing Z-axis transmissibility trends were also found when increasing the exposure acceleration level of the EGDADEx profile. In contrast, no increasing or decreasing trends in dominant frequency were observed when the exposure acceleration level of the EGDADEx profile was increased.

With respect to the HFEBAC profile, the lack of a significant trend in muscle activity was associated with a absence in a significant trend in trunk stiffness. Although no significant stiffness trends were found, the Y-axis stiffness was approaching a significant increasing trend. This increase in Y-axis stiffness coincided with a significant decreasing trend in T9 transmissibility. In addition, a significant decreasing dominant transmission frequency trend was found for the Z axes pitch transmissibility showed significant increasing trends as the exposure acceleration level of the HFEBAC exposure increased.

6.3.3 Biodynamic response trends related to exposure profile

While in an upright posture (0° FLEX/EXT, 0° LTB and 0°TWST), both field exposure
profiles (high exposure acceleration level EGDAlDE and HFEBAC spectra) displayed either significant decreasing muscle activity trends or decreasing trends approaching significance for many posterior trunk muscles when referenced to a random exposure profile (Table 6.13). Both profiles also showed a trend towards increased muscle activity in the external oblique muscles relative to the muscle activity seen in the random exposure profile. The magnitude of the aforementioned muscle activity changes was comparable between the two profiles. This pattern of muscle activity change coincided with similar significant changes to trunk stiffness in Y, Roll, and Pitch for both field profiles (Table 6.14). Furthermore, the X, Y, Roll, Pitch, and Yaw transmissibility and dominant transmission frequency demonstrated similar changes (either significant or approaching significance) at the same spinal levels when moving from the random profile to either the EGDAlDE or HFEBAC profiles. In the Z-axis, however, an interaction is present as the change from a random profile to the EGDAlDE and HFEBAC profiles coincided with different changes to seat-to-head transmissibility at the head (with the change to HFEBAC only approaching significance).

Taking a closer look at the relationship between stiffness, transmissibility and dominant transmission frequency, notable increasing trends in trunk stiffness and dominant transmission frequency to all spinal levels measured were found for the X and Y axes under an EGDAlDE

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Mean Change in the Percentage of Maximum Voluntary Contraction Due to Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Change From Random to EGDAlDE</td>
</tr>
<tr>
<td>Left Rectus Abdominus</td>
<td>-</td>
</tr>
<tr>
<td>Right Rectus Abdominus</td>
<td>-</td>
</tr>
<tr>
<td>Left Internal Oblique</td>
<td>-1.68</td>
</tr>
<tr>
<td>Right Internal Oblique</td>
<td>-</td>
</tr>
<tr>
<td>Left External Oblique</td>
<td>11.34*</td>
</tr>
<tr>
<td>Right External Oblique</td>
<td>14.81*</td>
</tr>
<tr>
<td>Left Thoracic Erector Spinae</td>
<td>-</td>
</tr>
<tr>
<td>Right Thoracic Erector Spinae</td>
<td>-</td>
</tr>
<tr>
<td>Left Lumbar Erector Spinae</td>
<td>-6.87</td>
</tr>
<tr>
<td>Right Lumbar Erector Spinae</td>
<td>-13.07</td>
</tr>
<tr>
<td>Left Multifidus</td>
<td>-</td>
</tr>
<tr>
<td>Right Multifidus</td>
<td>-11.87*</td>
</tr>
<tr>
<td>Left Latissimus</td>
<td>-8.69*</td>
</tr>
<tr>
<td>Right Latissimus</td>
<td>-10.40</td>
</tr>
</tbody>
</table>

Note: only p≤0.1 are reported. * indicates significance at p≤0.05.
<table>
<thead>
<tr>
<th>Profile Change</th>
<th>Axis</th>
<th>Trunk Stiffness</th>
<th>Transmissibility</th>
<th>Dominant Frequency</th>
<th>Transmissibility</th>
<th>Dominant Frequency</th>
<th>Transmissibility</th>
<th>Dominant Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>1.91</td>
<td>-</td>
<td>5.71*</td>
<td>-0.21*</td>
<td>3.44*</td>
<td>-0.59*</td>
<td>6.25*</td>
</tr>
<tr>
<td>From Random to EGDADE</td>
<td>Y</td>
<td>5.89*</td>
<td>-0.41*</td>
<td>1.14*</td>
<td>-0.73*</td>
<td>3.50*</td>
<td>-2.36*</td>
<td>2.71*</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>-</td>
<td>-0.18</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.59*</td>
<td>4.14*</td>
</tr>
<tr>
<td>Pitch</td>
<td>Roll</td>
<td>3.00*</td>
<td>-</td>
<td>-2.00</td>
<td>-1.33</td>
<td>-</td>
<td>-4.51</td>
<td>-</td>
</tr>
<tr>
<td>Yaw</td>
<td>Pitch</td>
<td>-3.08*</td>
<td>1.16*</td>
<td>-</td>
<td>0.72</td>
<td>-1.80*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Yaw</td>
<td>-</td>
<td>1.16*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>From Random to HFEBAC</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>4.00</td>
<td>-</td>
<td>3.83</td>
<td>-</td>
<td>3.71*</td>
</tr>
<tr>
<td>Pitch</td>
<td>Roll</td>
<td>5.80*</td>
<td>-0.43*</td>
<td>-</td>
<td>-0.71*</td>
<td>6.20*</td>
<td>-2.16*</td>
<td>4.00*</td>
</tr>
<tr>
<td>Yaw</td>
<td>Pitch</td>
<td>-4.06*</td>
<td>2.11*</td>
<td>-</td>
<td>1.65*</td>
<td>-</td>
<td>5.60*</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Yaw</td>
<td>-</td>
<td>2.19*</td>
<td>-</td>
<td>3.00*</td>
<td>-</td>
<td>6.70</td>
<td>-</td>
</tr>
<tr>
<td>From EGDADDE to HFEBAC</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-3.00*</td>
<td>-</td>
<td>-</td>
<td>-6.00*</td>
</tr>
<tr>
<td>Pitch</td>
<td>Roll</td>
<td>-0.52</td>
<td>-0.10*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Yaw</td>
<td>Pitch</td>
<td>1.62*</td>
<td>0.17*</td>
<td>-</td>
<td>0.27*</td>
<td>-</td>
<td>0.39*</td>
<td>-3.33*</td>
</tr>
<tr>
<td></td>
<td>Yaw</td>
<td>1.45*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>From EGDADDE to HFEBAC</td>
<td>X</td>
<td>-</td>
<td>1.51</td>
<td>-</td>
<td>2.98*</td>
<td>-</td>
<td>6.30</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: only p≤0.1 are reported. * indicates significance at p≤0.05. Translational trunk stiffness is reported in log(N/m) and rotational stiffness is reported in log(Nm/rad). Transmissibility is a unitless ratio. Dominant frequency is reported in Hz.
exposure, and Y axis under an HFEBAC exposure (Table 6.14). However, transmissibility decreased in these axes. Pitch also displayed the same mechanical behavior as X and Y with a decrease in trunk stiffness corresponding to decreases in dominant transmission frequency for the random to EGDADE condition at the C7 spinal level. There were no dominant frequency trends approaching significance for the HFEBAC pitch analysis. The significant reduction in pitch stiffness is associated with significant increases in transmission for both field profiles. On the other hand, roll displayed a tendency to decreasing dominant vibration transmission frequency with an increasing stiffness trend (seen when switching to the HFEBAC and EGDADE profile). Furthermore, there were decreasing transmissibility trends seen with increases in roll stiffness for the EGDADE profile (relative to the random profile).

The change from a random profile to the EGDADE and HFEBAC profiles coincided with similar changes to muscle activity, trunk stiffness, vibration transmissibility, and dominant vibration transmission frequency (refer to It was seen in Tables 6.13 and 6.14). Table 6.13 also indicates that there are no significant tendencies to increase or decrease muscle activity when the HFEBAC exposure was compared to the EGDADE profile. Despite the lack of significant trends in muscle activity when comparing the HFEBAC profile to the EGDADE profile, several significant increases and/or decreases in trunk stiffness, vibration transmissibility, and dominant vibration transmission frequency did occur (Table 6.14). This indicates that similar muscle activity levels will produce different biodynamic responses under different 6-DOF vibration exposure profiles.

6.3.4 Biodynamic response trends related to posture

To this point, the focus of the investigation has been the upright posture. Here, the effect of adopting non-neutral postures while exposed to both the EGDADE and HFEBAC high exposure acceleration level spectra is explored. Flexing the trunk had a significant number of subjects with decreased abdominal muscle activity relative to an upright seated posture under a high EGDADE exposure (Table 6.15). Extension on the other hand a significant number of subjects with increased abdominal muscle activity relative to an upright seated posture under a high EGDADE exposure (Table 6.15). Under the high HFEBAC exposure a similar trend in abdominal muscle activity is seen when flexing and extending for most of the abdominal
Table 6.15: Effect of postural changes on 14 trunk muscles.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Muscle</th>
<th>Mean Change in the Percentage of Maximum Voluntary Contraction Due to Posture</th>
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</thead>
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<tr>
<td></td>
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<td>-</td>
</tr>
<tr>
<td></td>
<td>Left Lumbar Erector Spinae</td>
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<tr>
<td></td>
<td>Right Lumbar Erector Spinae</td>
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</tr>
<tr>
<td></td>
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<td>-</td>
</tr>
<tr>
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Note: only \( p \leq 0.1 \) are reported. * indicates significance at \( p \leq 0.05 \). Translational trunk stiffness is reported in \( \log(\text{N/m}) \) and rotational stiffness is reported in \( \log(\text{Nm/rad}) \). Transmissibility is a unitless ratio. Dominant frequency is reported in Hz.
Muscles (Table 6.15). It is also worth noting that when seen, the average increase in muscle activity while extending was greater for the high EGDADExE by over 15% for both the left and right external oblique muscles. Furthermore, the posterior trunk muscles had almost no muscle activity tendencies under the high EGDADExE profile when flexed and extended. This lack of trend was contrasted by the increasing trend found for many posterior trunk muscles under the high HFEBAC profile exposure. For example the high HFEBAC profile had increasing muscle activity tendencies for two additional lumbar muscles when flexed, and six posterior trunk muscles when extended.

While LTB to the right, the right rectus abdominus and left external oblique had an increasing muscle activity trend for both the high EGDADExE and high HFEBAC profiles (significant in most cases) (Table 6.15). The high EGDADExE profile, however, had a tendency towards reduced muscle activity in the right internal oblique and right external oblique, with no trend seen with the high HFEBAC profile for those same muscles. Furthermore, the posterior trunk muscles had almost no muscle activity tendencies under the high EGDADExE profile when laterally bent, while a near significant increasing trend was found for both the right and left multifidus muscles under the high HFEBAC profile exposure. In addition, the left latissimus muscle showed completely opposite trends in muscle activity with the EGDADExE profile having decreased and the HFEBAC profile having increased muscle activity.

TWST produced few trends in muscle activity for both the high EGDADExE and high HFEBAC profiles (Table 6.15). There was a significant increasing trend for both profiles with respect to the left external oblique muscle, with the high EGDADExE producing over three times as much muscle activity than the high HFEBAC profile.

Considering the tri-planar combinations of FLEX/EXT, LTB, and TWST, it was found that these postures produced similar responses to that of isolated flexion and extension under the high EGDADExE exposure (Table 6.15). Some notable differences do occur though. The FLEX/LTB/TWST posture had an increasing trend (although not significant) for the left external oblique muscle. Thus the addition of LTB and TWST shifted left external oblique muscle’s response to one similar to an isolate LTB or TWST posture. With respect to the extension/LTB/TWST posture the average change in muscle activity was lower for every abdominal muscle measured when compared to the isolated extension posture under the high EGDADExE exposure. Under the high HFEBAC profile similar abdominal muscle trends occurred.
to those seen in the high EGDADE profile. Again the left external oblique muscle activity switched from a decreasing trend in isolated flexion to an increasing trend under the FLEX/LTB/TWST; and the EXT/LTB/TWST posture had average muscle activity changes that were lower for every abdominal muscle but one (left external oblique muscle) when compared to the isolated extension posture under the high HFEBAC exposure. Furthermore, much like the isolated single plane of motion trunk postures, the tri-planar combination postures both displayed increasing muscle activity tendencies for several posterior trunk muscles (typically only approaching significance though).

Comparing the instances when the two profiles both showed a significant or near significant trend for a given muscle and posture, it can be seen that although the direction of the change induced by the postural deviation remains the same, the profile with the greater muscle activity magnitude for a given posture differed. This combined with the clear differences in back muscle activity suggests that an interaction between posture, profile and back muscle activity exists.

Trunk stiffness increased in a significant number of subjects for all axes except Z while flexed under the high EGDADE profile exposure (Table 6.16). Conversely, the X, Y, Pitch and Yaw axes displayed decreased stiffness tendencies despite increased abdominal muscle activity when extending the trunk. The high HFEBAC profile (Table 6.17) had similar stiffness tendencies to the high EGDADE profile while flexing and extending.

While LTB the trunk to the right; a significant number of subjects had a reduction in Z-axis trunk stiffness under the high EGDADE exposure (Table 6.16). Pitch and Yaw trunk stiffness, however, increased in a significant number of subjects while exposed to the EGDADE profile. This was opposite to that found while subjects were extending in Z, Pitch and Yaw under the same exposure profile. There is a noticeable difference in the muscles activation trends seen while adopting a LTB compared to the extended posture (i.e. a reduction in the right internal and right external oblique muscles with LTB; Table 6.15). Flexion of the trunk also showed an increase in stiffness with a reduction in the right internal and right external oblique muscles in Pitch and Yaw while exposed to a high EGDADE profile. This same pattern appears in the FLEX/LTB/TWST combination posture. Therefore increasing the right internal and right external oblique muscle activity appears to reduce trunk stiffness under a high EGDADE exposure. No significant trunk stiffness trend was found for the high HFEBAC profile while
<table>
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<td>1.22*</td>
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</table>

Note: only $p \leq 0.1$ are reported. * indicates significance at $p \leq 0.05$. Translational trunk stiffness is reported in log(N/m) and rotational stiffness is reported in log(Nm/rad). Transmissibility is a unitless ratio. Dominant frequency is reported in Hz.
Table 6.16 Continued: Effect of postural changes on trunk stiffness, transmissibility, and dominant transmission frequency while exposed to the EGDADE vibration profile.

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<th>Posture</th>
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<th>Trunk Stiffness</th>
<th>Mean Change Due to Posture</th>
</tr>
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<tbody>
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<td></td>
<td></td>
<td>T9 Transmissibility &amp; Dominant Frequency</td>
<td>C7 Transmissibility &amp; Dominant Frequency</td>
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Note: only p ≤ 0.1 are reported. * indicates significance at p ≤ 0.05. Translational trunk stiffness is reported in log(N/m) and rotational stiffness is reported in log(Nm/rad). Transmissibility is a unitless ratio. Dominant frequency is reported in Hz.
Table 6.17: Effect of postural changes on trunk stiffness, transmissibility, and dominant transmission frequency while exposed to the HFEBAC vibration profile.

<table>
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<tr>
<th>Posture</th>
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Note: only \( p \leq 0.1 \) are reported. * indicates significance at \( p \leq 0.05 \). Translational trunk stiffness is reported in \( \log(\text{N/m}) \) and rotational stiffness is reported in \( \log(\text{Nm/rad}) \). Transmissibility is a unitless ratio. Dominant frequency is reported in Hz.
Table 6.17 Continued: Effect of postural changes on trunk stiffness, transmissibility, and dominant transmission frequency while exposed to the HFEBAC vibration profile.

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<th>Posture</th>
<th>Axis</th>
<th>Trunk Stiffness</th>
<th>Mean Change Due to Posture</th>
<th>T9</th>
<th>C7</th>
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<td>Dominant Frequency</td>
<td>Transmissibility</td>
<td>Dominant Frequency</td>
<td>Transmissibility</td>
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<td>Z</td>
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<td>-</td>
<td>5.29</td>
<td>-</td>
<td>2.51</td>
</tr>
<tr>
<td></td>
<td>Roll</td>
<td>0.48</td>
<td>-</td>
<td>5.29</td>
<td>-</td>
<td>2.51</td>
</tr>
<tr>
<td></td>
<td>Pitch</td>
<td>0.48</td>
<td>-</td>
<td>5.29</td>
<td>-</td>
<td>2.51</td>
</tr>
<tr>
<td></td>
<td>Yaw</td>
<td>0.87</td>
<td>-</td>
<td>2.71*</td>
<td>-</td>
<td>2.43*</td>
</tr>
</tbody>
</table>

Note: only p≤0.1 are reported. * indicates significance at p≤0.05. Translational trunk stiffness is reported in log(N/m) and rotational stiffness is reported in log(Nm/rad). Transmissibility is a unitless ratio. Dominant frequency is reported in Hz.
LTB (Table 6.17). However, the X-axis does demonstrate a tendency towards increased trunk stiffness that is approaching significance under the high HFEBAC exposure while LTB. The high EGDAGE profile had no significant trend in X trunk stiffness while LTB. The difference between the two profiles coincided with a difference in left and right multifidus muscle activity. The HFEBAC profile tended to increase the activity of the left and right multifidus muscles, where the high EGDAGE profile did not.

TWST, which produced few trends in muscle activity when exposed to both the high EGDAGE and high HFEBAC profiles (Tables 6.16 and 6.17 respectively), also demonstrated few trends in trunk stiffness. A tendency towards increased left external oblique and right multifidus activation while TWST and exposed to the high EGDAGE profile (Table 6.15) coincided with an increased Pitch and Yaw trunk stiffness. With the high HFEBAC exposure, trunk stiffness in pitch coincided with increased left external oblique and right rectus abdominus activation.

Adding LTB and TWST to a flexed posture while exposed to the high EGDAGE profile coincided with the same increasing stiffness tendency for Y, Pitch and Yaw as flexion alone (Table 6.16). This new posture, however, coincided with the loss of a stiffness trend for X and Roll while exposed to the high EGDAGE profile. The changes in trunk stiffness seen with the change from the upright seated posture to the FLEX/LTB/TWST posture while exposed to the high EGDAGE profile are likely the result of the noticeably different changes in trunk muscle activity (Table 6.15). Changing from an upright posture to a combination of extension, LTB and TWST had even more axes with no significant stiffness trend while exposed to the high EGDAGE profile. Here the extension/LTB/TWST combination had similar muscle activity trends to isolated extension, yet the stiffness trends differed greatly. This could be due in part to the lower average change in muscle activity seen in the abdominal muscles for the extension/LTB/TWST combination when compared to the isolated extension posture. Changes in FLEX/LTB/TWST trunk posture stiffness differed in Y, Z and Roll when comparing the high HFEBAC exposure (Table 6.17) to the high EGDAGE profile (Table 6.16). For the high HFEBAC profile there was no longer a stiffness trend in Y, and there was now a decreased stiffness trend in Z and an increased stiffness trend in Roll. The additional back muscle activity seen in Table 6.15 for the FLEX/LTB/TWST high HFEBAC exposure may be increasing trunk motions in Y and Z, thereby eliminating the increased Y trunk stiffness seen with the high
EGDADE profile and reducing the Z stiffness under a high HFEBAC exposure. This same back muscle activity appears to be reducing trunk rotations in Roll, increasing the Roll stiffness in the FLEX/LTB/TWST posture while exposed to the high HFEBAC profile. Furthermore, the extension/LTB/TWST posture displayed a number of near significant decreasing stiffness trends while exposed to the high HFEBAC profile. Again this differed greatly from the high EGDADE exposure. Much like the differences between the high EGDADE and high HFEBAC stiffness’s with respect to the FLEX/LTB/TWST posture shift, the changes in stiffness with respect to the EXT/LTB/TWST posture shift are also likely the result of the tendency towards additional back muscle activity. In addition the high HFEBAC displayed a greater average increase in right and left rectus abdominus and internal oblique activity, as well as a lower average increase in right and left external oblique activity when compared to the high EGDADE profile.

In flexion, the T9 transmissibility decreased with an increase in trunk stiffness for X, Y, Pitch and Yaw with the high EGDADE vibration exposure (Table 6.16). The same stiffness/T9 transmissibility relationship was found for X, Pitch and Yaw while extending; Z while LTB; and Y, pitch and Yaw while adopting the FLEX/LTB/TWST combination under the EGDADE exposure. The HFEBAC profile displayed the same stiffness and T9 transmissibility trends for all postures (Table 6.17). While adopting the extension/LTB/TWST posture under the EGDADE exposure, however, the increase in stiffness for the Z axis coincided with an increase in T9 transmissibility. When observed, dominant T9 transmissibility frequency a decreased when stiffness increased for both the EGDADE and HFEBAC high exposure profiles.

With regards to the C7 and head transmissibility, there are several instances where deviations from the previously mentioned increasing trunk stiffness/decreasing T9 transmissibility trend are seen. For example, the head transmissibility increased in X and C7 transmissibility increased in Pitch while flexed under the EGDADE exposure (Table 6.16). Likewise, the head transmissibility increase in X while LTB, and C7 transmissibility increased in Yaw while FLEX/LTB/TWST under the HFEBAC exposure (Table 6.17). Furthermore, there were a few occasions where increased transmissibility was seen at the head despite decreasing transmissibility trends observed at lower levels of the spine. For example, the head transmissibility is increased in X while flexing under the EGDADE vibration exposure despite a decrease in T9 transmissibility. This also occurred in Y while FLEX/LTB/TWST under the EGDADE exposure. This pattern was not observed under the HFEBAC exposure. The pattern
appeared at the C7 level in pitch while flexing under the EGDADExposure; Y and pitch while FLEX/LTB/TWST under the EGDADExposure; and Yaw while FLEX/LTB/TWST under the HFEBAC Exposure. In contrast, the head and C7 transmissibility displayed reductions in transmissibility in spite of increased transmission at the T9 spinal level under the EGDADExposure while LTB and TWST for the Z-axis. This pattern was also found in the X-axis while FLEX/LTB/TWST under the high EGDADExposure. This pattern of reductions in transmissibility in spite of increased transmission at the T9 spinal level was not observed under the high HFEBAC Exposure.

When the pattern could be observed, the dominant T9 transmission frequency decreased with an increase in trunk stiffness (X axis while flexed under EGDADExposure and Yaw while extended under the HFEBAC Exposure). Under the HFEBAC Exposure, this pattern was held at the higher spinal levels, with one exception (X-axis dominant C7 transmission frequency while extending/LTB/TSTW). Under the EGDADExposure the C7 and head dominant transmission frequencies behaved more like a column or beam with increased trunk stiffness trends demonstrating increased C7 and head dominant transmission frequency trends. Here, X-axis dominant C7 transmission frequency while flexing, Y and Yaw dominant head transmission frequency while extending are the exceptions.

6.4 DISCUSSION

Furthermore, the pattern of frequency dependence used by these guidelines is based on the subjective and biodynamic response of individuals exposed to vibration in a laboratory (Griffin 1998). These laboratory studies are again limited in the exposure axes and spectra utilized, as well as the fact that they are not directly linked to injury outcomes.

Another major limitation in current vibration exposure standards is the lack of consideration for operator posture. Operator postures have also been linked to musculoskeletal complaints in the low-back (Village, Morrison and Leong 1989; Bovenzi and Betta 1994; Toren 2001; Bovenzi, Pinto and Stacchini 2002; Hoy et al. 2005; Bovenzi et al. 2006; Okunribido, Magnusson and Pope 2006a; Okunribido, Magnusson and Pope 2006b; Eger et al. 2008; Jack et al. 2008a – Chapter 3; Okunribido, Magnusson and Pope 2008) and neck (Village, Morrison and Leong 1989; Eger et al. 2008; Jack et al. 2008a – Chapter 3), yet they are not considered in vibration risk assessments. Village, Morrison and Leong (1989), Bovenzi and Betta (1994), Bovenzi (1996), NIOSH (1997), Jack and Oliver (2008 - Chapter 2) and Jack et al. (2010 – Chapter 4) all caution that posture is a contributing factor to the WBV complaints experienced by operators. Bovenzi and Betta (1994) reported that vibration dose and postural load combined to increase the odds of LBP. Laboratory studies investigating biodynamic responses also report an interaction between posture and vibration exposure, with changes in transmission and attenuation peak magnitudes and frequencies occurring when different postures were adopted (Seidel et al. 1980; Wilder et al. 1982; Pope, Broman and Hansson 1990; Wilder et al. 1994; Zimmerman and Cook 1997; El-Khatib et al. 1998; Pope, Wilder and Magnusson 1998; Matsumoto and Griffin 2000). Unfortunately, these laboratory studies continue to utilize limited DOF, limited spectral exposures and a limited number of postures. Moreover, the postures and vibration exposures used in these laboratory studies are not based on field measurements, as only a few studies have directly measured operator postures in the field (Eklund et al. 1994; Gellerstedt 1998; Hermanns et al. 2008; Jack et al. 2008a – Chapter 3).

The current laboratory investigation incorporated 6-DOF exposure acceleration levels from Jack et al. (2010 – Chapter 4), 6-DOF exposure spectra from Jack et al. (Chapter 5) and triplanar trunk postures from Jack et al. (2008 – Chapter 3) in an attempt to gain a comprehensive understanding of how the body responds to vibration under field conditions. The low and high running RMS average exposure levels (Table 6.8), and the HFEBAC and EGDADE exposure spectra (Figures 6.6 and 6.7) occurred in the field while PUAL and driving. Although isolated
single plane of motion trunk postures rarely occur in the field, both the tri-planar trunk posture combinations investigated were observed in the field while monitoring the plough or grapple. The extension combination posture was observed while driving; however, the LTB was typically to the left as operators extended back and to the side while driving.

Jack and Oliver (2008 – Chapter 2) propose that vibration transmission may be the link between the apparent vibration exposure, posture and injury interaction discussed above. Greater exposure accelerations (Bovenzi and Betta 1994; Bovenzi 1996; Seidel et al. 1998; ISO 2631-1:1997; EU Directive 2002/44/EC) and non-neutral operator postures (Village, Morrison and Leong 1989; Bovenzi and Betta 1994; Bovenzi 1996; NIOSH 1997; Jack et al. 2008a – Chapter 3; Jack et al. 2010 – Chapter 4) have been associated with an increased risk of injury as well as increases in the stiffness of the spine (Adams 1995; Cholewicki and McGill 1996; McGill and Cholewicki 2001; Panjabi 2003). What is more, conditions that increase the stiffness or rigidity of a structure will increase the transmission of vibration through that structure as well as increase its natural frequency (Piersol and Paez 2010). Thus, spine stiffness and vibration transmission may be key components in WBV injury mechanisms.

Based on the available literature, it was hypothesized that increased spinal stiffness/stability due to muscle activity (Wilder et al. 1982; Cholewicki and McGill 1996; McGill and Cholewicki 2001), increased loading and loading frequencies from WBV exposure (Cholewicki and McGill 1996; Simunic et al. 2001; Panjabi 2003), and greater passive tissue resistance and muscle activity from non-neutral postures (Bottoms and Barber 1978; Adams 1995; Boden and Oberg 1998; Chaffin et al. 1999; Bluthner, Seidel and Hinz 2001; McGill and Cholewicki 2001; Toren 2001) would result in transmission peaks at higher frequencies and greater overall vibration transmission. The current study found that under random 6-DOF vibration exposures and field running RMS average exposure levels, voluntary trunk muscle activation while subjects sat in upright (0˚ FLEX/EXT, 0˚ LTB and 0˚TWST) posture, trunk stiffness, transmissibility, and dominant transmission frequencies increased as expected. Significant or near significant stiffness increases were observed in Y, Z, Roll and Yaw, with increased stiffness trends emerging in Pitch once p ≤ 0.16. These increases in stiffness coincided with increased transmissibility and dominant transmission frequencies for or about the same plane of motion. On the other hand, the X-axis had a significant decreasing trend in trunk stiffness when the trunk muscles were voluntarily activated. The same stiffness/dominant
transmission frequency relationship seen in the other axes held for the X-axis, with decreasing trunk stiffness trends coinciding with reduced dominant transmission frequency trends at all levels of the spine if \( p \leq 0.30 \). With the stiffness decrease in the X-axis, one might expect a decrease in transmissibility if the transmission relationship with stiffness in the other axes was maintained. The X-axis, however, does not follow suit again. Here, it was found that a decreasing stiffness tendency in the X-axis was not accompanied by declining transmissibility tendencies. Thus, an interaction between axis, stiffness and transmissibility appears to be present. This is likely due to the increased magnitude of low frequency vibration at the T9 and C7 spinal levels as well as the head. The muscle activity pattern may also be causing some exaggerated trunk motion in the X-axis with vibration exposure. In other words, the muscle activation to correct the subject’s posture as the vibration exposure moves them is likely out of sync with the vibration input, thereby enhancing the effects of vibration at superior levels of the spine (Wilder 1993; Pope, Wilder and Magnusson 1998).

In the field, operators would not perform a voluntary trunk muscle activation as described previously. However, muscle activation and stiffness increases could result from a combination of increased vibration exposure magnitude and/or dominant exposure frequency in the field. Increasing vibration exposure magnitudes has been reported to increase trunk muscle activity (Seidel et al. 1980; Wilder et al. 1982; Damkot et al. 1984; Seroussi et al. 1989; Village, Morrison and Leong 1989; Pope, Wilder and Magnusson 1998). The combination of increased muscle activity and tissue loading rates with increased vibration accelerations should increase the stiffness of the spine (Cholewicki and McGill 1996; McGill and Cholewicki 2001; Simunic et al. 2001; Panjabi 2003). This increased trunk stiffness should produce the same trend of increased vibration transmission and dominant transmission frequency seen in this study when trunk muscle activity was voluntarily increased. In the present study it was found that increasing the magnitude of acceleration for a 6-DOF random vibration exposure while the subject adopted an upright seated posture increased the activation of the posterior trunk muscles in a significant or near significant number of subjects. This increase in random vibration exposure acceleration level and subsequent posterior trunk muscle activity produce few changes in the biodynamic response. Significant increasing X and Y trunk stiffness trends were found, but only nearly significant decreasing trends were found for transmissibility in those axes. Furthermore, the dominant transmission frequency had a decreasing trend in Y with an increased trunk stiffness
tendency. These observations were the opposite of what was found with voluntarily increased trunk muscle activity. Thus it appears that the trunk muscle activity pattern produced to maintain the desired upright posture while exposed to increased 6-DOF random vibration levels in an upright posture is able to counteract the motions at the seat, decreasing the transmission of both high and low frequency motions to the upper body.

The trunk muscle activity trends with an increase in exposure acceleration level are different for the simulated 6-DOF field profiles. This indicates an interaction between profile and exposure level with respect to muscular response. Recall that the EGDADE profile was a low frequency dominant profile that occurred while driving a skidder and the HFEBAC profile occurred while picking-up a load and contained higher frequency accelerations. Increasing the exposure acceleration level of the EGDADE profile coincided with a significant number of subjects with increased rectus abdominus and external oblique muscle activation, with no trend in the posterior trunk muscle. Moreover, the HFEBAC profile showed no significant trends in trunk muscle activity. Despite differences in trunk muscle activity response trends, EGDADE and HFEBAC profiles demonstrated a similar increased stiffness and reduced transmission trend (when seen) to that of the random profile. Thus it appears that the trunk muscle activity pattern produced to maintain the desired upright posture while exposed to increased 6-DOF field vibration exposure levels in an upright posture is able to counteract the motions at the seat, decreasing the transmission of motions to the upper body just as they did under a random vibration exposure. Again the results are infrequent and more investigation needs to be conducted, but the emersion of a response trend contrary to that in the literature further suggests the need for vibration standards created from field based 6-DOF laboratory exposure studies.

Having found some interaction between profile and exposure acceleration level, a more direct investigation into the influence of profile on the biodynamic response was conducted. Here the high exposure acceleration level EGDAGE and HFEBAC exposures were compared to the high exposure acceleration level random profile while in an upright posture. Both field exposures displayed decreasing muscle activity trends for many posterior trunk muscles and increasing trunk muscle activity trends in the external oblique muscles relative to the trunk muscle activity seen in the random exposure profile. Thus under 6-DOF field exposures the back muscles were not as active as they were when exposed to 6-DOF random vibrations. In addition, the external oblique muscles were much more active under 6-DOF field exposures than when exposed to 6-
DOF random vibrations. This trunk muscle activity pattern is similar to that found when increasing the exposure acceleration level of the EGDAGE exposure. Increasing the exposure acceleration level of the EGDAGE exposure resulted in greater abdominal muscle activity for a number of subjects. In addition, the EGDAGE exposure magnitude comparison demonstrated X and Y stiffness increases and transmissibility decreased in a majority of subjects when exposure acceleration level was increased. The shift from a random profile to a field profile demonstrated similar results with a significant or near significant number of subjects with greater trunk stiffness in X and Y, as well as reduced transmissibility. Thus, the trunk muscle activity patterns utilized by the subjects again appear suitable for the reduction of vibration transmission in those axes. However, it appears that trunk muscle activity patterns can only cope with low frequency accelerations from the field. Dominant transmissibility frequency increased in X and Y for a significant or near significant number of subjects, indicating that low frequency vibrations were attenuated but higher frequency vibrations were not. A similar pattern was observed for pitch. Conversely, Roll displayed a noticeably different pattern with increased stiffness coinciding with decreased transmissibility and dominant transmission frequencies. It therefore appears that for Roll, trunk muscle activation patterns of the subjects tested are reducing both low and high frequency vibrations as they travel through the body.

It is important to note that despite similar differences in trunk muscle activity, trunk stiffness, vibration transmissibility, and dominant vibration transmission frequency between the random and EGDAGE or HFEBAC profiles, a number of discrepancies still existed. Therefore, the responses to the high exposure acceleration level EGDAGE and HFEBAC profiles were directly compared. With no significant trends in trunk muscle activation when comparing the high EGDAGE exposure to the high HFEBAC exposure, no trends in trunk stiffness might also be expected. In actuality, several stiffness trends were observed. Furthermore, the relationship between trunk stiffness, vibration transmissibility, and dominant vibration transmission frequency varied in a number of instances. This indicates that the interaction between trunk muscle activation patterns and 6-DOF exposure profile will influence the overall biodynamic response. Current vibration guidelines utilize frequency weightings based on biodynamic responses determined from isolated frequency, sinusoidal sweep, or random laboratory exposures and not 6-DOF field exposures since studies of this nature have yet to be conducted (refer to Tables 6.1 through 6.6). The current study has demonstrated that 6-DOF exposure spectra
produce responses noticeably different from a random profile. Of particular note are the greater
dominant translational transmission frequencies and lower dominant rotational transmission
frequencies under 6-DOF field exposures. Thus, current frequency weighting curves may need
revision.

To this point, the discussion has explored the influence of exposure characteristics on the
biodynamic responses in an upright posture. It has been demonstrated that posture can alter the
biodynamic response (Seidel et al. 1980; Wilder et al. 1982; Pope, Broman and Hansson 1990;
Wilder et al. 1994; Zimmerman and Cook 1997; El-Khatib et al. 1998; Pope, Wilder and
Magnusson 1998; Matsumoto and Griffin 2000; Hinz et al. 2001; Jack and Eger 2008). However, these studies are limited to exposures with only a few DOF and isolated single plane
of motion trunk postures (refer to Table 6.6). To address these shortcomings, the current study
explored the influence of several-isolated (flexion, extension, LTB and TWST) and combination
(FLEX/LTB/TWST and EXT/LTB/TWST) trunk postures while exposed to the two high
exposure acceleration level field profiles, EGDade and HFEBAC.

For a given exposure profile, clear differences in posterior and anterior trunk muscle
activation trends were observed between postures. However, the most notable observation in the
postural analysis was the difference between the posterior trunk muscle activity of the high
exposure acceleration level EGDade and HFEBAC exposures for the majority of postures
investigated. Increases in posterior muscle activity appeared in a significant or near significant
number of subjects under the HFEBAC exposure while no trends appeared in the EGDade
exposure. Abdominal muscle activity trends also differed with exposure profile but the muscle
responses varied between postures and muscles. For example, when flexing, the EGDade
exposure resulted in a majority of subjects having reduced left and right Rectus Abdominus
activity, but the HFEBAC exposure produced no trends. Furthermore, under the EGDade
exposure the right external oblique had an average increase in muscle activity greater than that of
the left external oblique, but the opposite pattern occurred with the HFEBAC exposure. This
indicates an interaction between exposure profile, posture and abdominal muscle activation. This
interaction also applies to the posterior trunk muscles as the increased muscle activation trends
were not consistent across all muscles and postures investigated.

The average change in stiffness as subjects moved from the upright posture to one of the
postures investigated differed with posture and exposure for a given axis. For example, when
flexing the average Pitch trunk stiffness was greater under the EGDADe profile (2.04 Nm/rad) than the HFEBAC profile (1.74 Nm/rad). However, the FLEX/LTB/TWST posture combination had a greater Pitch trunk stiffness under the HFEBAC profile (2.73 Nm/rad) profile than the EGDADe profile (2.46 Nm/rad). This indicates an interaction between posture, exposure and trunk stiffness. Although the magnitude of the stiffness trends observed increase or decrease with exposure profile for a given posture, the actual trend observed is the same. Thus, it appears that posture may have more of an influence on trunk stiffness than the exposure profile.

Focusing on transmissibility at the T9 spinal level, with the exception of the Z-axis while adopting an extension/LTB/TWST posture combination under the EGDADe exposure, posture and muscle activation combinations that lead to increased stiffness trends coincided with reduced vibration transmission and a decrease in dominant transmission frequency for both the EGDADe and HFEBAC exposure profiles when seen. The muscle activity and passive tissue restraint associated with each given posture seems able to mitigate the transmission of vibration to the T9 spinal level. This pattern holds true, although in the opposite direction, when stiffness decreased. Here, the posture and muscle activation combinations that lead to decreased stiffness trends coincided with increased vibration transmission and increased dominant transmission frequencies when observed. Thus, the muscle activity and passive tissue restraint associated with that posture are not able to mitigate the transmission of vibration to the T9 spinal level.

Shifting the focus to higher spinal levels, the increased stiffness and reduced vibration transmission pattern seen for non-neutral postures above also occurred for the head transmissibility, with a few exceptions (all limited to the X or Y-axes). Again, muscle activity and passive tissue restraint associated with each given posture seems able to mitigate the transmission of vibration. It should be noted that neck muscle activity required to maintain the subject’s gaze of the postural control targets also plays a role in reducing the vibration transmission to the head. When trunk stiffness decreased, like the T9 spinal level, the head transmissibility increased for any give posture and profile with the only exception occurring in the Z-axis while LTB under the EGDADe exposure. Once more, muscle activity and passive tissue restraint associated with a given posture were not able to mitigate the transmission of vibration up the spine. The muscle contractions of both the trunk and neck may be out of phase with those vibration inputs causing the motions at the head to be increased. Also, note that more transmissibility trends were observed under the EGDADe exposure than the HFEBAC,
indicating that a driving exposure has more of an influence on head motion for a given posture than that of a control operation exposure like the HFEBAC profile.

With regard to dominant transmission frequency, decreased stiffness trends still coincided with increased dominant transmission frequencies when observed (as they did at the T9 spinal level). However, an increase in trunk stiffness did not always coincide with a decrease in dominant transmission frequency. Thus, muscle activity and passive tissue responses were able to reduce high frequency vibrations in some instances (i.e. Roll while flexed under the EGDade exposure), but not in others (i.e. Pitch while LTB under the HFEBAC exposure). Transmissibility and dominant transmission frequency trends were infrequent for the C7 spinal level with the posture, stiffness, and vibration transmission patterns differing from that of the T9 spinal level or the head in a number of instances. This indicates another interaction is occurring, one that adds spinal level to the interactive effects of posture and stiffness on transmissibility and dominant transmission frequency.

Biodynamic responses found in the laboratory were infrequent, making it difficult to find patterns between postures, vibration exposures and musculoskeletal symptoms. That said, overlap between the field (Jack et al. 2008a - Chapter 3) and laboratory findings occurred in two instances. Operators with the greatest percentage of time extending the trunk >20° while driving in the field were the ones who reported musculoskeletal symptoms for the neck (Jack et al. 2008a - Chapter 3). In the laboratory under the high exposure acceleration level EGDade exposure (i.e., a typical driving exposure), this posture was associated with increased seat-to-head vibration transmission for nearly all planes of motion. Furthermore, in the field, the operator who reported LBP was found to spend the most time adopting a deep LTB to the left while driving, DOAL and PUAL (Jack et al. 2008a - Chapter 3). When exposed to a representative driving condition from the field in the laboratory, LTB was associated with greater Z-axis vibration transmission to the T9 spinal level. This lends support to the notion that increased vibration transmission plays a role in operator injury.

Several interactions were observed in this investigation between various combinations of profile, exposure level, axes, posture, muscle activity, stiffness, transmissibility, dominant transmission frequency, and spinal level. Unfortunately, the binomial probability calculations used in this study to find statistically significant trends only compare two variables at a time. As a result, potential interactions between variables can only be observed through differences in the
magnitude or direction of the trends found. The significance of that interaction cannot be determined. The posture evaluation was also hampered by the two variable comparison limitation of the binomial probability calculations used. Investigating more than a few postures would be time intensive and make locating interactive patterns difficult. Thus, only a few postures were utilized. Furthermore, the postures investigated were unsupported trunk postures. Anderson, Ortengren and Nachemson (1975) found that the use of backrests reduced lumbar and thoracic spinal muscle activity and lumbar vertebral disc pressures. Anderson, Ortengren and Nachemson (1975) also reported that the use of armrests (arms supported on a table) decreased trapezius muscle activity. These differences in muscle activity and mechanical characteristics of the spine due to back and arm rests would alter the responses found in the current thesis. The use of back and arm rests would also provide additional vibration inputs that can alter the biodynamic responses observed. Thus the findings of this study, although they provide valuable insight into the human response to complex field vibration exposures while adopting field measured postures, are only generalizable if they are compared to unsupported postures in the field. In the future, more postures should be explored, with special attention given to combination and supported postures since unsupported isolated single plane of motion trunk postures are rarely found in the field.

The number of exposure levels and spectra investigated were also limited. The findings of this thesis provided a preliminary look at the human biodynamic response to 6-DOF vibration exposures and postures found in the field, and although the acceleration levels and spectral profiles utilized were representative of typical driving and loading conditions found in Northern Ontario, they were not the only 6-DOF spectra and amplitude combinations observed in the field. As such, the findings are only generalizable to the conditions tested. What's more, the input accelerations utilized were created to match a representative field exposure, they were not actual field exposures. In addition, the rigid seat utilized in the laboratory does not allow the pelvis to rotate as it would in the field, again limiting the generalizability of the biodynamic investigation findings. Wilder and Pope (1996) discuss how the moment arm created by the anterior offset of the ischial tuberosities may induce an additional rocking motion in the pelvis within a vibration environment. This pelvic rocking may amplify the vibration motion transmitted to the spine (Wilder and Pope 1996).
CHAPTER 6: Field Exposure Spectra

This study found that the use of 6-DOF exposures resulted in a stiffness/vibration transmission relationship opposite to that expected (based on the findings of available research), but only two 6-DOF profiles were utilized and as such the effect of more 6-DOF exposures should be explored in the future. Furthermore, differences in the biodynamic response between axes for a given combination of profile, exposure level, posture, or muscle activity, had been found but no direct investigation into the effects of exposure axes were conducted. The current study looked at axes in isolation in an attempt to simplify the analyses and discussion. Future studies should look at how differences in 6-DOF exposure responses relate to differences in exposure axis profiles and exposure acceleration levels. Multiple input transfer functions are also recommended for future studies. Paddan and Griffin (1988a; 1988b; 1994; 2000), as well as Barnes and Rance (1974) demonstrate how isolated X,Y,Z, Roll, Pitch and Yaw inputs produce responses in all 6-DOF. These cross axis effects should be explored, particularly under field 6-DOF exposures.

Several trunk muscles were monitored in the current study, and the activation of those muscles was easily related to the stiffness and vibration transmission patterns observed for the T9 spinal level. The differences in response observed between spinal levels, particularly in the posture analysis, are likely due to neck muscle activity and stiffness changes at higher levels of the spine, which are required to keep the subjects gaze of the posture control target. Thus, neck muscle activation and stiffness calculations are also recommended for future studies. In addition, MVCs utilized in the laboratory portion of this thesis followed the protocol laid out by Brown and Potvin (2005). This entailed collecting MVC data for the abdominal and lumbar spinal muscles in a prone or supine position. However, subjects adopted various seated positions during testing and differences in electrode location and the amount of subcutaneous tissue between the electrode and muscle effects the EMG signal recorded. In the future the MVCs should be recorded in the seated position utilized during testing.

In addition to implications for the MVCs mentioned above, skin motion also affects the EMG and acceleration data recorded with skin mounted electrodes and kinematic marker triads. It is assumed that skin mounted markers are rigidly connected to underlying bony segments (Stagni et al. 2005), and thus accurately represent the movement of the underlying bone. Similarly, skin mounted EMG electrodes placed over a specific portion of a muscle are assumed to remain over those specific muscle fibers. Unfortunately, this is not the case. During
movement, markers located directly on the skin above anatomical landmarks undergo displacements relative to the underlying bone (Cappozzo et al. 1996) due to the interposition of soft tissues (Stagni et al. 2005). EMG electrodes also move relative to underlying muscles. These soft tissue artifacts (STA) can lead to an overestimation of joint motion (Leardini et al. 2005). Although STA has the same frequency content as the absolute movement of the underlying bone (Cappozzo et al. 1996), its effects can be minimized (Cappozzo et al. 1996; Leardini et al. 2005; Stagni et al. 2005). Precautions to minimize the STA effects and allow for more reliable results include placing markers on less fleshy areas far from joints (Cappozzo et al. 1996). This study mounted markers over vertebral spinous processes and utilized young lean males to help minimize the influence of STA. Cerveri et al. (2004) found that spinous processes sustained less STA due to the low-thickness of the soft tissue between the marker and the bony part. Leardini et al. (2005) discuss how STA minimization and compensation can also be accomplished through a dynamic calibration. One example of this would be the determination of subject skin resonance at the location of each skin mounted device. The resonant motion can then be controlled for with an appropriate de-noising technique. This type of procedure was not utilized in the current thesis, but is recommended for future studies. With respect to STA and EMG, the high-pass filtering of EMG signals recommended by Deluca (1997) will help to remove the influence of low-frequency skin motion, a technique that was employed during this thesis.

Finally, hand-dominance was not considered in the laboratory study. Although limited to chronic low-back pain sufferers, Sung, Spratt and Wilder (2004) found that hand-dominance was related to the response time and fatiguability of the right and left lumbar erector spinae and multifidus muscles. Since the pattern of muscle activation appeared to play a role in the biodynamic responses observed in the laboratory and the sequencing of right and left lumbar spinal muscle activation is influenced by handedness (Sung, Spratt and Wilder 2004), it would prudent to explore the effects of hand-dominance on trunk muscle responses under 6-DOF field vibration exposures and posture in the future.

6.5 CONCLUSION

It was clear that 6-DOF field exposures produced very different biodynamic responses than those expected from the literature with increased trunk stiffness often coinciding with
reductions in transmissibility and dominant transmission frequencies. This alone will hamper the effectiveness of current vibration exposure guidelines, which utilized frequency weightings derived from studies typically limited to isolated axis random vibration exposures. Moreover, the interactive effects of field tri-planar trunk postures and 6-DOF vibration exposures on trunk muscle activity, trunk stiffness, vibration transmissibility and dominant transmission frequency need to be accounted for if vibration guidelines are going to be effective.

Although limited to a few occurrences, the current laboratory study was able to relate the biodynamic responses found in the laboratory back to the musculoskeletal complaints of the skidder operators from whom the original posture and vibration exposures were derived. Trunk extension and LTB was associated with increased vibration transmission in the laboratory and increased neck and lower back pain in the field. Thus, it appears that increased vibration transmission does play a role in operator injury. Similar studies with a larger subject pool, and explore more complex tri-planar posture combinations and 6-DOF field vibration exposure should be conducted in the future.

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CHAPTER 7

GENERAL OVERVIEW AND RECOMMENDATIONS

7.1 GENERAL OVERVIEW

An initial literature review (Jack and Oliver 2008 – Chapter 2) found that translational and rotational vibration exposure and transmission through the body, transient vibrations and compressive/shear loading of the spine, static postures and repetitive movements of the trunk and limbs, spine stability/stiffness, work duration and muscle fatigue all interact to place MMOs at risk for musculoskeletal injury. Increases in trunk stiffness resulting from the aforementioned risk factor interactions would increase the transmission of vibration through the body, and increase the risk of low-back and/or neck pain. Of particular concern was the interaction between whole-body vibration (WBV), posture and injury. Operator low-back and/or neck pain has been associated with non-neutral operator postures (Village, Morrison and Leong 1989; Bovenzi and Betta 1994; Magnusson and Pope 1998; Toren 2001; Bovenzi, Pinto and Stacchini 2002; Kittusamy and Buchholz 2004; Hoy et al. 2005; Bovenzi et al. 2006; Okunribido, Magnusson and Pope 2006a; Okunribido, Magnusson and Pope 2006b; Eger et al. 2008; Jack et al. 2008 – Chapter 3; Okunribido, Magnusson and Pope 2008), and exposure accelerations (Bovenzi and Betta 1994; Wilkstrom, Kjellberg and Landstrom 1994; Bovenzi 1996; Schwarze et al. 1998; Bovenzi, Pinto and Stacchini 2002; Bovenzi et al. 2006; Burdorf and Hulshof 2006). Moreover, Village, Morrison and Leong (1989), Bovenzi and Betta (1994), Bovenzi (1996), and NIOSH (1997), all caution that posture is a contributing factor to the WBV complaints experienced by operators. Furthermore, the literature review by Jack and Oliver (2008 – Chapter 2) outlines possible mechanisms by which vibration exposure and posture can increase the stiffness of the spine and transmission of vibration through the trunk.

The available literature indicates that increased spinal stiffness/stability due to muscle
activity (Wilder et al. 1982; Cholewicki and McGill 1996; McGill and Cholewicki 2001), increased loading and loading frequencies from WBV exposure (Cholewicki and McGill 1996; Simunic et al. 2001; Panjabi 2003), and greater passive tissue resistance and muscle activity from non-neutral postures (Bottoms and Barber 1978; Cholewicki and McGill 1996; Boden and Oberg 1998; Chaffin et al. 1999; Bluthner, Seidel and Hinz 2001; McGill and Cholewicki 2001; Toren 2001) would result in transmission peaks at higher frequencies and greater overall vibration transmission. A consolidation of findings from several studies supports this hypothesis, with higher compressive spinal loading, decreased lumbar lordosis (a flattening of the lower back curvature), increased muscle activity, and increased stiffness/stability conditions generally resulting in transmission peaks at higher frequencies and greater vibration transmission (Seidel et al. 1980; Wilder et al. 1982; Pope, Broman and Hansson 1990; Wilder et al. 1994; Zimmerman and Cook 1997; El-Khatib et al. 1998; Pope, Wilder and Magnusson 1998; Hinz et al. 2001; Jack and Eger 2008). Since the aforementioned conditions are also associated with operator injuries, it seems apparent that spine stiffness and vibration transmission may be mediating factors for WBV injuries.

Despite the support for an interaction between WBV exposures and operators, current vibration health standards (i.e. ANSI S3.18:1979, 2001 ACGIH TLV, BS 6841:1987, ISO 2631-1:1997, EU Directive 2002/44/EC, EN 14253:2003, etc.) do not account for postures or all vibration exposure degrees-of-freedom (DOF). This may contribute to why mobile machine operators (MMOs) are still being injured. Currently vibration health guidelines only focus on the magnitude and frequency of vibration exposures in three directions (BS 6841:1987; ISO 2631-1:1997). The epidemiological studies relating vibration exposures to low-back and neck pain/injury are often limited to a few DOF, with minimal spectral data and virtually no rotational data (Jack et al. 2010 – Chapter 4; Chapter 5). In addition, the pattern of frequency dependence used by these guidelines is based on the subjective and biodynamic response of individuals exposed to vibration in laboratory studies (Griffin 1998), which are also limited in the exposure axes and spectra utilized. Moreover, the vibration exposures and postures used in these laboratory studies are not based on field measurements. Only a few studies report using simulated field exposure in their biodynamic laboratory studies (Dupis et al. 1991; Wilder et al. 1994; Bluthner, Seidel and Hinz 2001; Bluthner, Seidel and Hinz 2002; Schust et al. 2006; Jack and Eger 2008). In all cases, the simulated field exposures were limited to 3-DOF or less in the
laboratory. What’s more, only a few studies have directly measured operator postures in the field (Eklund et al. 1994; Gellerstedt 1998; Hermanns et al. 2008; Jack et al. 2008 – Chapter 3). This lack of posture data may also be hampering the effectiveness of postural interventions as well.

The intent of this thesis was to address the above study and guideline limitations by conducting a comprehensive investigation that combined tri-planar trunk posture measurements (Jack et al. 2008 – Chapter 3), 6-DOF vibration exposure acceleration (Jack et al. 2010 – Chapter 4) and spectra measurements (Chapter 5), and musculoskeletal injury reports from the field with a thorough biodynamic investigation in the laboratory (Chapter 6). Industry partnerships and operator complaints lead to a focus on forestry skidder operators in the field. However, the laboratory investigations focused on trends which could generalized to other vehicles.

7.1.1 Field study

An overview of the findings from the field study conducted for this thesis is presented in this section. The tri-planar trunk postures (Jack et al. 2008 – Chapter 3), 6-DOF vibration exposure acceleration (Jack et al. 2010 – Chapter 4) and spectra measurements (Chapter 5) are summarized below.

While driving their skidders in the field, the operators in this study typically sat with a forward facing and slightly extended trunk accompanied by a large lateral bend (LTB), likely the result of operators using the armrest to support the trunk. When the skidder operators picked-up (PUAL) or dropped-off (DOAL) a load, they adopted a large LTB while extending the trunk (greater than what was observed while driving), and twisted their trunk to the right. This posture is consistent with one which would be required to view the load. Finally, while ploughing logs, skidder operators extended their trunk, and were often bent and twisted to one side.

Mean translational ISO 2631-1:1997 running RMS weighted and unweighted accelerations from the field operation of forestry skidders in Northern Ontario were all in excess of 0.36 m/s² and 0.57 m/s², with the greatest average accelerations occurring while driving unloaded. With respect to the rotational accelerations, running RMS weighted and unweighted accelerations all exceeded 0.14 rad/s² and 0.76 rad/s² respectively. Here, the greatest average weighted rotational accelerations occurred while driving unloaded, but the greatest average
unweighted rotational accelerations occurred while ploughing. Furthermore, the greatest running RMS exposures measured occurred in the Y-axis for translational exposures and roll for the rotational exposures (both weighted and unweighted) while driving (driving loaded and driving unloaded). This running RMS axis pattern remained relatively consistent while ploughing logs and dropping off or picking up a load. The exceptions included the weighted X-axis which was greatest while dropping off a load, the weighted Z-axis which was greatest while picking up a load and the unweighted pitch axis was greatest while dropping off a load and ploughing.

Using unweighted 1/3-octave band running RMS average spectra to establish spectral profiles that occur while operating skidders in the field revealed several unique exposure spectra. Nine spectral profiles were found for the X-axis, thirteen for the Y-axis, six for the Z-axis, eight for Roll, seven for Pitch, and seven for Yaw. These profiles occurred in a number of skidders, and tended to appear under similar operating conditions across those skidders. Driving tasks were dominated by low frequency accelerations (<5 Hz), with some profiles containing higher frequency 1/3-octave band or DFT accelerations. While driving, dominant peaks were typically between 0.8Hz and 2Hz for translational and 2.5Hz and 4Hz for rotational axes (Roll and Pitch). Conversely, when DOAL and PUAL, signal dominance was typically at higher frequencies (>5 Hz) with dominant peaks between 8Hz and 31.5Hz for translational axes. Roll and Pitch accelerations on the other hand, had much more prevalent accelerations below 5Hz when DOAL and PUAL. Yaw accelerations were dominated by higher frequencies (>4Hz) in all conditions. Compiling the individual axis spectral profiles into 6-DOF combinations revealed that several 6-DOF combinations of the individual axes profiles occurred in the field. However, these 6-DOF profile combinations were unique to individual skidders.

Consolidating all of the findings from the field revealed two general patterns. When driving, operators were exposed to vibrations with higher accelerations and lower frequency exposures while adopting the most neutral postures. On the other hand, when DOAL, PUAL or ploughing, operators were exposed to vibrations with lower accelerations and higher frequency exposures while adopting the postures furthest away from neutral.

7.1.2 Laboratory study

The laboratory investigation conducted for this thesis incorporated tri-planar trunk
postures from Jack et al. (2008 – Chapter 3), 6-DOF exposure acceleration levels from Jack et al. (2010 – Chapter 4), and 6-DOF exposure spectra from Jack et al. (Chapter 5) in an attempt to gain a comprehensive understanding of how the body responds to vibration under field conditions. Subjects adopted isolated axial trunk twisting (TWST; 15° to the right), lateral trunk bending (LTB; 15° to the right), and trunk flexion/extension (FLEX/EXT, 15° of flexion or extension) as well as upright (0° FLEX/EXT, 0° LTB, and 0° TWST), and combination postures (15° flexion or 15° extension with 15° LTB and 15° TWST). These postures represented a neutral posture and a commonly adopted deviation from that neutral posture. Based upon the field data, 15° of TWST represents a common posture adopted by forestry skidder operators while driving loaded (DL), driving unloaded (DUL), dropping off a load (DOAL), picking up a load (PUAL), and Ploughing. The 15° LTB angle was common in operators who didn’t adopt the deep supported LTB to one side while they DL, DUL, DOAL PUAL and Ploughed. Similar to LTB, trunk EXT was typically performed with the trunk supported against a back rest. Therefore, the trunk EXT angle was a mirror of the 15° flexion angle. This flexion angle was selected because it represented the outer limit of what was seen in the field. Both tri-planar trunk posture combinations investigated were observed in the field while monitoring the plough or grapple. The extension combination posture was observed while driving; however, the LTB was typically to the left as operators extended back and to the side while driving. The low and high exposure acceleration levels, as well as the HFEBAC and EGD ADE exposure spectra utilized (Figures 6.6 and 6.7) were selected because they represented two distinct operating tasks in the field, driving and operating implements (i.e. picking up/dropping off a load). What’s more, the 6-DOF profiles chosen were selected because each individual axis spectral profile occurred in more than one skidder and differed between each axis of the two profiles. A random profile was also utilized such that comparisons between the biodynamic responses to field exposures and the commonly used random exposure could be made.

Increased spinal stiffness/stability due to muscle activity (Wilder et al. 1982; Cholewicki and McGill 1996; McGill and Cholewicki 2001), increased loading and loading frequencies from WBV exposure (Cholewicki and McGill 1996; Simunic et al. 2001; Panjabi 2003), and greater passive tissue resistance and muscle activity from non-neutral postures (Bottoms and Barber 1978; Cholewicki and McGill 1996; Boden and Oberg 1998; Chaffin et al. 1999; Bluthner, Seidel and Hinz 2001; McGill and Cholewicki 2001; Toren 2001) would result in transmission
peaks at higher frequencies and greater overall vibration transmission. To explore this hypothesis, several comparisons were made.

Initially, a comparison between normal and voluntarily increased trunk muscle activation under the random 6-DOF vibration exposure spectra and field exposure acceleration levels, while subjects sat in upright posture (0° FLEX/EXT, 0° LTB and 0°TWST) was conducted. This condition increased the trunk muscle activity and trunk stiffness, thereby allowing a probe into the relationship between trunk stiffness, transmissibility, and dominant transmission frequency. It was expected that increased muscle activity would increase trunk stiffness, transmissibility, and the dominant transmission frequency. For the most part, this is what was found for Y, Z, Roll, Pitch and Yaw. The X-axis on the other hand, had a decreasing trend in trunk stiffness when the trunk muscles were voluntarily activated. This reduction in X stiffness coincided with reduced dominant transmission frequency trends as expected, but vibration transmissibility did not decrease. It was suspected that the pattern of muscle activity may be causing some exaggerated trunk motion in the X-axis with vibration exposure, reducing trunk stiffness in that plane and increasing transmissibility.

In the field, operators would not voluntarily activate their trunk muscles as described previously. Muscle activation and stiffness increases could result from a combination of increased vibration exposure magnitude and/or dominant exposure frequency in the field. Increasing vibration exposure magnitudes has been reported to increase trunk muscle activity (Seidel et al. 1980; Wilder et al. 1982; Damkot et al. 1984; Seroussi et al. 1989; Village, Morrison and Leong 1989; Pope, Wilder and Magnusson 1998). The combination of increased muscle activity and tissue loading rates with increased vibration accelerations should increase the stiffness of the spine (Cholewicki and McGill 1996; McGill and Cholewicki 2001; Simunic et al. 2001; Panjabi 2003). Increasing the exposure acceleration level of acceleration for a 6-DOF random vibration exposure while the subject adopted an upright seated posture in the laboratory increased the activation of the posterior trunk muscles, but produced few changes in the biodynamic response. As expected, increases in X and Y trunk stiffness trends were found, but decreasing trends were found for transmissibility and dominant transmission frequencies. This was contrary to what was expected. It appeared that the trunk muscle activity pattern produced to maintain the desired upright posture while exposed to increased 6-DOF random vibration levels
in an upright posture was able to counteract the motions at the seat, decreasing the transmission of both high and low frequency motions to the upper body.

Under the simulated 6-DOF field profiles, the trunk muscle activity trends with an increase in exposure acceleration level were different. Increasing the exposure acceleration level of the EGDADE profile coincided with increased activation of anterior trunk muscles, and no trend in the posterior trunk muscle activation. The HFEBAC profile showed no trends in trunk muscle activity. Despite differences in trunk muscle activity response trends, EGDADE and HFEBAC profiles demonstrated a similar increased stiffness and reduced transmission trend to that of the random profile. Again, the trunk muscle activity pattern produced to maintain the desired upright posture while exposed to increased 6-DOF field vibration exposure levels in an upright posture was able to counteract the motions at the seat, decreasing the transmission of motions to the upper body. The emersion of a response trend contrary to that in the literature further suggests the need for vibration standards created from field based 6-DOF laboratory exposure studies.

Having found some interaction between exposure profile and exposure acceleration level, a more direct investigation into the influence of profile on the biodynamic response was conducted. High exposure acceleration level EGDAGE and HFEBAC exposures were compared to the high exposure acceleration level random profile while in an upright posture. Both field exposure profiles displayed decreasing muscle activity trends for many posterior trunk muscles and increasing trunk muscle activity trends in the external oblique muscles relative to the trunk muscle activity seen in the random exposure profile. Thus, under 6-DOF field exposures, back muscles are not as active as they were when exposed to 6-DOF random vibrations. In addition, the external oblique muscles are much more active under 6-DOF field exposures than when exposed to 6-DOF random vibrations. This trunk muscle activity pattern was similar to that found when increasing the exposure acceleration level of the EGDADE exposure. Again, the trunk muscle activity patterns utilized by the subjects appear suitable for the reduction of vibration transmission in those axes. However, it appears that that trunk muscle activity pattern can only cope with low frequency accelerations from the field as the dominant transmissibility frequency increased in X, Y and Pitch. Conversely, Roll displayed a noticeably different pattern with increased stiffness coinciding with decreased transmissibility and dominant transmission frequencies. It therefore appears that for Roll, trunk muscle activation patterns of the subjects
tested were reducing both low and high frequency vibrations as they traveled through the body.

Not only did the high exposure acceleration level EGDADAE and HFEBAC profiles have responses that differed from that of a random exposure, but they also differed from each other. Initially, no trends in trunk muscle activation were found when comparing the high EGDADAE exposure to the high HFEBAC exposure, so one might expect no trends in trunk stiffness. In actuality several stiffness trends were observed. Furthermore, the relationship between trunk stiffness, vibration transmissibility, and dominant vibration transmission frequency varied in a number of instances. Thus an interaction between trunk muscle activation patterns and 6-DOF exposure profile on the overall biodynamic response was evident.

The laboratory investigation findings discussed above have focused on the influence of exposure characteristics on biodynamic responses in an upright posture. It has been demonstrated that posture can augment the biodynamic response (Seidel et al. 1980; Wilder et al. 1982; Pope, Broman and Hansson 1990; Wilder et al. 1994; Zimmerman and Cook 1997; El-Khatib et al. 1998; Pope, Wilder and Magnusson 1998; Matsumoto and Griffin 2000; Hinz et al. 2001; Jack and Eger 2008). However, these studies are limited to exposures with only a few DOF and isolated postures. Here, the influence of several-isolated flexion, extension, LTB, TWST and combination (FLEX/LTB/TWST and EXT/LTB/TWST) trunk posture deviations from an upright seated posture on the biodynamic response were explored while subjects were exposed to the two high exposure acceleration level 6-DOF field profiles (EGDADE and HFEBAC).

With respect to muscle activity, clear differences in abdominal muscle activation trends were observed between postures for a given exposure profile. Posterior trunk muscle activation trends also differed between postures, but these posterior trunk muscle trends only appeared under the HFEBAC exposure since the EGDADAE profile demonstrated no influence on posterior trunk muscle activity. This demonstrated an interaction between trunk muscle activity, posture and exposure profile.

Trunk stiffness was also found to have an interaction between posture and exposure profile. It was noted, however, that although the magnitude of the stiffness trends observed increased or decreased with exposure profile for a given posture, the actual trend observed was the same. Thus, it appeared that posture had more of an influence on trunk stiffness than the exposure profile.

Turning the focus to vibration transmission, posture and muscle activation combinations
that lead to increased stiffness trends coincided with reduced vibration transmission and a decrease in dominant transmission frequency at the T9 spinal level for both the EGDAADE and HFEBAC exposure profiles. The muscle activity and passive tissue restraint associated with each given posture seemed able to mitigate the transmission of vibration to the T9 spinal level. This pattern held true, although in the opposite direction, when stiffness decreased. Here, the posture and muscle activation combinations that lead to decreased stiffness trends coincided with increased vibration transmission and increased dominant transmission frequencies when observed. Thus, it appears that the muscle activity and passive tissue restraint associated with that posture were not able to mitigate the transmission of vibration to the T9 spinal level. This increased stiffness and reduced vibration transmission pattern was also observed for Head transmissibility (with a few exceptions in the X or Y-axes). When trunk stiffness decreased, like the T9 spinal level, the seat-to-head transmissibility increased for any given posture and profile with the only exception occurring in the Z-axis while LTB under the EGDAADE exposure. Once more, muscle activity and passive tissue restraint associated with a given posture were not able to mitigate the transmission of vibration up the spine. The muscle contractions of both the trunk and neck may be out of phase with those vibration inputs causing the motions at the head to be increased. Also, note that far more transmissibility trends were observed under the EGDAADE exposure than the HFEBAC, indicating that a driving exposure has more of an influence on head motion for a given posture than that of a control operation exposure like the HFEBAC profile.

With regard to dominant transmission frequency, decreased stiffness trends still coincided with increased dominant transmission frequencies when observed (as they did at the T9 spinal level). However, an increase in trunk stiffness did not always coincide with a decrease in dominant transmission frequency. Thus, muscle activity and passive tissue responses were able to reduce high frequency vibrations in some instances (i.e., Roll while flexed under the EGDAADE exposure), but not in others (i.e., Pitch while LTB under the HFEBAC exposure). Transmissibility and dominant transmission frequency trends were sporadic for the C7 spinal level with the posture, stiffness, and vibration transmission patterns differing form that of the T9 or Head spinal level in a number of instances. This indicates another interaction, one that adds spinal level to the interactive effects of posture and stiffness on transmissibility and dominant transmission frequency.
7.1.3 Musculoskeletal injury connections

The previous sections summarized the findings of the field and laboratory studies. Here, connections between those findings and the results of a musculoskeletal injury survey administered in the field are summarized. The field study conducted found that operators with the greatest percentage of time extending the trunk >20° while driving were the ones who reported musculoskeletal symptoms for the neck. In addition, the operators who spent the most amount of time with a trunk flexed >10° while driving reported the most severe musculoskeletal symptoms for the neck. Extending the trunk would result in the operators flexing the neck in order to view their driving routes, while flexing the trunk would result in neck extension by the operators. Both of these neck postures have been found to increase C7-T1 joint loading and trapezius and cervical erector spinae muscle activity (Harms-Ringdahl et al. 1986). Increased joint loading can result in overexertion of tissues and increased cumulative loading, both of which are associate with increased risk of musculoskeletal injuries (Kumar 2001). Greater muscle activity is associated with increased muscle fatigue due to localized reductions in blood flow and the impairment of normal metabolic processes that can result in sensations of pain (Kroemer 1999; Kumar 2001). Therefore, increased joint loading and muscle activity due to flexed and extended postures may have caused the neck pain reported by the operators in this study.

The field investigation found that TWST was associated with neck pain. One operator from the field who complained of neck pain stated that the pain was the result of twisting to see the rear of the vehicle while picking up and dropping off a load. This operator was also exposed to the highest translational and rotational vibration exposures during those operating conditions. Another operator related neck pain directly to vibration exposure. Thus the interactive effects of adverse posture and high vibration exposure appear to lead to neck injury. This notion is supported by Village, Morrison and Leong (1989) who reported a high incidence of neck pain in load-haul-dump operators who have to rotate their trunk towards the direction of travel relative to other workers who face the direction of travel.

The field study also uncovered that one operator reported upper back symptoms. This operator was found to spend the greatest percentage of his time driving, picking-up a load (PUAL) and ploughing a load with a flexed trunk. Flexing the lumbar spine relative to the
sacrum may have been accompanied by some thoracolumbar spine and neck extension to view
the driving route and load. This posture has been found to increase the activity of thoracic erector
spinae (TES) and rhomboids muscles (Harms-Ringdahl et al. 1986; Hanson et al. 1991; O’Sullivan et al. 2006). Much like the neck, fatiguing contractions of the muscles in the upper
back for extended periods of time may explain the upper back symptoms.

Finally, one operator from the field reported low-back pain (LBP). This operator spent
the most time adopting a deep LTB to the left while driving, dropping-off a load (DOAL) and
PUAL. It was noted that the operator who reported LBP spent the majority of time while DOAL
within two distinct flexion/extension and TWST postures indicating frequent movement between
these two postures as the operator attempted to view the load. Pope, Goh and Magnusson (2002)
discuss how high levels of contralateral muscle activity occur to the direction of trunk rotation
and lateral bending, and how muscle activity is small on the ipsilateral side. This asymmetric
muscle activity differentially loads the joints and muscles of the low back. Prolonged and/or
repeated differential loading can result in disproportionate demands on the various muscles
surrounding a joint leading to different levels and rates of muscle fatigue (Kumar 2001). If these
patterns of fatigue are allowed to continue, the altered muscle kinetics may result in joint
kinematics and loading that differ from the normal and optimal pattern for that joint, potentially
leading to alterations in joint stability, stress concentrations, and injury (Kumar 2001; Pope, Goh
and Magnusson 2002). Furthermore, repeated flexion, lateral bending and twisting of the spine
can cause damage to the vertebrae and vertebral discs in vitro (Hardy et al. 1958; Wilder, Pope
and Frymoyer 1988; Callaghan and McGill 2001; Kuga and Kawabuchi 2001). Static twisted
trunk postures are also associated with LBP (NIOSH 1997), and although no reports of ill health
were associated with the tendency to TWST in this study, these postures were observed.
Twisting beyond 15° involves increased muscle effort (Boden and Oberg 1998; Toren 2001).
Several operators were found to exceed 15° of TWST while driving. This increased muscle effort
with TWST can be fatiguing and lead to pain.

When considering the WBV exposures, one operator who complained of LBP pain
associated that pain with vibration exposure. Bovenzi (1996) found a significant association
between WBV and low back complaints with an estimated odds ratio for LBP varying from 1.6
to 2.0 when weighted vector sum accelerations range between 0.7 and 0.9 m/s². This
investigation found that skidder operators were typically exposed to acceleration levels within
this range. However, the operators in this study who reported LBP were not exposed to the greatest exposure accelerations, but they were the operators who adopted the greatest LTB and forward flexion for the greatest percentage of time. Village, Morrison and Leong (1989), Bovenzi and Betta (1994), Bovenzi (1996), NIOSH (1997) and Jack and Oliver (2008 – Chapter 2) all caution that posture is a contributing factor to the WBV complaints experienced by operators. Bovenzi and Betta (1994) reported that vibration dose and postural load combined to increase the odds of LBP.

Links between spectral profiles and biodynamic responses were also explored. Unfortunately, the limited number of musculoskeletal complaints combined with the large number of varying exposure spectra made it difficult to find connections. Similarly, biodynamic responses monitored in the laboratory were infrequent, making it difficult to find patterns between postures, vibration exposures and musculoskeletal symptoms. However, overlap between the field and laboratory finding occurred in two instances. As previously stated, operators with the greatest percentage of time extending the trunk >20° while driving in the field were the ones who reported musculoskeletal symptoms for the neck. In the laboratory under the high exposure acceleration level EGDADE exposure (i.e., a typical driving exposure), this posture was associated with increased seat-to-head vibration transmission for nearly all planes of motion. Furthermore, in the field, the operator who reported LBP was found to spend the most time adopting a deep LTB to the left while driving, DOAL and PUAL. When exposed to a representative driving condition from the field in the laboratory, LTB was associated with greater Z-axis vibration transmission to the T9 spinal level. This lends support to the notion that increased vibration transmission plays a role in operator injury.

7.1.4 Study limitations

Although the field investigation conducted for this thesis was extensive, only eight operators were tested in the field. This limited sample size impaired the generalizability of the results as well as the ability to identify potential connections between the musculoskeletal health complaints of the skidder operators studied and the postures and vibration exposures they were exposed to.
With regard to the laboratory investigation that was conducted, the sample size was again a limitation with only nine subjects tested. A larger subject pool may have yielded less infrequent results making biodynamic response patterns and musculoskeletal injury connections more evident. In addition, the binomial probability calculations used in this study to find statistically significant trends only compare two variables at a time. As a result, potential interactions between variables could only be observed through differences in the magnitude or direction of the trends found. The statistical significance of an interaction could not be determined. The posture evaluation was also hampered by the two variable comparison limitation of the binomial probability calculations used. Investigating more than a few postures would be time consuming and make locating interactive patterns difficult. Thus, only a few postures were utilized. Furthermore, the postures investigated were unsupported trunk postures. Anderson, Ortengren and Nachemson (1975) found that the use of backrests reduced lumbar and thoracic spinal muscle activity and lumbar vertebral disc pressures. Anderson, Ortengren and Nachemson (1975) also reported that the use of armrests (arms supported on a table) decreased trapezius muscle activity. These differences in muscle activity and mechanical characteristics of the spine due to back and arm rests would alter the responses found in the current thesis. The use of back and arm rests would also provide additional vibration inputs that can alter the biodynamic responses observed. Thus the findings of this study, although they provide valuable insight into the human response to complex field vibration exposures while adopting field measured postures, are only generalizable if they are compared to unsupported postures in the field.

Just as only a few postures were investigated, the number of exposure levels and spectra investigated were also limited. The findings of this thesis provided a preliminary look at the human biodynamic response to 6-DOF vibration exposures and postures found in the field, and although the acceleration levels and spectral profiles utilized were representative of typical driving and loading conditions found in Northern Ontario, they were not the only 6-DOF spectra and amplitude combinations observed in the field. As such, the findings are only generalizable to the conditions tested. What's more, the input accelerations utilized were created to match a representative field exposure, they were not actual field exposures. In addition, the rigid seat utilized in the laboratory does not allow the pelvis to rotate as it would in the field, again limiting the generalizability of the biodynamic investigation findings. Wilder and Pope (1996) discuss how the moment arm created by the anterior offset of the ischial tuberosities may induce an
additional rocking motion in the pelvis within a vibration environment. This pelvic rocking may amplify the vibration motion transmitted to the spine (Wilder and Pope 1996).

Trunk muscle activity and stiffness values were calculated, but neck muscle activity and stiffness values were not evaluated. This limited the available biodynamic data for comparison to musculoskeletal injury reports of the neck. In addition, maximum voluntary contractions (MVCs) utilized in the laboratory portion of this thesis followed the protocol laid out by Brown and Potvin (2005). This entailed collecting MVC data for the abdominal and lumbar spinal muscles in a prone or supine position. However, subjects adopted various seated positions during testing and differences in electrode location and the amount of subcutaneous tissue between the electrode and muscle effects the EMG signal recorded. In the future the MVCs should be recorded in the seated position utilized during testing.

In addition to implications for the MVCs mentioned above, skin motion also affects the EMG and acceleration data recorded with skin mounted electrodes and kinematic marker triads. It is assumed that skin mounted markers are rigidly connected to underlying bony segments (Stagni et al. 2005), and thus accurately represent the movement of the underlying bone. Similarly, skin mounted EMG electrodes placed over a specific portion of a muscle are assumed to remain over those specific muscle fibers. Unfortunately, this is not the case. During movement, markers located directly on the skin above anatomical landmarks undergo displacements relative to the underlying bone (Cappozzo et al. 1996) due to the interposition of soft tissues (Stagni et al. 2005). EMG electrodes also move relative to underlying muscles. These soft tissue artifacts (STA) can lead to an overestimation of joint motion (Leardini et al. 2005). Although STA has the same frequency content as the absolute movement of the underlying bone (Cappozzo et al. 1996), its effects can be minimized (Cappozzo et al. 1996; Leardini et al. 2005; Stagni et al. 2005). Precautions to minimize the STA effects and allow for more reliable results include placing markers on less fleshy areas far from joints (Cappozzo et al. 1996). This study mounted markers over vertebral spinous processes and utilized young lean males to help minimize the influence of STA. Cerveri et al. (2004) found that spinous processes sustained less STA due to the low-thickness of the soft tissue between the marker and the bony part. Leardini et al. (2005) discuss how STA minimization and compensation can also be accomplished through a dynamic calibration. One example of this would be the determination of subject skin resonance at the location of each skin mounted device. The resonant motion can then be controlled for with
an appropriate de-noising technique. This type of procedure was not utilized in the current thesis, but is recommended for future studies. With respect to STA and EMG, the high-pass filtering of EMG signals recommended by Deluca (1997) will help to remove the influence of low-frequency skin motion, a technique that was employed during this thesis.

Finally, hand-dominance was not considered in the laboratory study. Although limited to chronic low-back pain sufferers, Sung, Spratt and Wilder (2004) found that hand-dominance was related to the response time and fatiguability of the right and left lumbar erector spinae and multifidus muscles. Since the pattern of muscle activation appeared to play a role in the biodynamic responses observed in the laboratory and the sequencing of right and left lumbar spinal muscle activation is influenced by handedness (Sung, Spratt and Wilder 2004), it would prudent to explore the effects of hand-dominance on trunk muscle responses under 6-DOF field vibration exposures and posture in the future.

7.2 RECOMMENDATIONS

The following recommendations are based on both the findings and limitations of this thesis. In the field operators should attempt to maintain a neutral trunk and neck posture. Trunk extension should be kept below 20° and trunk flexion should be kept below 10° while driving. Trunk twisting and LTB should be minimized as well, with TWST being kept below 15°. In addition, repetitive flexion/extension and twisting motions of the trunk should also be avoided. The repositioning of controls, cab frame components, working attachments, or any other object which would cause an operator to flex, extend, bend or twist the trunk in order to obtain the necessary field of view or operate the necessary controls for the task being performed could help improve operator postures and minimize the need for some repetitive motions. Furthermore, high translational and rotational vibration exposures should be avoided, particularly when adverse postures like twisting are adopted.

The use of 6-DOF exposures in the laboratory produced clearly different biodynamic responses than those expected (compared to studies with limited exposure DOF and posture), with increased trunk stiffness often coinciding with reduced transmissibility and dominant transmission frequencies. Moreover, field exposures produced biodynamic responses that significantly differed from the random exposures often used in laboratory studies. Of particular
note are the greater dominant translational transmission frequencies and lower dominant rotational transmission frequencies under 6-DOF field exposures. Thus, the current frequency weighting curves may need revision.

Future biodynamic studies used to establish health guidance for vehicle operators should therefore be based on 6-DOF field exposure levels and spectra. These studies should also incorporate field measured postures, with special attention given to combination postures since isolated trunk postures are rarely found in the field. As such, future field investigations should measure both translational and rotational vibration exposure at the operator/seat interface as well as tri-planar trunk and neck postures so that that data is available for use as inputs in biodynamic laboratory studies. Furthermore, more postures should be explored, with special attention given to combination and supported. The measurement of neck postures is also recommended because the laboratory investigation for this thesis suggested that differences in biodynamic responses observed between spinal levels, particularly in the posture analysis, are likely due neck muscle activity and stiffness changes at higher levels of the spine, which are required to keep the subjects gaze of the posture control target. Thus, neck muscle activation and stiffness calculations are also recommended for future studies.

Although muscle activation levels were monitored in the laboratory portion of this thesis, muscle activation patterns and sequencing with the vibration inputs were not explored. It appeared that the pattern of activation played a crucial role in the biodynamic responses observed. Thus, future studies should attempt to investigate the pattern of muscle activity when exposed to field 6-DOF exposures, under various field measured postures.

Differences in the biodynamic response between axes for a given combination of profile, exposure level, posture, or muscle activity, had also been found but no direct investigation into the effects of exposure axes were conducted. The laboratory study conducted for this thesis looked at axes in isolation in an attempt to simplify the analyses and discussion. Future studies should look at how differences in 6-DOF exposure responses relate to differences in exposure axis profiles and exposure acceleration levels. Multiple input transfer functions are also recommended for future studies. Paddan and Griffin (1988a; 1988b; 1994; 2000), as well as Barnes and Rance (1974) demonstrate how isolated X,Y,Z, Roll, Pitch and Yaw inputs produce responses in all 6-DOF. These cross axis effects should be explored, particularly under field-based 6-DOF exposures.
Finally, the field and laboratory studies conducted tested a limited number of vehicles and subjects. It is suggested that a greater number of operators be tested in the future so that the results can be more generalizable.

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Schust, M., Bluthner, R. and Seidel, H., 2006. Examination of perceptions (intensity, seat comfort, effort) and reaction times (brake and accelerator) during low-frequency vibration in x- or y-direction and biaxial (xy-) vibration of driver seats with activated and deactivated suspension. *Journal of Sound and Vibration*, 298, 606-626.


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APPENDIX A

THE RELATIONSHIP BETWEEN SEAT HEIGHT, KNEE FLEXION AND TRUNK FLEXION ANGLES DURING CLOSED PLANAR MOTIONS OF THE LOWER LIMB WHILE SEATED

A.1 INTRODUCTION

Adopted postures while driving a vehicle have been linked to musculoskeletal injuries (Griffin 1995; Reed, 1998; Michida et al. 2001). These postures are often reported qualitatively making guidelines difficult to establish. Thus, the quantitative assessment of postures while driving a vehicle is desired. In particular, quantitative investigations into trunk postures need to be conducted since complaints of low back pain are common among mobile machine operators (Hagen, Magnus and Vetlesen 1988; Axelsson and Ponten, 1990; Hansson 1990; Harstella, 1990; Bovenzi 1996; Synwoldt and Gellerstedt 2003).

Goniometry is a useful tool for the measurement of joint angles in vehicle operators due to its relative inexpensiveness, minimal subject encumbrance, and ease of use. When aligned over the hip, goniometers can be used to measure trunk angles. This approach requires the assumption that the lower limb is stationary and that all of the motion recorded is the result of the trunk moving. This is often not the case, with operators moving their legs voluntarily or as a result of momentum generated from transient vibration exposures created by driving on rough terrain. If one slides their foot towards the base of the seat, flexing and elevating their knee while the trunk is perfectly vertical, and increased trunk flexion angle would result. Conversely, sliding the foot away from the base of the seat, extending and lowering the height of the knee while the trunk is again perfectly vertical, would result in an increased trunk extension angle. The extent of the angle changes is a function on the individual’s anthropometry where the limb segment lengths will affect the angles seen (seat height will also affect the observed angles). For example, given the same foot and seat location, an individual with a larger shank segment length would
have a knee that is elevated higher, resulting in greater knee and trunk flexion. The same relationship holds true when the foot leaves the floor due to transient exposures. Here, a transient will cause the knee to move in the vertical direction while the foot typically is pulled towards the seat as a result of gravitational forces and a lack of voluntary muscle activation in those situations (i.e. one doesn’t extend their leg forward when they hit a bump with their vehicle). The leg motions described above are discrete and closed motions meaning that they have well defined beginning and end points and are predictable (Schmidt and Wrisberg 1998). Walking and standing up are examples of these types of motion with a clear relation between knee and trunk angles during the movement (Shumway-Cook and Woollacott 1995). The movements of interest in this study, however, resemble the knee and trunk angle relationship of cycling the most (Redfield and Hull 1986; Too and Landwer 2000).

Furthermore, with goniometry, it is assumed that the measurements accurately represent the movement of underlying bones. Unfortunately, during movement, measurement devices mounted directly on the skin (i.e. a goniometer) above anatomical landmarks undergo displacements relative to the underlying bone (Cappozzo et al. 1996), because of the interposition of soft tissues (Stagni et al. 2005). This interposition is the origin of two different sources of error: anatomical landmarks misallocation and skin artifact or soft tissue artifact (STA) (Leardini et al. 2005; Lucchetti et al. 2005; Stagni et al. 2005). Thus, misalignment of the goniometers as well as tissues shifting when subjects adopt testing postures (i.e goniometers are mounted while standing and then the subject sits) can result in measurement inaccuracies.

This study investigates the relationship between knee and trunk angles while considering the shank and thigh segment lengths as well as the seat height. Knowledge of that relationship will allow for the determination of observed trunk angles which are actually the result of leg movements, and provides the information needed to correct for those movements. In addition, this study also investigates the accuracy of the trunk and knee angles measured with a goniometer.
A.2 METHODS

A.2.1 Testing Procedure

15 male subjects were recruited from the general university population (refer to Table A.1 for subject characteristics). Subjects had four reflective markers placed on their ankle (lateral malleolus), knee (lateral malleolus), hip (greater trochanter), and the shoulder (glenohumeral joint). Subjects also had a Biometrics™ SG150 goniometer aligned over their hip and knee while standing. The subjects were then seated and instructed to slide their foot along the floor away from and towards the seat base, as well as conduct a vertical elevation and lowering of the knee while seated. These motions were repeated 10 times at three different seat heights (29.5cm, 41.5cm and 56.5cm). All movements were conducted in the sagittal plane while the subject’s trunk was constrained (via a backrest) to ensure that only the leg was moving. The marker positional data while conducting these movements was collected using a VICONTM 460 motion capture system and six M³mcam cameras with a sample rate of 120Hz. Raw goniometer voltages were simultaneously collected with the same VICONTM 460 motion capture system and 120Hz sampling rate.

<table>
<thead>
<tr>
<th>Table A.1: Subject information.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Age (Years)</td>
</tr>
<tr>
<td>Height (cm)</td>
</tr>
<tr>
<td>Weight (kg)</td>
</tr>
</tbody>
</table>

A.2.2 Data Analysis

The marker positional data and raw goniometers voltage data were subjected to a 20Hz low-pass second order Butterworth filter. Dot product calculations using marker positional data were then used to calculate joint angles from the camera data. The goniometers voltages were converted to joint angles with a calibration equation created from a 7-point calibration at the beginning of each test session. The subject’s thigh (distance from the greater trochanter to lateral
The relationship between seat height, shank and thigh length, and knee angle with the angle of trunk flexion was then determined using a step-wise multiple linear regression model. The knee and trunk angles (determined with the cameras) were normalized to the initial measured position of the subject. Here a positive change in angle represents a flexion of the knee or trunk from that initial position. The model used this normalized trunk angle as the dependent variable, and the normalized knee angle, shank length, thigh length, seat height, initial normalized knee and trunk angles, as well as age, weight and height as independent or predictor variables. Normalized residuals greater than ±3 standard deviations were treated as outliers and removed from the analysis.

In addition to the model creation, the goniometer determined angles were compared to those determined from the camera determined angles. Using the camera determined angles as the “true” angle, the absolute percent error between the two methods was calculated. All calculations were conducted using custom MatLab™ code (MatLab™ 6.5 was used) and data analyses were performed with the SPSS 9.0 statistical software package.

A.3 RESULTS

Initial data screening showed two distinct relationships between the normalized trunk flexion and knee flexion angles. These relationships could be seen for flexion and extension movements (refer to Figure A.1). Note that the majority of knee and trunk flexion occurred while raising the leg. Further analysis found a significant interaction (p<0.001) between the direction of movement and the normalized knee angle with the prediction of the normalized trunk angle. Thus an interaction variable was created (direction) and added to the Stepwise regression analysis.
**Figure A.1:** Trunk angle normalized to the initial measured seated position vs. knee angle normalized to the initial measured seated position. Note: positive angles indicate flexion and negative angles indicate extension of the knee and trunk.

The Stepwise regression analysis yielded a significant predictive model (p<0.001). The model explains 86.3% of the variance in the normalized trunk angle ($r^2=0.863$), and has a ±5.07° standard error of the estimate. The following model (Equation 1) for predicting trunk angles normalized to the initial measured postures was created (the variable definitions can be seen in Table A.2).

$$Y = 1.136X_1 + 0.259X_2 - 3.301X_3 + 0.0502X_4 - 0.0596X_5 + 0.189X_6 - 0.0909X_7 - 0.0908X_8 - 3.553$$  \hspace{1cm} (1)

**Table A.2:** Variable labels and descriptions for Equation 1.

<table>
<thead>
<tr>
<th>Label</th>
<th>Description</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>Normalized Trunk Angle (Degrees, + = Flexion)</td>
<td>-</td>
</tr>
<tr>
<td>$X_1$</td>
<td>$X_2*X_3$</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$X_2$</td>
<td>Normalized Knee Angle (Degrees, + = Flexion)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$X_3$</td>
<td>Movement Direction (0 = Extension, 1 = Flexion)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$X_4$</td>
<td>Seat Height (cm)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$X_5$</td>
<td>Shank Length (cm)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$X_6$</td>
<td>Initial Measured Knee Angle (Degrees)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$X_7$</td>
<td>Weight (kg)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$X_8$</td>
<td>Age (years)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

With respect to the comparison of the goniometer and camera determined angles, large differences were wound between the two methods of angle determination. An absolute percent
error of $27.824 \pm 12.453^\circ$ was found for the trunk, and $7.659 \pm 6.688^\circ$ for the knee (refer to Figure A.2).

**A.4 DISCUSSION**

It is acknowledged that the conditions covered in this study are not the only ones that may be encountered in the field. However, the movements utilized in this study are typical of those seen in the field. The predictive model created fit the data well, but the standard prediction error exceeded $5^\circ$. It was found that the majority of the prediction error stemmed from differences in movement patterns while the foot was on the floor, when the foot was being raised from the floor as the knee flexed and when the foot was being lowered as the knee extended. A preliminary look at a piecewise regression model utilizing separate predictive equations for each of these three conditions produced some improvements. Isolating leg motions while foot was in

![Trunk Angle vs Time](image1)

![Knee Angle vs Time](image2)

**Figure A.2**: Comparison of goniometer (solid line) and camera (dashed line) determined knee and trunk angles (Subject 9).
contact with the floor reduced the prediction error to 2.44° and produced an $r^2$ of 0.972. A model dedicated to knee/trunk extensions while lowering of the foot to the ground produced prediction errors of 4.90° and an improved $r^2$ of 0.921. However, when the foot was being raised from the ground, the predictive model created had a standard prediction error of 7.36° and an $r^2$ of 0.842. This increased error was mainly due to the different movement patterns of individual subjects. A subject specific joint motion calibration procedure should provide a more accurate prediction of trunk angles due to leg motions and in doing so help reduce goniometer measurement errors in the field.

Large differences were found between the goniometer and camera measured angles. These differences between the goniometer and camera angles may be the result of goniometers misalignment and coronal plane motions. As off plane motions were controlled in this study, the angle differences found in this study are likely the result of initial misalignment, as indicated by the angle offset seen in Figure A.2. Note that the movement patterns are the same. Also, the goniometers were placed on the subjects while they were standing, and the tissue displacements that occurred while they sat down could have also changed the alignment of the goniometers. In an attempt to remove this offset, the goniometers raw signal voltage had its bias removed (“zeroed”) while the goniometers was mounted on the subject with the subject in a know posture (90°flexion of the knee and trunk). This procedure greatly reduced the difference in angle determination between the goniometers and camera method (refer to Figure A.3). Using this “on subject zeroing” procedure, reduced the absolute percent errors to $3.178 \pm 4.108°$ and $3.975 \pm 3.787°$ for the trunk and knee respectively.

A.5 CONCLUSION

Goniometers can provide accurate field posture measurements. This is especially true when the raw output voltage of the goniometer is zeroed with the transducer on the subject in a known position prior to testing. Furthermore, the use of predictive equations to reduced errors in measured trunk angles by accounting for leg motions was found to be a viable procedure. Future investigations into subject specific joint motion calibrations should be conducted as they will likely produce more accurate trunk angle predictions and thereby reducing more error in trunk angles measured with a hip mounted goniometer.
Figure A.3: Comparison of goniometer (solid line) and camera (dashed line) determined knee and trunk angles with the goniometer bias removed while the subject is seated in a known position (Subject 9).

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APPENDIX B

THE USE OF MULTIPLE RESOLUTION CROSS-CORRELATIONS TO ALIGN SIMULTANEOUSLY COLLECTED WHOLE-BODY VIBRATION DATA

B.1 INTRODUCTION

Occupational exposure to seated whole-body vibration (WBV) has been associated with a variety of health problems including low back pain (Bottoms and Barber 1978; Hulshof and Veldhuijzen van Zanten 1987; Bovenzi and Betta 1994; NIOSH 1997; Bovenzi and Hulshof 1998). The occurrence and severity of these health complaints can be linked to WBV exposure levels (Bottoms and Barber 1978; Bovenzi and Betta 1994; ISO 2613-1:1997) and the postures adopted by the operators while being exposed to WBV (Village, Morrison and Leong 1989; Magnusson et al. 1996; NIOSH 1997). Although this association has been made, there has been little investigation into the interactive effects of posture and WBV exposures.

The apparent lack of 6-degree-of-freedom (6-DOF) exposure data sets in the available literature for the operator/seat interface (OSI) and vehicle chassis is another concern. Field studies used to discern the health effects associated with WBV exposure for health guidelines are limited to translational WBV exposures, but rotational vibration may have an impact on operator health (Jack and Oliver 2008 – Chapter 2). Thus, further investigations into the effects of 6-DOF WBV on health are necessary. The lack of comprehensive 6-DOF field data also limits the effectiveness of vehicle seat designs. Equipment manufacturers utilize suspension seats to attenuate WBV exposure levels in an attempt to improve operator comfort and reduce operator injuries related to WBV exposure. The lack of 6-DOF chassis WBV field data sets available for use as inputs while tuning the dynamic response of these seats undoubtedly result in less effective seat designs.

The field investigation deficiencies outlined above are partly due to the use of equipment with limited measurement capabilities. The limited memory and available channels for data
collection with most data logging systems has resulted in a lack of simultaneous 6-DOF WBV vehicle chassis, OSI and operator posture measurements. Comprehensive studies of this nature usually need to utilize more than one data logging system (Cation et al. 2008). Here, a time stamp must be applied so that the data time histories of the two different systems can be aligned. This type of alignment reduces the number of channels available for data collection as one channel from each data logger is required for the time stamp. Some researchers may require the use of all available data logger channels for data collection, and therefore an alternative means of aligning the data time histories from the two data logging systems is also required. This need has led these researchers to develop a multiple resolution cross-correlation (MRXcorr) procedure to align 6-DOF WBV data sets collected at the OSI and chassis of mobile forestry machinery. The MRXcorr utilizes selected multisensor data fusion techniques used in military target tracking and autonomous robotics (Smith and Singh 2006). In particular, concepts used to deal with out-of-sequence (OOS) data and multiple resolutonal filtering are used.

In multisensor tracking systems, the data from each sensor is received with its own discrete timestamp, but there are various pre-processing and propagation times, as well as different onsets of data collection from the different sensors resulting in some data arriving OOS (i.e., with a time lag) (Mallick, Coraluppi and Carthel 2001; Smith and Singh 2006). As a consequence of time discrepancies, several forward and backward prediction algorithms have been created for the online processing of OOS data (Hilton, Martin and Blair 1993; Mallick, Coraluppi and Carthel 2001; Nettleton and Durrant-Whyte 2001). The MRXcorr presented here is designed for post processing but still determines and aligns data time histories from multiple sensors, much like the aforementioned algorithms. Post processing enables the entire data set to be used for the alignment procedure, thus improving the accuracy of the alignment over forward and backward prediction models which only use a portion of the data available to predict another portion. These forward and backward prediction models may induce errors in the alignment resulting from errors generated by least square prediction algorithms. While forward and backward prediction algorithms do not perform as well as post processing data alignment techniques, they are well suited for online data alignment.

The MRXcorr also utilizes multiple resolutonal filtering, which allows data to be viewed with combinations of different levels of resolution (Smith and Singh 2006). Here, the MRXcorr uses a large amount of low resolution data for an initial alignment of the data, and then
progressively higher frequency data is added back to the original signal over a small specifically selected data window to improve the accuracy of the alignment. Smith and Singh (Smith and Singh 2006) stated that this division of labor between processing levels can improve performance, especially in environments with high background noise levels. In addition, with less data available at the lowest level, the computation time is decreased (Smith and Singh 2006).

This paper explores the capabilities of the MRXcorr for the alignment of simultaneously collected WBV data sets collected at the OSI and chassis, and validates its use.

B.2 METHODS

B.2.1 Six-degree-of-freedom whole-body vibration measurements

Simultaneous 6-DOF WBV measurements from the OSI and the chassis were determined for three forestry skidders operating in Northern Ontario boreal forest conditions during the summer of 2006. Two separate transducers and data acquisition systems (details are provided in the following sections) were used to collect the OSI and chassis WBV data. Each transducer was oriented such that the X-axis (refer to Figure B.1) of both transducers recorded the forward progression of the forestry skidders.

B.2.1.1 Operator/seat interface whole-body vibration measurement

Two Analog Devices Inc. (MA, USA) ADXL320EB dual axis accelerometers and three Analog Devices ADXRS150EB gyroscopes were orthogonally placed in a Delrin™ plastic casing, which was covered with soft rubber padding. The accelerometers were used to determine linear accelerations in the X-, Y- and Z-axes, while the gyroscopes determined angular velocities in pitch, roll and yaw (refer to Figure B.1). The Delrin™ casing with rubber padding was then placed on the seat surface and beneath the ischial tuberosities (buttock) of the operator. Raw sensor voltages were collected using a 12-bit SOMAT™ Series 2001 Field computer (nCode International Inc., MI, USA) at a sampling rate of 500 Hz.
**Figure B.1**: a) The basicentric orientation used to describe vibration in three translational and three rotational directions at the OSI. b) The orientation of the X and Y vibration axes measured on the chassis of a forestry skidder. Note: in both a) and b), the X-axis indicated the direction of forward progression.

**B.2.1.2 Chassis whole-body vibration measurement**

A MEMSense (SD, USA) sensor capable of measuring linear accelerations in the X-, Y- and Z-axes, and angular velocities in pitch, roll and yaw was housed in a rigid IP-65 rated polycarbonate casing (Hammond Manufacturing, NY, USA). The casing was mounted, using magnets, directly to the skidder chassis. Raw sensor voltages from the MEMSense transducer were collected using a 13-bit Biometrics Ltd. DataLOG No.P3X8 USB (VA, USA) data logger at a sampling rate of 500 Hz.
B.2.2 Multiple resolution cross-correlation procedure

A custom Matlab™ program was created to apply the following MRXcorr procedures for the alignment of 6-DOF WBV data time histories measured on the OSI and chassis of mobile forestry machinery (refer to Figure B.2). Initially, to attenuate high-end noise, all data were low-pass filtered with a cut-off frequency that was 1.5 times the upper bandwidth of the 6-DOF OSI and chassis WBV sensors. A discrete-time Fourier series (DFTS) was then performed on an initial 300,000 data point window at the start of each 6-DOF data set. The upper limit of the frequency spectrum for the initial window of data was determined from the DFTS. The initial data window was then low-pass filtered with the cut-off frequency set to the upper limit of the previously determined low frequency signal range. The low-passed data were then resampled at a rate that was 2n+1 that of the cut-off frequency used for the low-pass filter. A cross-correlation (Xcorr) was then conducted between the two channels of low passed data that measured the same axis (i.e., that measured accelerations in the X-axis on the OSI and chassis) for all six pairs of channels collected. The original data set was then shifted by the phase lag between the two data sets, as determined from the low resolution Xcorr.

The aligned low resolution data was then windowed (1,000 to 5,000 data points) where a high frequency signal was expected (i.e., while the vehicle was idling between start-up and the onset of driving). While idling, a vehicle should display high frequency engine noise in the range of 15-40Hz (based on idling rpm data reported in several manufacturer vehicle specification sheets) for both the OSI and chassis vibration measurements in the X- and Y-axes since seats are not designed to dampen vibrations in those axes. Griffin (1990) reports that X- and Y-axis vibration transmission ratios through the squab of a conventional seat can be near unity. Malchaire, Piette and Mullier (1996) found that seats mounted on rigid or mechanical anti-vibration suspensions had no influence on vibration levels in the X- and Y-axes. The window should also contain some low frequency signal to ensure that the low resolution Xcorr shift is maintained while higher resolution cross-correlations (Xcorrs) provide small adjustments to the previous alignment. The low frequency signals however, must be similar between the channels measuring the same axes. This is done to minimize the discrepancies between the OSI and chassis due to the operator moving. If the low frequency signal produced by the movement of the operator is not minimized, the Xcorrs may provide an improper data point shift estimate for
Figure B.2: Multiple resolution cross-correlation (MRXcorr) alignment algorithm.
Another DFTS was then conducted on the small window of low resolution aligned data to determine the frequency range for the two new data set windows. The windowed data were then low-passed filtered with the cut-off frequency set to the upper limit of the aforementioned frequency range. The low-passed data was then resampled at a rate that is 2n+1 that of the cut-off frequency used for the low-pass filter. Xcors were then conducted between the two channels that measured the same axis for all six channel pairs. The low-resolution shifted data set was then shifted by the phase lag between the two higher frequency content/higher resolution data sets, as determined from the Xcorr. Here, X- and Y-axes are given priority since they typically are the least affected by the seat dynamics as outlined earlier. The higher frequency content data is continually resampled at a progressively higher sample rate (i.e., the rate is doubled with each iteration) and shifted until the original sample rate is achieved. This results in a time history alignment at the original sample rate.

**B.2.3 Multiple resolution cross-correlation procedure validation**

Three validation tests were conducted to substantiate the use of the MRXcorr procedure.

**A.2.3.1 Test 1**

A 6-DOF data set from the chassis of a forestry skidder was aligned with the identical forestry skidder chassis data set after it had been altered to contain a known data point shift. A comparison of the known data point shift to the shift determined from the MRXcorr was then conducted to determine the MRXcorr’s accuracy in determining the known data shift.

**A.2.3.2 Test 2**

The same comparison of identical 6-DOF data sets with a known data point shift as in Test 1 was conducted. However, here a series of zero-lag Butterworth band-pass filters, signal gain modifications, and random noise were used to alter the shifted 6-DOF chassis data set so that its frequency content resembled that of actual 6-DOF OSI data from that same forestry skidder. More specifically, each individual DOF of chassis data underwent band-pass filtering such that
only the desired frequency range remained. These filtered chassis data were then amplified or attenuated to obtain a signal power for that frequency range that visually resembled that of the OSI. This was repeated for as many frequency ranges as required. Additionally, a random white noise signal was generated. This noise signal also underwent a similar band-pass filtering and gain modification to that of the chassis data, in order to add frequency components that were not present in the chassis data. The addition of all of the filtered and gain modified chassis and noise signals resulted in the final simulated OSI data used in the analysis. Figures B.3 through B.8 provide a comparison of the power spectra collected simultaneously on a forestry skidder OSI and chassis with the power spectrum of that exact chassis data which was altered to resemble the OSI data for the same forestry skidder. This was done to simulate differences one would see between vehicle OSI and chassis 6-DOF data sets due to seat dynamics and operator movements while eliminating any unknown phase shifts that the seat may produce since the zero-lag Butterworth filters have a linear zero-phase (Smith 1999). Once again, the induced shift was compared to the shift ascertained by the MRXcorr procedure to determine if the MRXcorr accurately determined the known data shift.

A.2.3.3 Test 3

Finally, the MRXcorr alignment procedure was applied to real 6-DOF WBV data sets collected on the OSI and chassis of three forestry skidders. Here, there is an unknown delay between the data collection onset of the two data time histories. The alignment determined by the MRXcorr was compared to an Xcorr conducted on the entire data set. Here, each of the three forestry skidder time histories were divided into twenty 5000-datapoint windows that were located at 5% intervals for each DOF, and each alignment method. A regression analysis was then conducted between the OSI and chassis time histories for each 5000-datapoint window on each skidder and axis for each alignment method. The alignment method which resulted in a higher percentage of the sample windows with greater $r^2$-values was then determined.
Figure B.3: A comparison of an X-axis acceleration power spectrum measured on a forestry skidder chassis (solid line in a) and b)), with an X-axis acceleration power spectrum measured on the forestry skidder OSI (dashed line in a)) and the chassis signal altered to resemble forestry skidder OSI data (dashed line in b)).
Figure B.4: A comparison of a Y-axis acceleration power spectrum measured on a forestry skidder chassis (solid line in a) and b)), with a Y-axis acceleration power spectrum measured on the forestry skidder OSI (dashed line in a)) and the chassis signal altered to resemble forestry skidder OSI data (dashed line in b)).
Figure B.5: A comparison of a Z-axis acceleration power spectrum measured on a forestry skidder chassis (solid line in a) and b)), with a Z-axis acceleration power spectrum measured on the forestry skidder OSI (dashed line in a)) and the chassis signal altered to resemble forestry skidder OSI data (dashed line in b)).
Figure B.6: A comparison of a Roll-axis velocity power spectrum measured on a forestry skidder chassis (solid line in a) and b)), with a Roll-axis velocity power spectrum measured on the forestry skidder OSI (dashed line in a)) and the chassis signal altered to resemble forestry skidder OSI data (dashed line in b)).
**Figure B.7**: A comparison of a Pitch-axis velocity power spectrum measured on a forestry skidder chassis (solid line in a) and b), with a Pitch-axis velocity power spectrum measured on the forestry skidder OSI (dashed line in a)) and the chassis signal altered to resemble forestry skidder OSI data (dashed line in b)).
Figure B.8: A comparison of a Yaw-axis velocity power spectrum measured on a forestry skidder chassis (solid line in a) and b)), with a Yaw-axis velocity power spectrum measured on the forestry skidder OSI (dashed line in a)) and the chassis signal altered to resemble forestry skidder OSI data (dashed line in b)).
B.3 RESULTS

B.3.1 Test 1

The MRXcorr precisely determined the known phase shift between two identical 6-DOF data sets. Here, a randomly selected 13,286 data point shift was applied to one of the 6-DOF data sets. The MRXcorr indicated that the exact same 13,286 data point shift was necessary to align all 6-DOF data sets.

B.3.2 Test 2

The MRXcorr precisely determined the 13,286 data point shift between the forestry skidder chassis signal and the identical chassis signal which was altered to resemble that forestry skidder’s OSI WBV signals in the X-, Z- and Yaw axes. In the Y-, Roll and Pitch axes it was found that the data sets were misaligned by one data point, which corresponded to a time history misalignment of 0.002 seconds.

B.3.3 Test 3

Finally, the MRXcorr alignment procedure was applied to actual field 6-DOF WBV data sets collected at the OSI and chassis of three forestry skidders. The data shifts determined by both the MRXcorr and Xcorr were similar (as seen in Table B.1), and when observing the aligned time histories, the MRXcorr aligned data time histories and the Xcorr time histories displayed similar patterns. However, the MRXcorr alignment did appear to be aligned better.

<table>
<thead>
<tr>
<th>Skidder</th>
<th>Determined Data Shift$^1$</th>
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<tr>
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<td>MRXcorr</td>
</tr>
<tr>
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</tr>
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<td>2</td>
<td>30027</td>
</tr>
<tr>
<td>3</td>
<td>948</td>
</tr>
</tbody>
</table>

$^1$The values reported are the absolute number of data points required to shift the OSI time history to the left or right such that it is aligned with the chassis time history.
(Figures B.9 and B.10). The better alignment of the time histories is confirmed by the fact that the $r^2$-values from the regressions between the two data sets were greater when the MRXcorr was used compared to the Xcorr, 83.6% of the time (based on all 360 time history windows from the three skidders and 6-DOF for each skidder) (Figure B.11). Figure B.12 displays the percentage of time that the $r^2$-values were greater for the twenty time history windows compiled from each forestry skidder and each DOF when the MRXcorr aligned the data time histories. It can be seen that in every combination of skidder and DOF, the MRXcorr aligned the data time histories better at least 55% of the time, with the majority of cases being aligned better by the MRXcorr 65% of the time or greater.

**B.4 DISCUSSION**

The MRXcorr technique presented here is simply a series of Xcorrs that on their own can accurately determine a data shift between two identical signals. What needs to be considered here is the fact that the two signals which are being aligned are not identical. The chassis signal is the input to the seat, but the dynamics of the seat suspension system and cushioning, as well as the movements of the operator on the seat alter that signal. The result is two similar but not identical signals. The power of the MRXcorr technique is in the novel utilization of windowing constraints that were designed to address these elements of signal distortion so that the effects of operator movement and seat dynamics are minimized. For example, the onset of engine start-up and initial idling prior to the onset of the forward progression of the machine was chosen because it is known that any low frequency movement would be the result of the operator moving and not terrain induced signal from driving. As well, while idling, high frequency engine noise is a more dominant signal than when the vehicle is being driven, thus this high frequency signal can now be used during the high resolution shift adjustments to accurately align the two signals. It should be noted though that the procedure requires the initial onset of forward progression to be included. If only the engine noise signal is used, the Xcorr utilized by the MRXcorr will look for the best fit for the data in the window analyzed. This could result in a seemingly arbitrary shift when considering the entire data set. Maintaining some of common low frequency driving signal for the higher resolution OSI and chassis data windows will allow the previous low frequency shift to be maintained, resulting in only a fine adjustment to the signal alignment during the
Figure B.9: Two 6-degree-of-freedom whole-body vibration datasets collected on the chassis (solid line) and seat (dashed line) of a forestry skidder which have been aligned with the multiple resolution cross-correlation alignment procedure and windowed between 190s and 195s.
**Figure B.10:** Two 6-degree-of-freedom whole-body vibration datasets collected on the chassis (solid line) and seat (dashed line) of a forestry skidder which have been aligned with a plain cross-correlation and windowed between 190s and 195s.
Figure B.11: The average percentage of trials where the MRXcorr alignment resulted in a greater $r^2$-value from a regression between the aligned OSI and chassis time histories. Note: for the X, Y, Z, Pitch, Roll and Yaw DOF, 60 5000-datapoint windows were used. For skidder 1, skidder 2 and skidder 3, 120 5000-datapoint windows were used. The overall percentage was based on 360, 5000-datapoint windows.

Figure B.12: The percentage of trials for each skidder on each DOF where the MRXcorr alignment resulted in a greater $r^2$-value from a regression between the aligned OSI and chassis time histories. Note: for each skidder on each DOF, twenty 5000-datapoint windows were used.
higher resolution alignments.

The initial validation tests conducted in this paper were designed to evaluate whether the MRXcorr could accurately determine a known data shift. Of particular concern was whether or not the MRXcorr could determine a known data shift when the datasets were not identical. These questions were answered in Tests 1 and 2. In both instances the MRXcorr was able to determine the induced data shifts. The ability to determine the data shift when the signals resembled field OSI and chassis 6-DOF WBV signals, lends great support for the MRXcorr’s ability to align complex field vibration measurements. This is further substantiated by the fact that the MRXcorr performed better than another simple alignment technique (Xcorr) as demonstrated by Test 3.

It was also noted during Test 3, that when the Xcorr procedure did align the data time histories better (i.e., had greater $r^2$-values); it appeared to be due to low frequency phase shifts in the data time histories that were not accounted for by the MRXcorr. The Xcorr was conducted on the entire length of the data time histories. As a result, the Xcorr was able to capture these low frequency phase shifts (likely due to the operator changing position on the seat thereby altering the seating dynamics) that occurred throughout the data time history and incorporate those signal changes into its alignment determination. The MRXcorr, however, only conducted its low frequency alignment on the first 300,000 data points. This fact means that the MRXcorr did not utilize these distortions in the low frequency signal for its alignment determination. It is therefore suggested that future use of the MRXcorr procedure should utilize a larger low resolution window (i.e. between 50% to 100% of the data time history length) to account of any phase changes in the data time histories being aligned. Since the data has been resampled at a lower resolution, the processing time will not be greatly affected by the use of a larger data window.

The ability to align simultaneously collected 6-DOF WBV data sets collected on the OSI and chassis will allow researchers to determine seat dynamics under field conditions. The dynamic seat responses determined in the field can then be compared to laboratory studies to substantiate the laboratory results and validate the conclusions. As well, representative field data for chassis exposures will provide researchers with an accurate input for dynamic seat testing which can be used to investigate and optimize 6-DOF transmission characteristics for a seat in a laboratory setting. Two studies have measured both OSI and chassis vibrations levels, however, these studies did not collect the OSI and chassis data simultaneously (Parsons, Whitham and Griffin 1979; Smith and Kwak 1979). As a result, cross spectral density calculations were used
to determine seat transfer functions with the phase information being omitted due to its probable inaccuracy. If the OSI and chassis data had been collected simultaneously via the same measurement system, the phase information could have been calculated accurately. Researchers may find it difficult and costly to obtain a measurement system with the necessary twelve channels. The application of the MRXcorr process as outlined in this paper will allow researchers an alternative method to acquire aligned WBV data. Our MRXcorr allows researchers to collect the OSI and chassis WBV data with two separate measurement systems and then combine the data later. Like the cross spectral density approach mentioned earlier, the MRXcorr process does not allow one to determine precise phase lags for transfer functions. One can however, determine phase lags between different axes if they are normalized to an axis of interest. In addition, unlike the cross spectral density method discussed above, the MRXcorr enables one to create time histories of aligned data that can be used as OSI and chassis inputs during laboratory investigations into WBV and health, comfort, and seat dynamics. As well, the aligned time histories can be windowed to determine transfer functions and WBV exposure magnitudes for specific instances in time.

Another benefit of this MRXcorr technique is the fact that it only uses a portion of a very large data set. As a result, less computer memory is required and the program takes less time to run. These authors found that some of the data files collected were too large to run an Xcorr, despite the 1.0GB of RAM available in the analyzing computer.

B.5 CONCLUSION

The MRXcorr presented here was proven to accurately align identical 6-DOF WBV data sets and a simulated 6-DOF OSI WBV data set with its chassis counterpart. As well, the specific considerations that the MRXcorr technique affords to the alignment of OSI and chassis WBV signals have proven to make the technique more accurate than an Xcorr between the two data sets. Therefore, the MRXcorr procedure is a viable means of aligning OSI and chassis WBV data signals collected from different data loggers. The ability of the MRXcorr to align the complex data sets in this paper suggests that it is a promising technique which could be applied to other biomechanical data sets involving multiple data collection systems.
REFERENCES

Smith, D. and Singh, S., 2006. Approaches to multisensor data fusion in target tracking: A survey. Institute of Electrical and Electronics Engineers Transactions on Knowledge and Data Engineering, 18(12), 1696-1710.

APPENDIX C

VALIDATION OF THE VICON™ 460 CAMERA SYSTEM TO DETERMINE WHOLE-BODY VIBRATION ACCELERATIONS

C.1 INTRODUCTION

Operators of mobile equipment (i.e. transport vehicles, dozers, haulage trucks, load-haul-dump vehicles, forklifts, tractors, locomotives, buses) are exposed to potentially harmful levels of whole-body vibration (WBV) (Village, Morrison and Leong 1989; Thalheimer 1996). These harmful levels of vibration -- which depend on the magnitude, direction (axis), frequency, and duration of exposure to vibration (Herrington and Morse 1995; Bovenzi 1996) -- can be either directly or indirectly connected to many health problems (Seidel 1993; Bovenzi 1996; Thalheimer 1996). It is therefore necessary to study how the body responds to vibration under a number of conditions in order to implement effective strategies to reduce these health risks. Jack and Oliver (2008) highlight the need for such studies to investigate the interacting effects of posture, muscle activity, and WBV exposures on vibration transmission through the body. Presently, the literature on WBV transmission is limited with respect to; the amount of muscle activation, the types of postures, the exposure levels and types of exposures, used as well as the location of and amount of acceleration measurements made on the body. This leaves many gaps in the knowledge needed to fully understand how the body responds to WBV. In order to get a better understanding of the body’s response to WBV a more detailed study needs to be undertaken, where many levels of the spine are measured for translational and rotational vibration transmission in concert with several muscle activation measurements and postures adopted.

In order to measure accurately the various spinal positions, acceleration levels and EMG levels at several different locations; many markers, accelerometers, and electrodes will need to be placed on the subject. Not only will this be time consuming, require a lot of memory for data
storage and processing, be potentially costly, and hinder subject recruitment; it can also adversely affect the results. The large number of wires and attachments can be cumbersome and may affect how the subject reacts to vibration exposure because of altered muscle activation patterns associated with discomfort from all the measurement devices attached to them. This notion is supported by Rahmatalla et al. (2006). Furthermore, inaccuracies in measurements can result from increased skin motion (skin artifacts) with increased mass on the skin. Wires can also be a problem by restricting and altering normal motion patterns (subjects may respond differently than normal in order to avoid pulling on wires or the unfamiliar feel of having many wires attached to them). Furthermore, experimental errors can potentially be introduced if one of the wires were to become caught on something, thereby impeding or inducing motions which augment the results. In addition, studies that intend on using motion analysis in combination with vibration and muscle activation measurements will use many digitization markers, EMG electrodes, and accelerometers mounted on the skin. All of these skin mounted devices will result in a lot of clutter. This clutter can influence the subject’s natural motions, introduce skin artifacts, and cause some of the markers to not be visible to the cameras. All of the aforementioned can introduce errors into the study (i.e. lost markers introduce errors in the three dimensional (3D) reconstruction of two dimensional (2D) camera data with direct linear transform calculations leading to missing data that needs to be interpolated). The ability to eliminate some of the measurement devices (i.e. the accelerometers, and their wires) could reduce some of these problems.

If a high sample rate/high resolution camera system could reliably and accurately reproduce vibration measurements (both translational and rotational), one could reduce skin motion errors as well as problems related to the use of wires and the encumberment of the subject. The use of cameras also eliminates the need to control for accelerations detected due to the angular motions of an accelerometer, since gravity is not used as a reference. Thus, the purpose of this study was to determine if a VICON™ 460 motion capture system could be used to determine translational and rotational WBV accelerations.
C.2 PART 1 – TRANSLATIONAL ACCELERATION MEASUREMENT LIMITATIONS

C.2.1 Methods

A Bruel and Kjaer™ 4810 electromechanical shaker (controlled with a Bruel and Kjaer™ 2706 power amplifier and a Brule and Kjaer™ 2010 hydrodyne analyzer) and a mechanical lever arm (Figure C.1) were used to produce RMS average accelerations of $10.69 \pm 1.08 \text{ m/s}^2$, $7.26 \pm 0.59 \text{ m/s}^2$, $3.24 \pm 0.59 \text{ m/s}^2$, and $1.28 \pm 0.10 \text{ m/s}^2$ in the Z-axis (vertical axis) at each of 30Hz, 25Hz, 20Hz, 15Hz, 10Hz, 5Hz, and 3Hz frequency levels. A VICON™ 460 motion capture system (with six M²mcam cameras) recorded a reflective marker (at the end of the lever arm) vibrated at each amplitude and frequency combination while a Crossbow™ CXL04LP3 accelerometer also recorded the accelerations. Each amplitude and frequency combination was recorded for 5 seconds with a sampling rate of 250Hz and a pixel resolution of 1020 x 656 (horizontal x vertical).

![Figure C.1: Bruel and Kjaer™ 4810 electromechanical shaker with a Crossbow™ CXL04LP3 accelerometer and a reflective marker attached to a mechanical lever arm.](image)

The raw digitized VICON™ and accelerometer data were fourth order zero lag Butterworth filtered (cutoff frequency of 45Hz; ISO 2631-1:1997). The VICON™ data were then double differentiated to provide acceleration values. The accelerometer data were corrected
for acceleration changes due to the angular motion of the lever arm. A 1/3-octave band-pass filter was then applied to the VICON™ and accelerometer data and peak and RMS average acceleration levels were calculated for 1/3 octave bands with center frequencies ranging from 3.15Hz to 31.5Hz, for each combination of the input acceleration and frequency level (ISO 2631-1:1997). The accelerometer data was double integrated (high-pass filtered at 0.5Hz) to determine the amplitude of vibration displacements for each 1/3 octave band (3.15Hz to 31.5Hz) and each combination of acceleration and frequency.

The absolute percent difference between the VICON™ and accelerometer peak and RMS average acceleration values were then calculated for all 1/3 octave bands, input acceleration and frequency combination. The displacement needed in order to determine accelerations from the cameras within 5% absolute difference of the accelerometer was determined and then the minimum peak, RMS average, and ISO 2631-1:1997 weighted RMS average accelerations that the camera system can resolve in the Z-, X-, and Y-axes using that displacement for each 1/3 octave center frequency was calculated.

### C.2.2 Results

It was found that displacements equal to or greater than 0.1mm produced differences less than 5% between the VICON™ 460 motion capture system and an accelerometer for both absolute peak and RMS average accelerations (Table C.1). The minimum peak and RMS average accelerations that the VICON™ 460 motion capture system can determine using peak-to-peak displacements of 0.1mm for frequencies ranging from 1Hz to 31.5Hz can be seen in Table C.2.

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<th>Input Displacements (mm)</th>
<th>Absolute Percent Error (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Peak Acceleration</td>
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<tr>
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<tr>
<td>0.025</td>
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## Table C.2: Minimum peak and RMS average translational accelerations that the VICON™ 460 motion capture system can determine†.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Peak acceleration (m/s²)</th>
<th>RMS acceleration (m/s²)</th>
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<td>0.001 0.002 0.002</td>
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<td>0.006</td>
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<td>0.453 0.071 0.071</td>
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† Values calculated using 0.1mm peak-to-peak displacements at the frequency of interest.

†† Values calculated in accordance with the health guidelines from the ISO 2631-1:1997 Standard, “Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 1: General requirements”.

APPENDIX C: Camera Validation
C.3 PART 2 – ROTATIONAL ACCELERATION MEASUREMENT LIMITATIONS

It has been determined that the VICON™ 460 motion capture system can accurately and reliably resolve displacements of 0.1mm. This information along with some Pythagorean math can be used to determine the separation of markers required to resolve a given angle. For example, Two 9mm markers placed 1cm apart (center-to-center) will have an angular resolution of 0.01 radians (or 0.57°) assuming that one marker travels 0.1mm (the requirement to maintain a 95% accuracy with the camera system) relative to the other in a given plane of motion. Placing those same markers 2cm apart will have an angular resolution of 0.005 radians (or 0.29°). Therefore, the greater the separation between two markers, the greater the system’s rotational resolution.

With the above in mind, a triad of markers was created (Figure C.2) were the greatest separation between any two markers was 8.5cm. This separation was chosen because it afforded

![Figure C.2: Marker triad. Note: the center-to-center distance between marker 1 and 2, as well as 1 and 3 is 5.5cm. The distance between marker 2 and 3 is 8.5cm.](image-url)
a compact set-up while providing a marker separation that did not impair the VICON™ marker reconstructions necessary to provide 3D marker coordinate data. In other words, markers were all visible with no overlap. This 8.5cm marker spacing meant that the system would have a rotational resolution of 0.001 radians (or 0.057°). Using this angle as the peak-to-peak rotational resolution, Table C.3 outlines the minimum peak, RMS average, and ISO 2631-1:1997 weighted RMS average angular accelerations that the VICON™ 460 motion capture system can theoretically determine with this marker set-up and the same 1020 x 656 pixel resolution used in Part 1.

The marker set-up and VICON™ 460 motion capture system combination outline above provide a viable tool for determining angular accelerations. However, the aforementioned set-up ought to be validated under actual experimental conditions and angle calculations procedures (matrix rotation calculations). The experiment outlined below addresses this necessity.

C.3.1 Methods

A Parallel Robotic Systems Corporation (PRSCO) 6-degree-of-freedom (DOF) robotic platform was used to produce peak rotational accelerations of 0.17 rad/s², 0.70 rad/s², and 1.75 rad/s² in the Yaw-axis (vertical axis) at each of 1Hz and 2.5Hz. Peak rotational accelerations of 0.17 rad/s² and 0.70 rad/s² were also produced at 5Hz. A VICON™ 460 motion capture system (with six M²mcam cameras) recorded the motion of a rigid triad of reflective marker (Figure C.2) vibrated at each amplitude and frequency combination. The VICON™ motion capture data were recorded for 10 seconds with a sampling rate of 250Hz and a pixel resolution of 1020 x 656.

The raw digitized VICON™ data were fourth order zero lag Butterworth filtered. The cutoff frequencies were set to 1.5-times the frequency of interest (i.e. 1.5Hz, 3.75Hz, and 7.5Hz; ISO 2631-1:1997). The filtered data was then entered into a custom Matlab™ program utilizing matrix rotation calculations outlined in Hamill and Selbie (2004). The angle time histories calculated were then double differentiated to provide rotational acceleration values. These rotational acceleration time histories were then compared the original rotational acceleration time histories used for input commands to the robot. The percent difference between the absolute peak and RMS accelerations of the two rotational acceleration time histories were then calculated.
Table C.3: Minimum peak and RMS average rotational accelerations that the VICON™ 460 motion capture system is expected to determine.†

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<tr>
<th>Frequency (Hz)</th>
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<th>RMS acceleration (rad/s²)</th>
<th>ISO Weighted RMS acceleration (rad/s²)</th>
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</thead>
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<td>Roll, Pitch, and Yaw</td>
<td>Roll, Pitch, Yaw</td>
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† Values calculated using 0.001 radian peak-to-peak angular displacements at the frequency of interest.
†† Values calculated in accordance with the comfort guidelines from the ISO 2631-1:1997 Standard, “Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 1: General requirements”.

APPENDIX C: Camera Validation
C.3.2 Result

The mean percent difference between the absolute peak and RMS rotational accelerations determined by the VICON™ 460 motion capture system and those produced by the PRSCO robot were 5.44±3.87% and 3.57±2.44% respectively.

C.4 DISCUSSION

This study based its measurements on camera fields of view in the order of 1.5m x 1.2m, a field of view that completely captures a seated subject. By focusing the cameras onto a smaller field of view, the resolution of the system can be increased. Thus, smaller acceleration levels can be measured if the cameras are focused in on a smaller area. Increasing the camera field of view or increasing the sampling rate will reduce the resolution of the system thereby inducing more errors in the determination of acceleration levels when the displacements are near 0.1mm. In such a case the amplitudes of the various vibrations will have to be larger in order for the VICON™ 460 motion capture system to accurately determine the accelerations. The acceleration levels that can be determined using a motion capture system will be unique to each situation and should be established prior to any formal testing. The attainment of those minimal acceleration levels can be done using a similar method to this study.

It is important to note that the 5Hz, 0.17 rad/s² exposure tested corresponds to a peak-to-peak angular displacement of 0.0035 radians or 0.02°. This resolution is nearly three times greater than that originally predicted. Although some additional error (9% and 7% for the absolute peak and RMS rotational accelerations) was found for the smallest angular motion exposure, the camera system still resolved the marker triad rotational accelerations accurately. Using this new angle as the peak-to-peak rotational resolution, Table C.4 outlines the minimum peak, RMS average, and ISO 2631-1:1997 weighted RMS average angular accelerations that the VICON™ 460 motion capture system has been determine capable of measuring with this marker set-up and 1020 x 656 pixel resolution.

When using a camera system to determine WBV levels on the human body, the body’s natural attenuation of vibration must be taken into account to ensure that the WBV exposure levels will not be attenuated to a level that will induce large errors if a camera system is used to
Table C.4: Minimum peak and RMS average rotational accelerations that the VICON™ 460 motion capture system can determine.

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† Values calculated using 0.001 radian peak-to-peak angular displacements at the frequency of interest.
†† Values calculated in accordance with the comfort guidelines from the ISO 2631-1:1997 Standard, "Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 1: General requirements".
determine those vibrations. Translational seat-to-head transfer functions from Wilder et al. (1982), Paddan and Griffin (1988a and 1988b), Wilder et al. (1994), Zimmerman and Cook (1997) and Jack and Eger (2008) were combined with the results in Table C.2 and compared to field exposure data from Parsons, Whitham and Griffin (1979), Village, Morrison and Leong (1989), Marsili, Ragni and Vassalini (1998), Kumar et al. (2001), Salmoni et al. (2002), Rehn et al. (2005), Cation et al. (2008) and Jack et al. (Chapter 5), to determine if the VICON™ 460 motion capture system could be used in transmissibility studies utilizing field exposures as inputs. Similarly, rotational seat-to-head transfer functions from Paddan and Griffin (1994) and Paddan and Griffin (2000) were combined with the results in Table C.4 and compared to field exposure data from Parsons, Whitham and Griffin (1979), Cation et al. (2008) and Jack et al. (Chapter 5). It was determined that studies using RMS average input accelerations found at the operator/seat interface of several vehicles (standard automobiles, much machines and load-haul-dump vehicles from mining, skidders and forwarders from forestry, Tractors in agriculture) could use the VICON™ 460 motion capture system to determine vibration levels in seat-to-head transmissibility studies. The VICON™ 460 motion capture system can be used to detect head vibrations below 10Hz for most translational exposures found in the field. Depending on the vehicle and exposure axis, translational head vibrations can be detected up to 25Hz with the motion capture system used in this study. Rahmatalla et al. (2006) found that their motion capture system could accurately detect head motions up to 16Hz while subjects were exposed to simulated heavy construction machine vibrations. As for rotational vibrations, the VICON system can detect head vibrations as high as 5Hz when exposed to field vibrations. Knowledge of exposure levels used and potential vibration attenuation by the researcher will be important in drawing conclusions. Furthermore, coherence calculations should be conducted to verify that attenuated accelerations at superior levels of the spine are still linearly related to the input vibrations. Low coherence values can be indicative of inaccurate vibration measurements.

C.5 CONCLUSION

The VICON™ 460 motion capture system with six M²mcam cameras, a 1.5m x 1.2m field of view, and a sampling rate of 250Hz appears to be well suited for the capture of peak and RMS average accelerations associated with WBV exposures in mobile machines. The system
also appears to be well suited for 6-DOF transmission studies using WBV exposures from many industrial machines up to 10Hz for translational and 5Hz for rotational accelerations (depending on exposure levels). The VICON™ system does have the capacity to be used for translational studies up to 25Hz depending on the input exposure utilized.

REFERENCES


Rahmatalla, S., Xia, T., Contratto, M., Wilder, D., Frey-Law, L., Kopp, G., Grosland, N., 2006. 3D displacement, velocity, and acceleration of seated operators in a whole-body vibration...


APPENDIX D

FIELD STUDY CONSENT FORM

The informed consent form presented to subjects/skidder operators during the field posture and whole-body vibration exposure data collection can be seen in the pages to follow.
CONSENT TO PARTICIPATE IN RESEARCH

Evaluation of Whole-body-vibration and Sitting Postures During Skidder Operation in the Forestry Industry

You are asked to participate in a research study conducted by Robert Jack, a Ph.D. student from the Department of Biophysics at the University of Guelph. The results of this study will be incorporated into the Ph.D. thesis of Robert Jack. The research that you are being asked to participate in is funded by both the Natural Sciences and Engineering Research Council of Canada and Timberjack (Woodstock, ON).

If you have any questions or concerns about the research, please feel free to contact Robert Jack at _______________ (email: rjack@uoguelph.ca), or principal investigator Dr. Michele Oliver at (519) 824-4120 ext. 52117 (email: moliver@uoguelph.ca).

PURPOSE OF STUDY

The purpose of the study is to measure both translational and rotational whole-body vibration exposure levels and monitor operator postures during the operation of skidders. Relationships between these exposures and postures with reported injuries and driver characteristics will be drawn. Relationships between cab designs and adopted driving postures will also be drawn.

The ultimate goal of the study is to establish better guidelines for the design and operation of skidders and mobile equipment in general.

PROCEEDURES

If you volunteer to participate in this study, you will be asked to do the following things. You will be asked to fill out a questionnaire regarding your work and injury history, as well as various aspects of the operation of a skidder that affect driving postures. You will then be asked to have four joint angle measurement devices attached to the skin over your knee, hip, lower back and shoulders. You will also be asked to have a spring loaded switch attached to the heal of your boot. Finally, you will also be asked to sit on a pad designed to measure vibration while you drive a skidder. All data measurements will be taken under regular operating conditions and will last approximately 1.5 hours.

POTENTIAL RISKS AND DISCOMFORTS

The nature of the participant’s job itself puts them at risk for physical injury and discomfort, but at no time will the participant be subjected to any conditions other than those which they would be exposed to during their normal work day. Also, the devices attached to the participant’s skin may be uncomfortable and adhesives could result in skin irritation. To reduce skin irritation from the mounting of devices with adhesive tape, participants may be excused from the study without fear of reprisal if they have a skin allergy. Also, a skin lotion will be made available if participants do have skin that becomes irritated, and will be allowed to remove themselves from the study. Finally, an accelerometer placed on the seat pan may also be uncomfortable. The seat pan accelerometer was designed such that the participant comes in contact with a soft interface that distributes pressure evenly to improve comfort and relieve pressure points.

Also, participants may be worried that responses given while surveyed or field values obtained may have a negative impact on their status with their employer (i.e. fear of repercussions if findings regarding them indicate poor productivity or health hazards). Be assured that all information obtained for the study will be confidential and that no mention of participant names will ever be used.

POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY

Immediately, the participants will be informed of musculoskeletal workplace hazards and how to minimize these risks with current knowledge, as well as the flaws with the current knowledge. Participants will also be able to voice...
their opinions about health hazards of their occupation without fear of reprisal. Ultimately, more detailed and comprehensive ergonomic guidelines will be established which will hopefully be used in the design of various types of mobile equipment to reduce participant injuries and improve their productivity.

CONFIDENTIALITY

Every effort will be made to ensure confidentiality of any identifying information that is obtained in connection with this study. Only members of the research team will have access to the data collected, and all information obtained will be strictly confidential. You will be given an ID number to keep track of the various forms of data collected, but absolutely no identifying information will be recorded (i.e. names, employee ID numbers, SIN, etc.).

PARTICIPATION AND WITHDRAWL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may exercise the option of removing your data from the study. You may also refuse to answer any questions you don’t want to answer and still remain in the study.

RIGHTS OF RESEARCH PARTICIPANTS

You may withdraw your consent at anytime and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this study. This study has been reviewed and received ethics clearance through the University of Guelph Research Ethics Board. If you have questions regarding your rights as a research participant, contact:

Research Ethics Officer
University of Guelph
437 University Center
Guelph, ON, N1G 2W1
Telephone: (519) 824-4120 ext. 56606
E-mail: sauld@uoguelph.ca
Fax: (519) 821-5236
SIGNATURE OF RESEARCH PARTICIPANT/LEGAL REPRESENTATIVE

I have read the information provided for the study “Evaluation of Whole-body-vibration and Sitting Postures During Skidder Operation in the Forestry Industry” as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

_________________________________________
Name of Participant (please print)

_________________________________________
Name of Legal Representative (if applicable)

_________________________________________   _____________________
Signature of Participant or Legal Representative   Date

SIGNATURE OF WITNESS

_________________________________________
Name of Witness (please print)

_________________________________________   _______ ______________
Signature of Witness      Date
APPENDIX E

FIELD STUDY TESTING PACKAGE

The following pages contain the skidder and operating trial data collection sheets as well as the “Evaluation of Whole-body-vibration and Sitting Postures During Skidder Operation in the Forestry Industry” questionnaire used in this study.
**Skidder Data**

- **Date:** ____________________  **Time:** ____________________
- **Vehicle Type:** __________________________________________
- **Vehicle Size:** __________________________________________
- **Vehicle ID Number:** _____________________________________
- **Maintenance:** ___________________________________________
- **Tire Pressure:** __________________________________________
- **Seat Height:** ____________________________________________
- **Operator ID Number:** ____________________________________
- **Other Comments:** _________________________________________

**Pictures:**

**Description**

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Evaluation of Whole-body-vibration and Sitting Postures During Skidder Operation in the Forestry Industry

Musculoskeletal Disorder and Operator Cab Design Questionnaire

BACKGROUND INFORMATION

This questionnaire is part of the “Evaluation of Whole-body-vibration and Sitting Postures During Skidder Operation in the Forestry Industry” study being conducted by principle investigator Dr. Michele Oliver and Robert Jack a Ph.D. student at the University of Guelph.

Up to 7% of employees in Canada, United States, and Some European countries are exposed to harmful levels of whole-body vibrations (WBV). Skidders have been identified as producers of potentially harmful levels of WBV. Currently, available data on WBV in skidders is limited and exposure guidelines do not account for postures or rotational vibration.

This form will be analyzed, and the results of this questionnaire will be used to determine relationships between various forms of vibration exposures and adopted postures recorded during the operation of skidders and reported musculoskeletal injuries. Relationships between skidder cab design (control location, vision obstructers) and adopted postures will also be drawn.

No one from the company you work for will see your comments and individual results will not be reported.

This questionnaire will take approximately 15 minutes to complete. There are no correct answers to the questions. We hope you will take the time to share this information with us. Results of this questionnaire will be used to help identify recommendations in order to improve your health and safety when operating a skidder as well as other forms of mobile equipment.

INSTRUCTIONS

➢ Your answer to each question is very important to this study, but you may choose to skip any questions you do not feel comfortable answering.

➢ If you have completed the questionnaire please seal it in the envelope provided and return it to the University of Guelph representative.

THANK YOU FOR YOUR PARTICIPATION

If you have any questions regarding this questionnaire please feel free to contact:

Robert Jack
Principle Investigator
University of Guelph
Email: rjack@uoguelph.ca

Dr. Michele Oliver
Faculty Advisor
University of Guelph
(519) 824-4120 x52117
Email: moliver@uoguelph.ca
Musculoskeletal Disorder and Operator Cab Design Questionnaire

Part A: Background Information

1. What is your current age? ______________
2. Are you male or female? male female
3. What is your current weight? ______________
4. What is your current height? ______________
5. How many years have you operated mobile equipment? ______________
6. How many years have you operated a skidder? ______________
7. Do you typically drive a skidder? Yes No
8. What other types of mobile equipment do you operate on a regular basis?
   • ___________________________________________________________________
   • ___________________________________________________________________
   • ___________________________________________________________________
   • ___________________________________________________________________
   • ___________________________________________________________________
   • ___________________________________________________________________
9. How many hours (on average) do you operate a skidder each day? ______________
10. How many hours (on average) do you operate other mobile equipment each day? ______________
11. How would you describe your body type?
    Mesomorph Ectomorph Endomorph
12. How would you rate your physical fitness level?
    poor average above average excellent
13. How many times a week are you physically active?
    0 times/week 1-2 times/week 3-4 times/week 5 or more times/week
14. On average, how many minutes are your activity sessions?
    0-14 min 15-29 min 30-44 min over 45 mins
15. Shank length? ______________
16. Thigh length? ______________
Part B: Musculoskeletal Disorders

The body has been divided into nine different areas (right). Please refer to this picture when answering the questions regarding body areas trouble (ache, pain, numbness or discomfort).

Instructions

1. For each body region you will be asked to indicate if you have had trouble in the area in the last year, month, week, or day.

2. If you indicated you had pain in the area please provide a rating score to describe the severity of the pain, at the worst episode that you felt (rate your most recent episode).

Rating Score
1 = mild ache, pain, numbness or discomfort
2 = moderate ache, pain, numbness or discomfort
3 = severe ache, pain, numbness or discomfort
4 = very, very severe ache, pain, numbness or discomfort

3. You will then be asked to comment on events or activities that triggered the ache, pain, numbness or discomfort.

4. You will then be asked to provide any suggestions that could alleviate or prevent the triggered ache, pain, numbness or discomfort.

4. You will then be asked if the ache, pain, numbness or discomfort has resulted in a change in activities or lost work time.

If you have any questions while completing this form please ask one of the research assistants present.
Neck

15. Have you experienced any neck trouble (ache, pain, numbness or discomfort):
   ❑ Yes - Please indicate the last episode.
   ❑ over 1 year ago  ❑ 6-12 months ago  ❑ 1-6 months ago
   ❑ 2-4 weeks ago  ❑ 1-2 weeks ago  ❑ within the last week  ❑ today
   ❑ No (go to question on the next body part)

16. Please rate the severity of your last episode. (Indicate by marking the scale below with an X)

   1       2       3       4
   Mild    Moderate Severe Very Severe

17. What task or activity do you think brought on the problem with your neck?

   ____________________________________________________________
   ____________________________________________________________

18. Do you have any suggestions to avoid future neck problems?

   ____________________________________________________________
   ____________________________________________________________

19. Have you ever had to change duties or jobs or miss work because of your neck trouble?
   ❑ Yes ❑ No
Shoulder

20. Have you experienced any shoulder trouble (ache, pain, numbness or discomfort):
   ❑ Yes - Please indicate the last episode.
   ❑ over 1 year ago ❑ 6-12 months ago ❑ 1-6 months ago
   ❑ 2-4 weeks ago ❑ 1-2 weeks ago ❑ within the last week ❑ today
   ❑ No (go to question on the next body part)

21. Please rate the severity of your last episode. (Indicate by marking the scale below with an X)

   1       2       3       4
   Mild    Moderate Severe Very Severe

22. What task or activity do you think brought on the problem with your shoulder?

   ___________________________________________________________

   ___________________________________________________________

23. Do you have any suggestions to avoid future shoulder problems?

   ___________________________________________________________

   ___________________________________________________________

24. Have you ever had to change duties or jobs or miss work because of your shoulder trouble?
   ❑ Yes       ❑ No
Upper Back

25. Have you experienced any upper back trouble (ache, pain, numbness or discomfort):
   ❑ Yes - Please indicate the last episode.
     ❑ over 1 year ago   ❑ 6-12 months ago   ❑ 1-6 months ago
     ❑ 2-4 weeks ago    ❑ 1-2 weeks ago    ❑ within the last week   ❑ today
   ❑ No (go to question on the next body part)

26. Please rate the severity of your last episode. (Indicate by marking the scale below with an X)

   1 | 2 | 3 | 4
   ---|---|---|---
   Mild | Moderate | Severe | Very Severe

27. What task or activity do you think brought on the problem with your upper back?

________________________________________________________________________
________________________________________________________________________

28. Do you have any suggestions to avoid future upper back problems?

________________________________________________________________________
________________________________________________________________________

29. Have you ever had to change duties or jobs or miss work because of your upper back trouble?
   ❑ Yes       ❑ No
Elbows

30. Have you experienced any elbows trouble (ache, pain, numbness or discomfort):
   ❑ Yes - Please indicate the last episode.
      ❑ over 1 year ago ❑ 6-12 months ago ❑ 1-6 months ago
      ❑ 2-4 weeks ago ❑ 1-2 weeks ago ❑ within the last week ❑ today
   ❑ No (go to question on the next body part)

31. Please rate the severity of your last episode. (Indicate by marking the scale below with an X)

   1     2     3     4
   Mild  Moderate  Severe  Very Severe

32. What task or activity do you think brought on the problem with your elbows?

   __________________________________________________________
   __________________________________________________________

33. Do you have any suggestions to avoid future elbows problems?

   __________________________________________________________
   __________________________________________________________

34. Have you ever had to change duties or jobs or miss work because of your elbows trouble?
   ❑ Yes    ❑ No
Low Back

35. Have you experienced any low back trouble (ache, pain, numbness or discomfort):
   ❑ Yes - Please indicate the last episode.
     ❑ over 1 year ago  ❑ 6-12 months ago  ❑ 1-6 months ago
     ❑ 2-4 weeks ago  ❑ 1-2 weeks ago  ❑ within the last week  ❑ today
   ❑ No (go to question on the next body part)

36. Please rate the severity of your last episode. (Indicate by marking the scale below with an X)

   1  2  3  4
   Mild  Moderate  Severe  Very Severe

37. What task or activity do you think brought on the problem with your low back?

   __________________________________________________________
   __________________________________________________________

38. Do you have any suggestions to avoid future low back problems?

   __________________________________________________________
   __________________________________________________________

39. Have you ever had to change duties or jobs or miss work because of your low back trouble?
   ❑ Yes  ❑ No
Wrist/Hands

40. Have you experienced any wrist/hand trouble (ache, pain, numbness or discomfort):
   ☐ Yes - Please indicate the last episode.
       ☐ over 1 year ago    ☐ 6-12 months ago    ☐ 1-6 months ago
       ☐ 2-4 weeks ago     ☐ 1-2 weeks ago     ☐ within the last week  ☐ today
   ☐ No (go to question on the next body part)

41. Please rate the severity of your last episode. (Indicate by marking the scale below with an X)

   1 2 3 4
   Mild Moderate Severe Very Severe

42. What task or activity do you think brought on the problem with your wrist/hand?

   ____________________________________________________
   ____________________________________________________

43. Do you have any suggestions to avoid future wrist/hand problems?

   ____________________________________________________
   ____________________________________________________

44. Have you ever had to change duties or jobs or miss work because of your wrist/hand trouble?
   ☐ Yes    ☐ No
**Hips/Thighs/Buttocks**

45. Have you experienced any hip, thigh or buttocks trouble (ache, pain, numbness or discomfort):
   - ☐ Yes - Please indicate the last episode.
     - ☐ over 1 year ago
     - ☐ 6-12 months ago
     - ☐ 1-6 months ago
     - ☐ 2-4 weeks ago
     - ☐ 1-2 weeks ago
     - ☐ within the last week
     - ☐ today
   - ☐ No (go to question on the next body part)

46. Please rate the severity of your last episode. (Indicate by marking the scale below with an X )

1 | 2 | 3 | 4
---|---|---|---
Mild | Moderate | Severe | Very Severe

47. What task or activity do you think brought on the problem with your hip, thigh or buttocks?

________________________________________________________________________
________________________________________________________________________

48. Do you have any suggestions to avoid future hip, thigh or buttocks problems?

________________________________________________________________________
________________________________________________________________________

49. Have you ever had to change duties or jobs or miss work because of your hip, thigh or buttocks trouble?
   - ☐ Yes
   - ☐ No
Knees

50. Have you experienced any knees trouble (ache, pain, numbness or discomfort):
   - Yes - Please indicate the last episode.
     - over 1 year ago
     - 6-12 months ago
     - 1-6 months ago
     - 2-4 weeks ago
     - 1-2 weeks ago
     - within the last week
     - today

   - No (go to question on the next body part)

51. Please rate the severity of your last episode. (Indicate by marking the scale below with an X)

   1. Mild
   2. Moderate
   3. Severe
   4. Very Severe

52. What task or activity do you think brought on the problem with your knees?

   _____________________________________________________________
   _____________________________________________________________

53. Do you have any suggestions to avoid future knees problems?

   _____________________________________________________________
   _____________________________________________________________

54. Have you ever had to change duties or jobs or miss work because of your knees trouble?
   - Yes
   - No
Ankles/Feet

55. Have you experienced any ankle/foot trouble (ache, pain, numbness or discomfort):
   ☐ Yes - Please indicate the last episode.
   ☐ over 1 year ago ☐ 6-12 months ago ☐ 1-6 months ago
   ☐ 2-4 weeks ago ☐ 1-2 weeks ago ☐ within the last week ☐ today
   ☐ No (go to question on the next body part)

56. Please rate the severity of your last episode. (Indicate by marking the scale below with an X)

   1 Mild  2 Moderate  3 Severe  4 Very Severe

57. What task or activity do you think brought on the problem with your ankle/foot?

   __________________________________________________________________________
   __________________________________________________________________________

58. Do you have any suggestions to avoid future ankle/foot problems?

   __________________________________________________________________________
   __________________________________________________________________________

59. Have you ever had to change duties or jobs or miss work because of your ankle/foot trouble?
   ☐ Yes  ☐ No
Part C – Posture and Cab Design (Control and Vision Requirements)

60. When operating a skidder, are there any times where you have to adjust your posture in order see what you are doing or where you are going?
   🗼 Yes   🗼 No

61. If you answered “Yes” above, please describe as many of these situations as possible in the table below.

<table>
<thead>
<tr>
<th>Task Description</th>
<th>How often does this occur?</th>
<th>How was visibility impaired? What couldn’t be seen?</th>
<th>What aspect of the cab design impaired your visibility?</th>
<th>How did your impaired visibility affect you posture? Describe the posture of the neck, shoulders, trunk, hips, and legs.</th>
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</table>
62. When operating a skidder, are there any times where you have to adjust your posture in order to manipulate the machine’s controls?

- Yes
- No

63. If you answered “Yes” above, please describe as many of these situations as possible in the table below.

<table>
<thead>
<tr>
<th>Task Description</th>
<th>How often does this occur?</th>
<th>Describe why you have to change your posture to manipulate the machine’s controls during the task</th>
<th>Describe the adopted posture of the neck, shoulders, trunk, hips, and legs.</th>
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THANK YOU FOR YOUR

PARTICIPATION
APPENDIX F

LABORATORY STUDY CONSENT FORM

The informed consent form presented to participants of the biodynamic response laboratory study can be seen in the pages to follow.
CONSENT TO PARTICIPATE IN RESEARCH

The Biodynamic Response of Human Subjects Exposed Vibration Acceleration Profiles and Postures Found in the Northern Ontario Forestry Industry

You are asked to participate in a research study conducted by Robert Jack, a Ph.D. student from the Department of Biophysics at the University of Guelph. The results of this study will be incorporated into the Ph.D. thesis of Robert Jack. The research that you are being asked to participate in has been funded by the Natural Sciences and Engineering Research Council of Canada, the Ontario Ministry of Training, Colleges and Universities, and John Deere (Grimsby, ON).

If you have any questions or concerns about the research, please feel free to contact Robert Jack at (519) 824-4120 ext. 58847 (email: riack@uoguelph.ca), or principal investigator Dr. Michele Oliver at (519) 824-4120 ext. 52117 (email: moliver@uoguelph.ca).

PURPOSE OF STUDY

The purpose of this research is to characterize the seated human body’s response to vibration, and determine factors which influence that response. The results of this study will facilitate the development of mathematical models of the human body which can be used to aid in the design of off-road vehicle seats, cabs and operating procedures. Occupational vibration exposures and driving postures have been strongly linked to low-back and neck pain. Current prevention guidelines attempt to minimize the risk of pain in occupational drivers, but the occurrence of low-back and neck pain symptoms is still highly prevalent among occupational drivers. A possible reason for the ineffectiveness of these guidelines may be the fact that they are based on studies that do not reflect actual occupational vibration exposures and postures. This study will address those issues by investigating the influence of several field measured postures and vibration exposures on the transmission of vibration through the body. The ultimate goal of the study is to establish better guidelines for the design and operation of forestry skidders and mobile equipment in general.

PROCEDURES

If you volunteer to participate in this study, you will be asked to do the following things. You will initially be asked to complete a Physical Activity Readiness Questionnaire and your blood pressure will be measured. As per the Physical Activity Readiness Questionnaire, if your blood pressure is greater than 144/94 or you answer “yes” to any of the questionnaire questions, you will be excluded from participation due to elevated cardiovascular risk factors which preclude you from the performance of maximum voluntary muscle contractions. You will then be asked to provide information regarding your age, physical activity prior to the experiment, musculoskeletal injury history (if you are currently suffering from or frequently suffer from back and/or neck pain or have a documented spinal disorder please excuse yourself from this study), and information regarding your vibration exposure experience (if you have operated heavy equipment for an occupation for over five years please excuse yourself from this study). After this initial verbal survey, your standing and sitting height, as well as your neck and waist will be measured via a tape measure. Subsequently, you will undergo a series of skin-fold measurements in order to determine your body composition (body fat percentage) and subcutaneous adipose (body fat) distribution. Refer to Figure F.1 for the location of the skinfold measurements.

Next, seven pairs of electromyography (EMG) electrodes will be affixed to your skin with adhesive tape, on the left and right sides of the body. Refer to Figure F.2 for the location of the EMG electrode placements. You will then have to conduct a series of high intensity muscle contractions known as maximal voluntary reference contractions or MVCs. These MVCs will include three five-second isometric (non-moving) back extensions against resistance while lying on your stomach with your hips and legs secured; isometric trunk curls (to the left, right, and directly anterior to the body) against resistance while the feet are flat, the knees are up, and the ankles are secured; and a simultaneous pull of the arm inferiorly and posteriorly while your shoulder is abducted 90° and the elbow flexed 90°. Each of the MVCs will have a two minute break between them. At this point, 48 individual reflective markers and 4 rigid marker triads will be affixed to your skin with adhesive tape as indicated in Figure F.3.
Figure F.1: Skinfold and girth measurement locations. Note: skinfold measurement locations are marked by a short double line that also indicates the direction of the skinfold. The girth measurements are denoted by the dotted lines.

Figure F.2: Electromyographic (EMG) electrode placement locations. Note: A pair of solid black dots represents an EMG electrode pair, and the electrode pairs will be oriented as seen in this figure. The reference electrodes were placed over the medial tibial malleoli.
Figure F.3: Reflective marker and marker triad placement locations. Note: A solid black circle with a white center represents a reflective marker. A triangle with three reflective markers denotes a marker triad.

You will then sit on the rigid surface of a Kistler force plate mounted on a robotic platform which is programmed to vibrate in a specific predetermined pattern. You will be randomly exposed to three different vibration exposure profiles at three different vibration acceleration levels. The exposure profiles will include a randomly generated movement pattern also known as a random broad-band white noise spectrum, and two vibration exposure profiles previously found in the forestry industry. The vibration acceleration levels utilized are the same as those experienced by machine operators in the forestry industry. Exposure to vibration for the duration of the testing will be kept below the ISO 2631-1:1997 health caution zone, placing you at a minimal risk for injury. While exposed to the aforementioned vibrations, you will randomly adopt combinations of two trunk twisting, two lateral trunk bending, and three trunk flexion/extension postures with your arms relaxed at your sides and your hands lightly touching your thighs. To aid in the maintenance of these postures, you will have a laser pointer mounted on the chest and you are asked to hold its light over a predetermined target. In all posture combinations, your trunk will be unsupported, but your legs will be supported. The postures you will be adopting represent postures found to occur during actual operating tasks in the forestry industry. You will adopt each of the above postures with both a normal and elevated trunk muscle activity level. The normal muscle activity condition will involve the normal adoption of the test postures, while the elevated trunk muscle activity condition will have you adopt the same postures but this time you will voluntarily increase in your trunk muscle activity by tensing your trunk muscles.

You will be exposed to each combination of vibration, posture and muscle activity for 10-seconds followed by a 3-second break between exposures. After every three exposures, a 60 second rest break will be provided, and a 120 second break will be provided after every 9 exposures until all test combinations had been completed. The rest breaks were included to minimize your potential fatigue and discomfort. The entire testing duration including set-up, skin-fold measurements, MVCs and vibration exposures will last approximately 4 hours.

POTENTIAL RISKS AND DISCOMFORTS

Excessive exposure to whole-body vibration can be uncomfortable and long-term, has been associated with low-back pain and injury. This risk of injury due to the vibration exposures has been minimised by ensuring that those levels are below the ISO 2631-1:1997 health guidance caution zone. A foot rest and guard rail will be provided so that you can stabilise yourself during the vibration exposure and to ensure that you do not fall off the seat. A “dead-
man” switch will also be provided to you, so that you can immediately stop the robot platform motion if you feel the need to do so. Also, the combination of vibration exposure and non-neutral postures you will be exposed to can be uncomfortable and fatiguing. You will be provided ample rest between test trials to minimize this potential for discomfort and fatigue. As well, all postures adopted are within normal ranges found in industry.

Caution must be exercised when using an experimental apparatus to apply vibration to human subjects in order to ensure subject safety in response to machine failure. The safety of the motion platform has been assessed based on the guidelines in ISO 13090-1. You will be physically protected from the moving parts of the robotic platform by the design of the machine. You will be seated above the moving parts of the robot platform and unable to be struck by any of the moving parts of the platform. In the case of mechanical failure or loss of control, the motion of the platform is very limited and it would be impossible to strike any objects in the surrounding environment. In terms of the safety of the machine control, the platform is controlled entirely under displacement control, and accordingly, if the platform motion deviates from the desired motion, the platform shuts down, brakes to a stop and is held in position by brakes.

You are asked to conduct MVCs during the experiment which require you to work against your own static limits (you are resisting your own movements), but at no time are you overloaded by external sources (i.e. weights). Individuals may develop some latent soreness from this procedure, which would be comparable to that experienced by individuals initiating a new exercise regimen. However, for eligible participants this should not prove to be any more injurious than their normal exercise regimen. The MVCs may also place individuals at risk for untoward cardiovascular events. The subject pool selected combined with the use of cardiovascular screening with the Physical Activity Readiness Questionnaire and blood pressure measurements means that only low risk individuals will be allowed to partake in this study, therefore no such events are expected.

You may find the tape used to affix items to your skin to be uncomfortable and adhesives could result in skin irritation. You may excuse yourself from the study if you have a skin allergy, or your skin becomes irritated during the experiment. A skin lotion will be made available if participants do have skin that becomes irritated. Also, note that all of the devices attached to you operate at low temperatures and are all covered with a non-conductive coating to shield you from contact with any electrical currents.

Finally, you will also be required to wear a pair of snug shorts and no shirt during the experimental testing. Some individuals maybe uncomfortable or embarrassed with such a requirement. Likewise, some individuals may find the skinfold procedure uncomfortable or embarrassing. If you feel uncomfortable or feel embarrassed at any point during the testing session you are free to terminate and leave the study.

**POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY**

The results of this research may help reduce the incidence of injury from occupational exposure to whole-body vibration, thereby reducing costs to companies through reduced workers compensation premiums and other injury related costs, as well as reduce costs to the public health care system associated with the treatment of vibration related injuries. In addition, improvements in operator comfort and productivity may also occur through the implementation of guidelines created from more comprehensive studies like that proposed here. This in turn benefits the workers as well as the companies they work for.

**CONFIDENTIALITY**

Every effort will be made to ensure confidentiality of any identifying information that is obtained in connection with this study. Only members of the research team will have access to the data collected, and all information obtained will be strictly confidential. You will be given an ID number to keep track of the various forms of data collected, but absolutely no identifying information will be recorded (i.e. names, ID numbers, SIN, etc.).
PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may exercise the option of removing your data from the study. You may also refuse to answer any questions you don’t want to answer and still remain in the study.

RIGHTS OF RESEARCH PARTICIPANTS

You may withdraw your consent at anytime and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this study. This study has been reviewed and received ethics clearance through the University of Guelph Research Ethics Board. If you have questions regarding your rights as a research participant, contact:

Research Ethics Officer
University of Guelph
437 University Center
Guelph, ON, N1G 2W1

Telephone: (519) 824-4120 ext. 56606
E-mail: sauld@uoguelph.ca
Fax: (519) 821-5236
SIGNATURE OF RESEARCH PARTICIPANT/LEGAL REPRESENTATIVE

I have read the information provided for the study “The Biodynamic Response of Human Subjects Exposed Vibration Acceleration Profiles and Postures Found in the Northern Ontario Forestry Industry” as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

_________________________________________
Name of Participant (please print)

_________________________________________
Name of Legal Representative (if applicable)

_________________________________________   _____________________
Signature of Participant or Legal Representative   Date

SIGNATURE OF WITNESS

_________________________________________
Name of Witness (please print)

_________________________________________   _______ ______________
Signature of Witness      Date
APPENDIX G

LABORATORY STUDY TESTING PACKAGE

The pages to follow contain the subject; pre-screening, anthropometric and physical activity data collection forms used during the biodynamic response laboratory study. Also provided are the preliminary measurement and trial checklists. The whole-body vibration trial checklist provided is a randomly selected example.
Are you currently suffering from or frequently suffer from back and/or neck pain?  yes  no
Do you have a documented spinal disorder?  yes  no
Have you operated heavy equipment for an occupation for over five years?  yes  no

*** If the subject answers yes to any of the above questions, they are to be excused from this study.

<table>
<thead>
<tr>
<th>Describe any vibration exposures that you do experience (sources, years of exposure, daily exposure amounts)</th>
</tr>
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</table>

Administered PAR-Q  yes  no

Recorded blood pressure  mmHg

*** If the subject answers yes to any of the PAR-Q questions or has a blood pressure greater than 144/94, they are to be excused from this study.

| Age  years |
|Standing height  cm |
|Sitting height (to top of head)  cm |
|Sitting height (to mid- sternum)  cm |
|Sitting height (to greater trochanter)  cm |
|Weight  kg |
|Percent body fat from bioelectric impedance  % |
|Time of day  hr:min |

Description of any physical activity prior to testing session
APPENDIX G: Laboratory Testing Package

Girths (cm)

<table>
<thead>
<tr>
<th></th>
<th>Measure 1</th>
<th>Measure 2</th>
<th>Measure 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck</td>
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<tr>
<td>Just inferior to the larynx with the tape sloping slightly downward to the front.</td>
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<tr>
<td>Mid-abdominal</td>
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<td></td>
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<tr>
<td>Level of the umbilicus.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Skinfolds (mm)

<table>
<thead>
<tr>
<th></th>
<th>Measure 1</th>
<th>Measure 2</th>
<th>Measure 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triceps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The subject’s right arm is held close to the body at a 90° angle while the midpoint between the acromion and olecranon process is determined. The skinfold grasped 1cm above that point with the arm hanging straight down and measured 1cm below the grasp point.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subscapular</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The skinfold is grasped 1cm below and 1cm to the medial side of the inferior angle of the scapula, with the skin at a 45° from the upper medial to the lower lateral portion. The skinfold is measured 1cm down the fold from the grasp to the inferior lateral side.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The skinfold is grasped 1cm above the level of the maximum calf circumference on the medial side of the right leg while it is bent 90° and the foot is supported. The skinfold measurement is taken 1cm below this point.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thigh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The skinfold is taken over the middle of the thigh at a point 1cm above the halfway point between the patella and the mid-point of the inguinal ligament (halfway between the anterior superior iliac spine and the symphysis pubis). The skinfold measurement is taken 1cm below this point.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chest</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The skinfold is taken 1cm diagonally superior to the halfway point of the anterior axillary fold and the nipple. The measurement is taken 1cm diagonally inferior to the grasp.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abdomen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The skinfold is taken 2cm to the right of the umbilicus and 1cm above that point. The measurement is taken 1cm inferior to the grasp.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suprailium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The skinfold is taken slightly posterior to the axillary line above the iliac crest. The measurement is taken anterior to the grasp site 1cm down the downward diagonal fold.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMG electrodes attached</td>
<td>Right</td>
<td>Left</td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td><strong>Rectus abdominus</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3cm lateral to the umbilicus.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>External oblique</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Approximately 15cm lateral to the umbilicus and sloping 45° downward from the superior lateral electrode to the inferior medial electrode.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Internal oblique</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Approximately midway between the anterior superior iliac spine and symphysis pubis, above inguinal ligament and sloping 20° upward from the inferior lateral electrode to the superior medial electrode.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Latissimus dorsi</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral to T9 over the belly and sloping 55° downward from the superior lateral electrode to the inferior medial electrode.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Thoracic erector spinae</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5cm lateral to T9 spinous process.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lumbar erector spinae</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3cm lateral to L3 spinous process.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Multifidus</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2cm lateral to L4-5 spinous processes.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MVCs collected</strong></td>
<td>MVC 1</td>
<td>MVC 2</td>
<td>MVC 3</td>
</tr>
<tr>
<td><strong>Isometric back extensions against resistance while lying prone with their hips and legs secured.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Isometric trunk curls to the left, right, and directly anterior to the body against resistance while subjects sit with their feet flat, knees up, and their ankles secured.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subjects simultaneously pull inferiorly and posteriorly against resistance with their shoulder abducted 90° and the elbow flexed 90° as they stand.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reflective markers attached</td>
<td>Single</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>--------</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>Vertex</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Occipital crest marker triad</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>7th cervical vertebral marker triad</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Suprasternale</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Acromion process</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>9th thoracic vertebral marker triad</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>5th lumbar vertebral marker triad</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Antero-superior iliac spine</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Postero-superior iliac spine</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Greater trochanter</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Mid-thigh</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Lateral femoral epicondyle</td>
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</tr>
<tr>
<td>Medial femoral epicondyle</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Lateral border of tibial head</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Anterior tibial crest</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Lateral malleolus</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Heel</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Head of 1st metatarasal</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Head of 5th metatarasal</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Greater tuberosity</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Mid-arm</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Lateral humeral epicondyle</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Medial humeral epicondyle</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Radial head</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Radial styloid</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Ulnar styloid</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Base of 2nd metacarpal</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Head of 2nd metacarpal</td>
<td>_______</td>
<td>______</td>
<td></td>
</tr>
<tr>
<td>Head of 5th metacarpal</td>
<td>_______</td>
<td>______</td>
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</tbody>
</table>
### Joint center calibration movements completed

<table>
<thead>
<tr>
<th>Movement Description</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee extension with a stationary thigh. Limit the motion to the sagittal plane.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Translate the knee forward over the foot such that the ankle is flex but the foot remains stationary. Limit the motion to the sagittal plane.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With the arms at the subject's side trace a medium size circle with the elbow.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flex the elbow with the upper arm stationary and the hand in the hamer position. Limit the motion to the sagittal plane.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-range flexion/extension of the wrist with the hand in the hamer position and the forearm stationary. Limit the motion to the transverse plane.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-range adduction/adduction of the wrist with the hand in the hamer position and the forearm stationary. Limit the motion to the sagittal plane.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Static trial collected

- **Zero the force plate with subject off of the plate first**

<table>
<thead>
<tr>
<th>Position</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facing forward</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facing right</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facing backwards</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facing left</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Static force plate data collection

- Feet/legs supported
- Feet/legs unsupported
**APPENDIX G: Laboratory Testing Package**

<table>
<thead>
<tr>
<th>WBV trials completed</th>
<th>Zeroed</th>
<th>Zeroed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2-146</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 22-123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 10-568</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 10-479</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 3-352</td>
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<td></td>
</tr>
<tr>
<td>6 9-946</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 17-132</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 6-975</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 12-689</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 5-847</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 13-123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 14-321</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 15-312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 8-186</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 24-231</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 10-231</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 1-563</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 18-123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19 4-847</td>
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</tr>
<tr>
<td>20 2-237</td>
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<tr>
<td>21 12-713</td>
<td></td>
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<tr>
<td>22 5-523</td>
<td></td>
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</tr>
<tr>
<td>23 7-263</td>
<td></td>
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</tr>
<tr>
<td>24 6-431</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 1-471</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 21-132</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 7-758</td>
<td></td>
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</tr>
<tr>
<td>28 2-598</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29 23-132</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 11-416</td>
<td></td>
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<tr>
<td>31 19-321</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32 6-268</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33 20-312</td>
<td></td>
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</tr>
</tbody>
</table>

***120s break and force plate zeroing after these trials***
**Appendix G: Laboratory Testing Package**

### WBV Trial Code Key

<table>
<thead>
<tr>
<th>VMC1</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VMC2</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
</tr>
</tbody>
</table>

Number codes for the posture assignments

<table>
<thead>
<tr>
<th>PROF1</th>
<th>AMP1</th>
<th>AMP2</th>
<th>AMP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PROF2</th>
<th>AMP1</th>
<th>AMP2</th>
<th>AMP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PROF3</th>
<th>AMP1</th>
<th>AMP2</th>
<th>AMP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

Number codes for the vibration exposure assignments

***The final xx-xxx trial code indicates the:***

(1-24 posture code)-(3 separate 1-9 vibration exposure codes, i.e. xx-exposure1 exposure2 exposure3)

- **FLEX/EXT 1** = 0° ± 5°
- **FLEX/EXT 2** = 15° ± 5°
- **FLEX/EXT 3** = -15° ± 5°
- **TWST 1** = 0° ± 5°
- **TWST 2** = 15° ± 5°
- **LTB 1** = 0° ± 5°
- **LTB 2** = 15° ± 5°
- **VMV 1** = Normal
- **VMV 2** = Elevated muscle activity
- **PROF 1** = Random noise
- **PROF 2** = EGDADE
- **PROF 3** = HFEBAC
- **AMP 1** = Low
- **AMP 2** = Middle
- **AMP 3** = High
APPENDIX H

CUSTOM WHOLE-BODY VIBRATION ANALYSIS MATLAB CODE

The following pages contain the custom “wbv_processing” MatLab™ code used to process the vibration exposure data collected in the field.
function [peak_UNweighted, peak_weighted, RMS_UNweighted, RMS_weighted, CF_UNweighted, CF_weighted, third_octave_RMS_UNweighted, third_octave_RMS_weighted, running_RMS_UNweighted, running_RMS_weighted, MTVV_UNweighted, MTVV_weighted, MTVV_aw_ratio_UNweighted, MTVV_aw_ratio_weighted, running_RMS_X_third_octave_UNweighted, running_RMS_X_third_octave_weighted, running_RMS_Y_third_octave_UNweighted, running_RMS_Y_third_octave_weighted, running_RMS_Z_third_octave_UNweighted, running_RMS_Z_third_octave_weighted, running_RMS_roll_third_octave_UNweighted, running_RMS_roll_third_octave_weighted, running_RMS_pitch_third_octave_UNweighted, running_RMS_pitch_third_octave_weighted, running_RMS_yaw_third_octave_UNweighted, running_RMS_yaw_third_octave_weighted, X_DFTspectraldata_UNweighted, X_DFTspectraldata_weighted, Z_DFTspectraldata_UNweighted, Z_DFTspectraldata_weighted, Roll_DFTspectraldata_UNweighted, Roll_DFTspectraldata_weighted, Pitch_DFTspectraldata_UNweighted, Pitch_DFTspectraldata_weighted, Yaw_DFTspectraldata_UNweighted, Yaw_DFTspectraldata_weighted, VTV_translational_RMS_UNweighted, VTV_translational_RMS_weighted, VTV_6DOF_RMS_UNweighted, VTV_6DOF_RMS_weighted, VTV_translational_running_RMS_UNweighted, VTV_translational_running_RMS_weighted, VTV_6DOF_running_RMS_UNweighted, VTV_6DOF_running_RMS_weighted] = wvb_processing(data, sf, bpfclow, bpfcup, octbfclow, octbfcup, AT, overlap)

% This code is used to process 6DOF WBV data collected with the custom seat pad transducer created by Robert Jack in 2006 (data columns are as follows: % -- Time X Y Z Rx Ry Rz). It will analyse the WBV data in accordance with % ISO 2631-1 using standard MatLab functions as well as some functions from % the Axiom EduTech VibraTools Suite 7.0.1 TM vibration analysis toolbox. %

% The data is initially band-pass filtered %
% The rotational data are then be converted from velocities to % accelerations and from degrees to radians %
% Data will then be weighted (using VibraTools Wk, Wd, and We filters) and % processed both with and without weighting, and as a continuous band and as % 1/3-octave band data. 1/3-octave band data is determined by applying a % 1/3-octave band data filter to the weighted data and then processing that % data as outlined in ISO 2631-1:1997. VibraTools "fanters" function was modified % (to "fanters2") and used to calculate the RMS average for each 1/3-octave % band of the weighted accelerations it is applied too. %
% The peak weighted and RMS accelerations will be calculated for each trial % and the crest factors will be calculated.
% The running RMS weighted accelerations (linear 1-second sliding window % averaging), maximum transient vibration value (MTVV = the peak % acceleration from the running RMS time history), and the ratio % MTVV/aw will be calculated (aw = weighted rms acceleration). The code % allows one to specify the amount of overlap used for each window.
% Data will then be collapsed across frequency and axes to give "vector sum" % and "vibration total value" data
% PSD analyses will also be conducted. A hanning window was applied to each % data window prior to averaging. The same averaging time used for the % running RMS average will be used here.
% The output variables of the code are as follows
% peak_Unweighted & weighted
% col 1 = X
% col 2 = Y
% col 3 = Z
% col 4 = Roll
% col 5 = Pitch
% col 6 = Yaw
% RMS_Unweighted & weighted --> continuous band or frequency sum or vector sum
% col 1 = X
% col 2 = Y
% col 3 = Z
% col 4 = Roll
% col 5 = Pitch
% col 6 = Yaw
% CF_UNweighted & weighted
% col 1 = X
% col 2 = Y
% col 3 = Z
% col 4 = Roll
% col 5 = Pitch
% col 6 = Yaw
% third_octave_RMS_UNweighted & weighted
% col 1 = 1/3 octave bin center frequency
% col 2 = X
% col 3 = Y
% col 4 = Z
% col 5 = Roll
% col 6 = Pitch
% col 7 = Yaw
% running_RMS_UNweighted & weighted --> continuous band or frequency sum or vector sum
% MTVV_UNweighted & weighted
% MTVV_aw_ratio_UNweighted & weighted
% row 1 = mean  
% row 2 = std  
% row 3 = min  
% row 4 = max  
%  
% col 1 = X  
% col 2 = Y  
% col 3 = Z  
% col 4 = Roll  
% col 5 = Pitch  
% col 6 = Yaw  
%  
% running_RMS_AXIS?_third_octave_UNweighted & weighted  
%  
% col 1 = 1/3 octave bin center frequency  
% col 2 = mean RMS acceleration  
% col 3 = std  
% col 4 = min  
% col 5 = max  
%  
% AXIS?_DFTspectraldata_UNweighted & weighted  
%  
% col 1 = DFT frequency bin  
% col 2 = mean signal power  
% col 3 = std  
% col 4 = min  
% col 5 = max  
%  
% VTV_translational_RMS_UNweighted & weighted --> summed across axes  
% VTV_6DOF_RMS_UNweighted & weighted --> summed across axes  
% VTV_translational_running_RMS_UNweighted & weighted --> summed across axes  
% VTV_6DOF_running_RMS_UNweighted & weighted --> summed across axes  
%  
% NOTE: that some of the lower overlap percentages will result in some data  
% at the end of the trials not being used for averaging (occurs with  
% percentages less than 50%).  
%  
% NOTE: In the future the rotational data collected should be used to remove  
% g*sin theta error will be removed from the accelerometer data  
%  
% created by Robert J. Jack April 30th 2008  
%  
% Get time history  
%  
% time(:,1)=data(:,1);
% Initial band-pass filter

nyq=sf/2;

[b1,a1]=butter(2,bpfclow/nyq,'high');
dataHP=filter(b1,a1,data);
clear data

[b1,a1]=butter(2,bpfcup/nyq,'low');
dataBP=filter(b1,a1,dataHP);
clear dataHP

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%
% Convert rotational velocities to accelerations and degrees to radians
% calculate the length of the data time histories

arraysize=size(dataBP);
length=arraysize(:,1);
newlength=length-4;   % need to remove 4 data points from the end of the
data time history because the derivative formula
% used to convert the rotational velocities to
% accelerations is a 4-point formula, meaning that
% the last 4 data points are lost due to the math

acceldataBP(:,1:3)=dataBP(1:newlength,2:4);
deltat=1/sf;

[original,derive,endsize]=derivative(dataBP(:,5),deltat);
acceldataBP(:,4)=deg2rad(derive(:,1));

[original,derive,endsize]=derivative(dataBP(:,6),deltat);
acceldataBP(:,5)=deg2rad(derive(:,1));

[original,derive,endsize]=derivative(dataBP(:,7),deltat);
acceldataBP(:,6)=deg2rad(derive(:,1));
clear original
clear derive
clear dataBP

% NOTE: derivatives are taken before the data is padded in order to
% minimize processing time

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %%%%%
%%%%%%%%%%%%%%%%%%%%
% Initially pad the data such that the trial has 115 seconds of mirror
% image data added to both ends of the trial. This is done to ensure the
% accuracy of the 1/3-octave analyses, which are inaccurate (i.e. measurement
% error of less than 3 dB at a confidence level of 90%) at lower
% frequencies (i.e. 0.5Hz) when the trial length is less than 227s. It also
% helps control errors associated with butterworth filter ringing at the
% start and end of the time histories

% calculate the amount of padding need to make the data file the newlength

IIIpadding=115*sf;

% create an inverted mirror image of the end of the data that is the
% necessary padding length and pad the data

arraysize=size(acceldataBP);
IIIlength=arraysize(:,1);

post_datapadding=padarray(acceldataBP,IIIpadding+2,'symmetric','post');
pre_datapadding=padarray(acceldataBP,IIIpadding+2,'symmetric','pre');

inverted_post_datapadding=(post_datapadding(IIIlength+1:IIIlength+IIIpadding+2,:))*-1;
inverted_pre_datapadding=(pre_datapadding(1:IIIpadding+2,:))*-1;

clear post_datapadding
clear pre_datapadding

acceldataBPpadded=[inverted_pre_datapadding(2:IIIpadding+1,:);acceldataBP;inverted_post_datapadding(2:IIIpadding+1,:)];

clear inverted_post_datapadding
clear inverted_pre_datapadding

clear acceldataBP

% NOTE: to get the window over the original data, IIIpadding will have to
% be used along with IIIpadding+IIIlength

% Weight the acceleration data using ISO 2631-1 filters provided by
% VibraTools. (Wk,Wd,We)

WacceldataBPpadded(:,1)=isofiltw(acceldataBPpadded(:,1),sf,'wd');
WacceldataBPpadded(:,2)=isofiltw(acceldataBPpadded(:,2),sf,'wd');
WacceldataBPpadded(:,3)=isofiltw(acceldataBPpadded(:,3),sf,'wk');
WacceldataBPpadded(:,4)=isofiltw(acceldataBPpadded(:,4),sf,'we');
WacceldataBPpadded(:,5)=isofiltw(acceldataBPpadded(:,5),sf,'we');
WacceldataBPpadded(:,6)=isofiltw(acceldataBPpadded(:,6),sf,'we');

% NOTE: applying the ISO weightings after the data has been padded will
% remove any high frequency noise induced by the padding process (which
% itself was designed to have the smoothest possible transitions between
% padded data.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculate the peak and RMS accelerations, and the crest factor for both % weighted and Unweighted data. Using the original section of data.

peak_UNweighted=max(abs(acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,1:6)));
peak_weighted=max(abs(WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,1:6)));

RMS_UNweighted(:,1)=(mean(acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,1).*acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,1)))^0.5;
RMS_UNweighted(:,2)=(mean(acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,2).*acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,2)))^0.5;
RMS_UNweighted(:,3)=(mean(acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,3).*acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,3)))^0.5;
RMS_UNweighted(:,4)=(mean(acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,4).*acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,4)))^0.5;
RMS_UNweighted(:,5)=(mean(acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,5).*acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,5)))^0.5;
RMS_UNweighted(:,6)=(mean(acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,6).*acceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,6)))^0.5;

RMS_weighted(:,1)=(mean(WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,1).*WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,1)))^0.5;
RMS_weighted(:,2)=(mean(WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,2).*WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,2)))^0.5;
RMS_weighted(:,3)=(mean(WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,3).*WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,3)))^0.5;
RMS_weighted(:,4)=(mean(WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,4).*WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,4)))^0.5;
RMS_weighted(:,5)=(mean(WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,5).*WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,5)))^0.5;
RMS_weighted(:,6)=(mean(WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,6).*WacceldataBPpadded(IIIpadding+1:IIIpadding+IIIlength,6)))^0.5;

CF_UNweighted=peak_UNweighted./RMS_UNweighted;
CF_weighted=peak_weighted./RMS_weighted;

% Calculate the 1/3 octave band time histories data for the entire trial % and the RMS accelerations for those time histories Using the original % section of data.

[Spec,f] = fanters3(acceldataBPpadded(:,1),sf,octbfclow,octbfcup); %[Spec,f] -- f=1/3 octave centerfrequencies, Spec = acceleration time histories for the 1/3 octave frequency bin.
X_third_octave_UNweighted=Spec;
third_octave_RMS_UNweighted(:,1)=f;

[loopl,col]=size(f);
clear col
for i=1:loopl
third_octave_RMS_UNweighted(i,2)=(mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end
clear Spec

[Spec,f] = fanters3(acceldataBPpadded(:,2),sf,octbfclow,octbfcup);
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```
Y_third_octave_UNweighted=[Spec];
for i=1:loopl
    third_octave_RMS_UNweighted(i,3)=(mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end

clear Spec

[Spec,f] = fanters3(acceldataBPpadded(:,3),sf,octbfcup,octbflow);
Z_third_octave_UNweighted=[Spec];
for i=1:loopl
    third_octave_RMS_UNweighted(i,4)=(mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end

clear Spec

[Spec,f] = fanters3(acceldataBPpadded(:,4),sf,octbfcup,octbflow);
Roll_third_octave_UNweighted=[Spec];
for i=1:loopl
    third_octave_RMS_UNweighted(i,5)=(mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end

clear Spec

[Spec,f] = fanters3(acceldataBPpadded(:,5),sf,octbfcup,octbflow);
Pitch_third_octave_UNweighted=[Spec];
for i=1:loopl
    third_octave_RMS_UNweighted(i,6)=(mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end

clear Spec

[Spec,f] = fanters3(acceldataBPpadded(:,6),sf,octbfcup,octbflow);
Yaw_third_octave_UNweighted=[Spec];
for i=1:loopl
    third_octave_RMS_UNweighted(i,7)=(mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end

clear Spec

[Spec,f] = fanters3(WacceldataBPpadded(:,1),sf,octbfcup,octbflow); %[Spec,f] -- f=1/3 octave center frequencies, Spec = acceleration time histories for the 1/3 octave frequency bin.
X_third_octave_weighted=[Spec];
third_octave_RMS_weighted(:,1)=f;
for i=1:loopl
end
```

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third_octave_RMS_weighted(i,2) = (mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end

clear Spec
[Spec, f] = fanters3(WacceldataBPpadded(:,2), sf, octbfcup, octbfcup);
Y_third_octave_weighted=[Spec];
for i=1:loopl
third_octave_RMS_weighted(i,3) = (mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end

clear Spec
[Spec, f] = fanters3(WacceldataBPpadded(:,3), sf, octbfcup, octbfcup);
Z_third_octave_weighted=[Spec];
for i=1:loopl
third_octave_RMS_weighted(i,4) = (mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end

clear Spec
[Spec, f] = fanters3(WacceldataBPpadded(:,4), sf, octbfcup, octbfcup);
Roll_third_octave_weighted=[Spec];
for i=1:loopl
third_octave_RMS_weighted(i,5) = (mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end

clear Spec
[Spec, f] = fanters3(WacceldataBPpadded(:,5), sf, octbfcup, octbfcup);
Pitch_third_octave_weighted=[Spec];
for i=1:loopl
third_octave_RMS_weighted(i,6) = (mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end

clear Spec
[Spec, f] = fanters3(WacceldataBPpadded(:,6), sf, octbfcup, octbfcup);
Yaw_third_octave_weighted=[Spec];
for i=1:loopl
third_octave_RMS_weighted(i,7) = (mean(Spec(i,IIIpadding+1:IIIpadding+IIIlength).*Spec(i,IIIpadding+1:IIIpadding+IIIlength)))^0.5;
end

clear Spec
% Clamp the original section of data and remove the padded ends so that moving averages can be calculated

NEW_acceldataBP(:, :) = acceldataBPpadded(IIIpadding + 1:IIIpadding + IIIlength, :);
NEW_WacceldataBP(:, :) = WacceldataBPpadded(IIIpadding + 1:IIIpadding + IIIlength, :);

clear acceldataBPpadded
clear WacceldataBPpadded

NEW_X_third_octave_UNweighted(:, :) = X_third_octave_UNweighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear X_third_octave_UNweighted
NEW_Y_third_octave_UNweighted(:, :) = Y_third_octave_UNweighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear Y_third_octave_UNweighted
NEW_Z_third_octave_UNweighted(:, :) = Z_third_octave_UNweighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear Z_third_octave_UNweighted
NEW_Roll_third_octave_UNweighted(:, :) = Roll_third_octave_UNweighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear Roll_third_octave_UNweighted
NEW_Pitch_third_octave_UNweighted(:, :) = Pitch_third_octave_UNweighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear Pitch_third_octave_UNweighted
NEW_Yaw_third_octave_UNweighted(:, :) = Yaw_third_octave_UNweighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear Yaw_third_octave_UNweighted

NEW_X_third_octave_weighted(:, :) = X_third_octave_weighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear X_third_octave_weighted
NEW_Y_third_octave_weighted(:, :) = Y_third_octave_weighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear Y_third_octave_weighted
NEW_Z_third_octave_weighted(:, :) = Z_third_octave_weighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear Z_third_octave_weighted
NEW_Roll_third_octave_weighted(:, :) = Roll_third_octave_weighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear Roll_third_octave_weighted
NEW_Pitch_third_octave_weighted(:, :) = Pitch_third_octave_weighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear Pitch_third_octave_weighted
NEW_Yaw_third_octave_weighted(:, :) = Yaw_third_octave_weighted(:, IIIpadding + 1:IIIpadding + IIIlength);
clear Yaw_third_octave_weighted

% Moving average data

windowsize = AT * sf;
overlapdp = (overlap / 100) * windowsize;

% calculate the number of windows to fit into the data time history

numberwindows = newlength / windowsize;

% if an integer number of windows can't fit into the data time history
% calculate how much padding is required to get an integer number of windows
% and then create a padded time history, using the mirror image of the last data points in the time history.

numberwindowsrounded = round(numberwindows);

if numberwindowsrounded < numberwindows
newnumberwindows=numberwindowsrounded+1;
else
    newnumberwindows=numberwindowsrounded;
end

newlength2=newnumberwindows*windowsize;

% calculate the amount of padding need to make the data file the newlength
if newlength2 > newlength
    padding=newlength2-newlength;
else
    padding=0;
end

% create an inverted mirror image of the end of the data that is the
% necessary padding length and pad the data
initial_NEW_acceldataBPpadding=padarray(NEW_acceldataBP.padding+2,'symmetric','post');
inverted_NEW_acceldataBPpadding=(initial_NEW_acceldataBP.padding(newlength+1:newlength2+2,:))*-1;
clear initial_NEW_acceldataBP.padding
NEW_acceldataBPpadded=[NEW_acceldataBP.inverted_NEW_acceldataBP.padding(2;padding+1,:)];
clear inverted_NEW_acceldataBP.padding

initial_NEW_WacceldataBP.padding=padarray(NEW_WacceldataBP.padding+2,'symmetric','post');
inverted_NEW_WacceldataBP.padding=(initial_NEW_WacceldataBP.padding(newlength+1:newlength2+2,:))*-1;
clear initial_NEW_WacceldataBP.padding
NEW_WacceldataBP.padded=[NEW_WacceldataBP.inverted_NEW_WacceldataBP.padding(2;padding+1,:)];
clear inverted_NEW_WacceldataBP.padding

initial_NEW_X_third_octave_UNweighted.padding=padarray(NEW_X_third_octave_UNweighted.padding+2,'symmetric','post');
inverted_NEW_X_third_octave_UNweighted.padding=(initial_NEW_X_third_octave_UNweighted.padding(newlength+1:newlength2+2,:))*-1;
clear initial_NEW_X_third_octave_UNweighted.padding
NEW_X_third_octave_UNweighted_padded=[NEW_X_third_octave_UNweighted.inverted_NEW_X_third_octave_UNweighted.padding(2;padding+1,:)];
clear inverted_NEW_X_third_octave_UNweighted.padding

initial_NEW_Y_third_octave_UNweighted.padding=padarray(NEW_Y_third_octave_UNweighted.padding+2,'symmetric','post');
inverted_NEW_Y_third_octave_UNweighted.padding=(initial_NEW_Y_third_octave_UNweighted.padding(newlength+1:newlength2+2,:))*-1;
clear initial_NEW_Y_third_octave_UNweighted.padding
NEW_Y_third_octave_UNweighted_padded=[NEW_Y_third_octave_UNweighted.inverted_NEW_Y_third_octave_UNweighted.padding(2;padding+1,:)];
clear inverted_NEW_Y_third_octave_UNweighted.padding

initial_NEW_Z_third_octave_UNweighted.padding=padarray(NEW_Z_third_octave_UNweighted.padding+2,'symmetric','post');
inverted_NEW_Z_third_octave_UNweighted.padding=(initial_NEW_Z_third_octave_UNweighted.padding(newlength+1:newlength2+2,:))*-1;
clear initial_NEW_Z_third_octave_UNweighted.padding

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NEW_Z_third_octave_UNweighted_padded=[NEW_Z_third_octave_UNweighted;inverted_NEW_Z_third_octave_UNweightedpadded(2:padding+1,:)];
clear inverted_NEW_Z_third_octave_UNweightedpadded
clear NEW_Z_third_octave_UNweighted

initial_NEW_Roll_third_octave_UNweightedpadded=padarray(NEW_Roll_third_octave_UNweighted,padding+2,'symmetric','post');
inverted_NEW_Roll_third_octave_UNweightedpadded=(initial_NEW_Roll_third_octave_UNweightedpadded(newlength+1:newlength2+2,:))^-1;
clear initial_NEW_Roll_third_octave_UNweightedpadded
NEW_Roll_third_octave_UNweighted_padded=[NEW_Roll_third_octave_UNweighted;inverted_NEW_Roll_third_octave_UNweightedpadded(2:padding+1,:)];
clear inverted_NEW_Roll_third_octave_UNweightedpadded
clear NEW_Roll_third_octave_UNweighted

initial_NEW_Pitch_third_octave_UNweightedpadded=padarray(NEW_Pitch_third_octave_UNweighted,padding+2,'symmetric','post');
inverted_NEW_Pitch_third_octave_UNweightedpadded=(initial_NEW_Pitch_third_octave_UNweightedpadded(newlength+1:newlength2+2,:))^-1;
clear initial_NEW_Pitch_third_octave_UNweightedpadded
NEW_Pitch_third_octave_UNweighted_padded=[NEW_Pitch_third_octave_UNweighted;inverted_NEW_Pitch_third_octave_UNweightedpadded(2:padding+1,:)];
clear inverted_NEW_Pitch_third_octave_UNweightedpadded
clear NEW_Pitch_third_octave_UNweighted

initial_NEW_X_third_octave_weightedpadded=padarray(NEW_X_third_octave_weighted,padding+2,'symmetric','post');
inverted_NEW_X_third_octave_weightedpadded=(initial_NEW_X_third_octave_weightedpadded(newlength+1:newlength2+2,:))^-1;
clear initial_NEW_X_third_octave_weightedpadded
NEW_X_third_octave_weighted_padded=[NEW_X_third_octave_weighted;inverted_NEW_X_third_octave_weightedpadded(2:padding+1,:)];
clear inverted_NEW_X_third_octave_weightedpadded
clear NEW_X_third_octave_weighted

initial_NEW_Y_third_octave_weightedpadded=padarray(NEW_Y_third_octave_weighted,padding+2,'symmetric','post');
inverted_NEW_Y_third_octave_weightedpadded=(initial_NEW_Y_third_octave_weightedpadded(newlength+1:newlength2+2,:))^-1;
clear initial_NEW_Y_third_octave_weightedpadded
NEW_Y_third_octave_weighted_padded=[NEW_Y_third_octave_weighted;inverted_NEW_Y_third_octave_weightedpadded(2:padding+1,:)];
clear inverted_NEW_Y_third_octave_weightedpadded
clear NEW_Y_third_octave_weighted
initial_NEW_Z_third_octave_weighted_padded=[NEW_Z_third_octave_weighted;inverted_NEW_Z_third_octave_weighted_padded(2:padding+1,:)];
clear inverted_NEW_Z_third_octave_weighted_padded
clear NEW_Z_third_octave_weighted

initial_NEW_Roll_third_octave_weighted_padded=[NEW_Roll_third_octave_weighted;inverted_NEW_Roll_third_octave_weighted_padded(2:padding+1,:)];
clear inverted_NEW_Roll_third_octave_weighted_padded
clear NEW_Roll_third_octave_weighted

initial_NEW_Pitch_third_octave_weighted_padded=[NEW_Pitch_third_octave_weighted;inverted_NEW_Pitch_third_octave_weighted_padded(2:padding+1,:)];
clear inverted_NEW_Pitch_third_octave_weighted_padded
clear NEW_Pitch_third_octave_weighted

initial_NEW_Yaw_third_octave_weighted_padded=[NEW_Yaw_third_octave_weighted;inverted_NEW_Yaw_third_octave_weighted_padded(2:padding+1,:)];
clear inverted_NEW_Yaw_third_octave_weighted_padded
clear NEW_Yaw_third_octave_weighted

%%%%% Start processing the data with the moving window

% Calculate the shift
shift=(sf*AT)-overlapdp;

% Calculate the hanning window size and create window
hannsize=windowsize;
hannwindow=hann(hannsize);

% Calculate frequency bins for DFT
halfhannsize=hannsize/2;
DFTfreq = sf*(0:halfhannsize)/hannsize; % DFTfreq=(sample rate)*(0:0.5*hannsize)/hannsize
halfhannsizeplusone=hannsize+1;
X_DFTspectraldata_UNweighted(:,1)=DFTfreq(:,1);
Y_DFTspectraldata_UNweighted(:,1)=DFTfreq(:,1);
Z_DFTspectraldata_UNweighted(:,1)=DFTfreq(:,1);
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Roll_DFTspectraldata_UNweighted(:,1)=DFTfreq(:,);
Pitch_DFTspectraldata_UNweighted(:,1)=DFTfreq(:,);
Yaw_DFTspectraldata_UNweighted(:,1)=DFTfreq(:,);

X_DFTspectraldata_weighted(:,1)=DFTfreq(:,);
Y_DFTspectraldata_weighted(:,1)=DFTfreq(:,);
Z_DFTspectraldata_weighted(:,1)=DFTfreq(:,);
Roll_DFTspectraldata_weighted(:,1)=DFTfreq(:,);
Pitch_DFTspectraldata_weighted(:,1)=DFTfreq(:,);
Yaw_DFTspectraldata_weighted(:,1)=DFTfreq(:,);

% calculate the total number of windows to be used based on the overlap
% selected

for i=1:newlength2
    if (((i-1)*shift)+windowsize)<=newlength2;
        windowsfitting(i,1)=1;
    else
        windowsfitting(i,1)=0;
    end
end

totalnumberwindows=sum(windowsfitting(:,1));

for i=1:totalnumberwindows
    if i==1
        %ISO

running_RMS_UNweighted(i,1)=(mean(NEW_acceldataBPpadded(i:windowsize,1).*NEW_acceldataBPpadded(i:windowsize,1))).^0.5;

running_RMS_UNweighted(i,2)=(mean(NEW_acceldataBPpadded(i:windowsize,2).*NEW_acceldataBPpadded(i:windowsize,2))).^0.5;

running_RMS_UNweighted(i,3)=(mean(NEW_acceldataBPpadded(i:windowsize,3).*NEW_acceldataBPpadded(i:windowsize,3))).^0.5;

running_RMS_UNweighted(i,4)=(mean(NEW_acceldataBPpadded(i:windowsize,4).*NEW_acceldataBPpadded(i:windowsize,4))).^0.5;

running_RMS_UNweighted(i,5)=(mean(NEW_acceldataBPpadded(i:windowsize,5).*NEW_acceldataBPpadded(i:windowsize,5))).^0.5;

running_RMS_UNweighted(i,6)=(mean(NEW_acceldataBPpadded(i:windowsize,6).*NEW_acceldataBPpadded(i:windowsize,6))).^0.5;

running_RMS_weighted(i,1)=(mean(NEW_WacceldataBPpadded(i:windowsize,1).*NEW_WacceldataBPpadded(i:windowsize,1))).^0.5;

running_RMS_weighted(i,2)=(mean(NEW_WacceldataBPpadded(i:windowsize,2).*NEW_WacceldataBPpadded(i:windowsize,2))).^0.5;

running_RMS_weighted(i,3)=(mean(NEW_WacceldataBPpadded(i:windowsize,3).*NEW_WacceldataBPpadded(i:windowsize,3))).^0.5;

running_RMS_weighted(i,4)=(mean(NEW_WacceldataBPpadded(i:windowsize,4).*NEW_WacceldataBPpadded(i:windowsize,4))).^0.5;

running_RMS_weighted(i,5)=(mean(NEW_WacceldataBPpadded(i:windowsize,5).*NEW_WacceldataBPpadded(i:windowsize,5))).^0.5;

running_RMS_weighted(i,6)=(mean(NEW_WacceldataBPpadded(i:windowsize,6).*NEW_WacceldataBPpadded(i:windowsize,6))).^0.5;
running\_RMS\_weighted(i,4)=(mean(NEW\_WacceldataBPpadded(i:windowsize,4).*NEW\_WacceldataBPpadded(i:windowsize,4))).^0.5;

running\_RMS\_weighted(i,5)=(mean(NEW\_WacceldataBPpadded(i:windowsize,5).*NEW\_WacceldataBPpadded(i:windowsize,5))).^0.5;

running\_RMS\_weighted(i,6)=(mean(NEW\_WacceldataBPpadded(i:windowsize,6).*NEW\_WacceldataBPpadded(i:windowsize,6))).^0.5;

for j=1:loopl

running\_RMS\_X\_third\_octave\_UNweighted(i,j)=(mean(NEW\_X\_third\_octave\_UNweighted\_padded(i:windowsize,j).*NEW\_X\_third\_octave\_UNweighted\_padded(i:windowsize,j))).^0.5;

running\_RMS\_Y\_third\_octave\_UNweighted(i,j)=(mean(NEW\_Y\_third\_octave\_UNweighted\_padded(i:windowsize,j).*NEW\_Y\_third\_octave\_UNweighted\_padded(i:windowsize,j))).^0.5;

running\_RMS\_Z\_third\_octave\_UNweighted(i,j)=(mean(NEW\_Z\_third\_octave\_UNweighted\_padded(i:windowsize,j).*NEW\_Z\_third\_octave\_UNweighted\_padded(i:windowsize,j))).^0.5;

running\_RMS\_Roll\_third\_octave\_UNweighted(i,j)=(mean(NEW\_Roll\_third\_octave\_UNweighted\_padded(i:windowsize,j).*NEW\_Roll\_third\_octave\_UNweighted\_padded(i:windowsize,j))).^0.5;

running\_RMS\_Pitch\_third\_octave\_UNweighted(i,j)=(mean(NEW\_Pitch\_third\_octave\_UNweighted\_padded(i:windowsize,j).*NEW\_Pitch\_third\_octave\_UNweighted\_padded(i:windowsize,j))).^0.5;

running\_RMS\_Yaw\_third\_octave\_UNweighted(i,j)=(mean(NEW\_Yaw\_third\_octave\_UNweighted\_padded(i:windowsize,j).*NEW\_Yaw\_third\_octave\_UNweighted\_padded(i:windowsize,j))).^0.5;

running\_RMS\_X\_third\_octave\_weighted(i,j)=(mean(NEW\_X\_third\_octave\_weighted\_padded(i:windowsize,j).*NEW\_X\_third\_octave\_weighted\_padded(i:windowsize,j))).^0.5;

running\_RMS\_Y\_third\_octave\_weighted(i,j)=(mean(NEW\_Y\_third\_octave\_weighted\_padded(i:windowsize,j).*NEW\_Y\_third\_octave\_weighted\_padded(i:windowsize,j))).^0.5;

running\_RMS\_Z\_third\_octave\_weighted(i,j)=(mean(NEW\_Z\_third\_octave\_weighted\_padded(i:windowsize,j).*NEW\_Z\_third\_octave\_weighted\_padded(i:windowsize,j))).^0.5;

running\_RMS\_Roll\_third\_octave\_weighted(i,j)=(mean(NEW\_Roll\_third\_octave\_weighted\_padded(i:windowsize,j).*NEW\_Roll\_third\_octave\_weighted\_padded(i:windowsize,j))).^0.5;

running\_RMS\_Pitch\_third\_octave\_weighted(i,j)=(mean(NEW\_Pitch\_third\_octave\_weighted\_padded(i:windowsize,j).*NEW\_Pitch\_third\_octave\_weighted\_padded(i:windowsize,j))).^0.5;

running\_RMS\_Yaw\_third\_octave\_weighted(i,j)=(mean(NEW\_Yaw\_third\_octave\_weighted\_padded(i:windowsize,j).*NEW\_Yaw\_third\_octave\_weighted\_padded(i:windowsize,j))).^0.5;

end

%PSD

windowedNEW\_acceldataBPpadded(:,1)=NEW\_acceldataBPpadded(i:hannsize,1).*hannwindow(:,1);
X\_Y = fft(windowedNEW\_acceldataBPpadded(:,1),hannsize);    %complex discrete fourier transform of data
% Scale power spectrum of fourier transform and control for the end
% bands having half the width of the other bands to creat power
APPENDIX H: Vibration Analysis MatLab Code

\% spectral density = (EU^2/Hz)
X_Pyy = (2*(abs(X_Y))/hannsize); \%*2 is because the hanning window cuts 1/2 the power from the signal therefore have to add that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes from)
X_Pyy(2:halfhannsizeplusone-1)=X_Pyy(2:halfhannsizeplusone-1)*2; \%ends have 1/2 the bandwidth of the other frequencies therefore they are not doubled
X_Pyy=X_Pyy.^2;
X_grtc(:,1)=X_Pyy(:,);
X_DFTspectraldata_UNweighted(:,i+1)=X_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,1)=NEW_WacceldataBPpadded(i:hannsize,1).*hannwindow(:,1);
XW_Y = fft(windowedNEW_WacceldataBPpadded(:,1),hannsize);
XW_Pyy = (2*(abs(XW_Y))/hannsize);
XW_Pyy(2:halfhannsizeplusone-1)=XW_Pyy(2:halfhannsizeplusone-1)*2;
XW_Pyy=XW_Pyy.^2;
XW_grtc(:,1)=XW_Pyy(:,);
X_DFTspectraldata_weighted(:,i+1)=XW_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,2)=NEW_WacceldataBPpadded(i:hannsize,2).*hannwindow(:,1);
Y_Y = fft(windowedNEW_WacceldataBPpadded(:,2),hannsize);
Y_Pyy = (2*(abs(Y_Y))/hannsize);
Y_Pyy(2:halfhannsizeplusone-1)=Y_Pyy(2:halfhannsizeplusone-1)*2;
Y_Pyy=Y_Pyy.^2;
Y_grtc(:,1)=Y_Pyy(:,);
Y_DFTspectraldata_UNweighted(:,i+1)=Y_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,2)=NEW_WacceldataBPpadded(i:hannsize,2).*hannwindow(:,1);
YW_Y = fft(windowedNEW_WacceldataBPpadded(:,2),hannsize);
YW_Pyy = (2*(abs(YW_Y))/hannsize);
YW_Pyy(2:halfhannsizeplusone-1)=YW_Pyy(2:halfhannsizeplusone-1)*2;
YW_Pyy=YW_Pyy.^2;
YW_grtc(:,1)=YW_Pyy(:,);
Y_DFTspectraldata_weighted(:,i+1)=YW_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,3)=NEW_WacceldataBPpadded(i:hannsize,3).*hannwindow(:,1);
Z_Y = fft(windowedNEW_WacceldataBPpadded(:,3),hannsize);
Z_Pyy = (2*(abs(Z_Y))/hannsize);
Z_Pyy(2:halfhannsizeplusone-1)=Z_Pyy(2:halfhannsizeplusone-1)*2;
Z_Pyy=Z_Pyy.^2;
Z_grtc(:,1)=Z_Pyy(:,);
Z_DFTspectraldata_UNweighted(:,i+1)=Z_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,3)=NEW_WacceldataBPpadded(i:hannsize,3).*hannwindow(:,1);
ZW_Y = fft(windowedNEW_WacceldataBPpadded(:,3),hannsize);
ZW_Pyy = (2*(abs(ZW_Y))/hannsize);
ZW_Pyy(2:halfhannsizeplusone-1)=ZW_Pyy(2:halfhannsizeplusone-1)*2;
ZW_Pyy=ZW_Pyy.^2;
ZW_grtc(:,1)=ZW_Pyy(:,);
Z_DFTspectraldata_weighted(:,i+1)=ZW_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,4)=NEW_WacceldataBPpadded(i:hannsize,4).*hannwindow(:,1);
Roll_Y = fft(windowedNEW_WacceldataBPpadded(:,4),hannsize);
Roll_Pyy = (2*(abs(Roll_Y))/hannsize);
Roll_Pyy(2:halfhannsizeplusone-1)=Roll_Pyy(2:halfhannsizeplusone-1)*2;
Roll_Pyy=Roll_Pyy.^2;
Roll_grtc(:,1)=Roll_Pyy(:,);
APPENDIX H: Vibration Analysis MatLab Code

Roll_DFTspectraldata_UNweighted(:,i+1)=Roll_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,4)=NEW_WacceldataBPpadded(i:hannsize,4).*hannwindow(:,1);
RollW_Y = fft(windowedNEW_WacceldataBPpadded(:,4),hannsize);
RollW_Pyy = (2*(abs(RollW_Y))/hannsize);
RollW_Pyy(2:halfhannsizeplusone-1)=RollW_Pyy(2:halfhannsizeplusone-1)*2;
RollW_Pyy=RollW_Pyy.^2;
RollW_grtc(:,1)=RollW_Pyy(:);
Roll_DFTspectraldata_weighted(:,i+1)=RollW_grtc(1:halfhannsizeplusone);

windowedNEW_acceldataBPpadded(:,5)=NEW_acceldataBPpadded(i:hannsize,5).*hannwindow(:,1);
Pitch_Y = fft(windowedNEW_acceldataBPpadded(:,5),hannsize);
Pitch_Pyy = (2*(abs(Pitch_Y))/hannsize);
Pitch_Pyy(2:halfhannsizeplusone-1)=Pitch_Pyy(2:halfhannsizeplusone-1)*2;
Pitch_Pyy=Pitch_Pyy.^2;
Pitch_grtc(:,1)=Pitch_Pyy(:);
Pitch_DFTspectraldata_UNweighted(:,i+1)=Pitch_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,5)=NEW_WacceldataBPpadded(i:hannsize,5).*hannwindow(:,1);
PitchW_Y = fft(windowedNEW_WacceldataBPpadded(:,5),hannsize);
PitchW_Pyy = (2*(abs(PitchW_Y))/hannsize);
PitchW_Pyy(2:halfhannsizeplusone-1)=PitchW_Pyy(2:halfhannsizeplusone-1)*2;
PitchW_Pyy=PitchW_Pyy.^2;
PitchW_grtc(:,1)=PitchW_Pyy(:);
Pitch_DFTspectraldata_weighted(:,i+1)=PitchW_grtc(1:halfhannsizeplusone);

windowedNEW_acceldataBPpadded(:,6)=NEW_acceldataBPpadded(i:hannsize,6).*hannwindow(:,1);
Yaw_Y = fft(windowedNEW_acceldataBPpadded(:,6),hannsize);
Yaw_Pyy = (2*(abs(Yaw_Y))/hannsize);
Yaw_Pyy(2:halfhannsizeplusone-1)=Yaw_Pyy(2:halfhannsizeplusone-1)*2;
Yaw_Pyy=Yaw_Pyy.^2;
Yaw_grtc(:,1)=Yaw_Pyy(:);
Yaw_DFTspectraldata_UNweighted(:,i+1)=Yaw_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,6)=NEW_WacceldataBPpadded(i:hannsize,6).*hannwindow(:,1);
YawW_Y = fft(windowedNEW_WacceldataBPpadded(:,6),hannsize);
YawW_Pyy = (2*(abs(YawW_Y))/hannsize);
YawW_Pyy(2:halfhannsizeplusone-1)=YawW_Pyy(2:halfhannsizeplusone-1)*2;
YawW_Pyy=YawW_Pyy.^2;
YawW_grtc(:,1)=YawW_Pyy(:);
Yaw_DFTspectraldata_weighted(:,i+1)=YawW_grtc(1:halfhannsizeplusone);

else
k=(i-1)*shift;

%ISO

running_RMS_UNweighted(i,1)=(mean(NEW_acceldataBPpadded(k+1:k+windowsize,1).*NEW_acceldataBPpadded(k+1:k+windowsize,1))).^0.5;

running_RMS_UNweighted(i,2)=(mean(NEW_acceldataBPpadded(k+1:k+windowsize,2).*NEW_acceldataBPpadded(k+1:k+windowsize,2))).^0.5;

running_RMS_UNweighted(i,3)=(mean(NEW_acceldataBPpadded(k+1:k+windowsize,3).*NEW_acceldataBPpadded(k+1:k+windowsize,3))).^0.5;
running_RMS_UNweighted(i,4) = (mean(NEW_acceldataBPpadded(k+1:k+windowsize,4).*NEW_acceldataBPpadded(k+1:k+windowsize,4))).^0.5;

running_RMS_UNweighted(i,5) = (mean(NEW_acceldataBPpadded(k+1:k+windowsize,5).*NEW_acceldataBPpadded(k+1:k+windowsize,5))).^0.5;

running_RMS_UNweighted(i,6) = (mean(NEW_acceldataBPpadded(k+1:k+windowsize,6).*NEW_acceldataBPpadded(k+1:k+windowsize,6))).^0.5;

running_RMS_weighted(i,1) = (mean(NEW_WacceldataBPpadded(k+1:k+windowsize,1).*NEW_WacceldataBPpadded(k+1:k+windowsize,1))).^0.5;

running_RMS_weighted(i,2) = (mean(NEW_WacceldataBPpadded(k+1:k+windowsize,2).*NEW_WacceldataBPpadded(k+1:k+windowsize,2))).^0.5;

running_RMS_weighted(i,3) = (mean(NEW_WacceldataBPpadded(k+1:k+windowsize,3).*NEW_WacceldataBPpadded(k+1:k+windowsize,3))).^0.5;

running_RMS_weighted(i,4) = (mean(NEW_WacceldataBPpadded(k+1:k+windowsize,4).*NEW_WacceldataBPpadded(k+1:k+windowsize,4))).^0.5;

running_RMS_weighted(i,5) = (mean(NEW_WacceldataBPpadded(k+1:k+windowsize,5).*NEW_WacceldataBPpadded(k+1:k+windowsize,5))).^0.5;

running_RMS_weighted(i,6) = (mean(NEW_WacceldataBPpadded(k+1:k+windowsize,6).*NEW_WacceldataBPpadded(k+1:k+windowsize,6))).^0.5;

for j=1:loopl

running_RMS_X_third_octave_UNweighted(i,j) = (mean(NEW_X_third_octave_UNweighted_padded(k+1:k+windowsize,j).*NEW_X_third_octave_UNweighted_padded(k+1:k+windowsize,j))).^0.5;

running_RMS_Y_third_octave_UNweighted(i,j) = (mean(NEW_Y_third_octave_UNweighted_padded(k+1:k+windowsize,j).*NEW_Y_third_octave_UNweighted_padded(k+1:k+windowsize,j))).^0.5;

running_RMS_Z_third_octave_UNweighted(i,j) = (mean(NEW_Z_third_octave_UNweighted_padded(k+1:k+windowsize,j).*NEW_Z_third_octave_UNweighted_padded(k+1:k+windowsize,j))).^0.5;

running_RMS_Roll_third_octave_UNweighted(i,j) = (mean(NEW_Roll_third_octave_UNweighted_padded(k+1:k+windowsize,j).*NEW_Roll_third_octave_UNweighted_padded(k+1:k+windowsize,j))).^0.5;

running_RMS_Pitch_third_octave_UNweighted(i,j) = (mean(NEW_Pitch_third_octave_UNweighted_padded(k+1:k+windowsize,j).*NEW_Pitch_third_octave_UNweighted_padded(k+1:k+windowsize,j))).^0.5;

running_RMS_Yaw_third_octave_UNweighted(i,j) = (mean(NEW_Yaw_third_octave_UNweighted_padded(k+1:k+windowsize,j).*NEW_Yaw_third_octave_UNweighted_padded(k+1:k+windowsize,j))).^0.5;

running_RMS_X_third_octave_weighted(i,j) = (mean(NEW_X_third_octave_weighted_padded(k+1:k+windowsize,j).*NEW_X_third_octave_weighted_padded(k+1:k+windowsize,j))).^0.5;

running_RMS_Y_third_octave_weighted(i,j) = (mean(NEW_Y_third_octave_weighted_padded(k+1:k+windowsize,j).*NEW_Y_third_octave_weighted_padded(k+1:k+windowsize,j))).^0.5;
running_RMS_Z_third_octave_weighted(i,j)=(mean(NEW_Z_third_octave_weighted_padded(k+1:k+windowsize,j).*NEW_Z_third_octave_weighted_padded(k+1:k+windowsize,j))).^0.5;

running_RMS_Roll_third_octave_weighted(i,j)=(mean(NEW_Roll_third_octave_weighted_padded(k+1:k+windowsize,j).*NEW_Roll_third_octave_weighted_padded(k+1:k+windowsize,j))).^0.5;

running_RMS_Pitch_third_octave_weighted(i,j)=(mean(NEW_Pitch_third_octave_weighted_padded(k+1:k+windowsize,j).*NEW_Pitch_third_octave_weighted_padded(k+1:k+windowsize,j))).^0.5;

running_RMS_Yaw_third_octave_weighted(i,j)=(mean(NEW_Yaw_third_octave_weighted_padded(k+1:k+windowsize,j).*NEW_Yaw_third_octave_weighted_padded(k+1:k+windowsize,j))).^0.5;
end

%PSD

windowedNEW_acceldataBPpadded(:,1)=NEW_acceldataBPpadded(k+1:k+hannsize,1).*hannwindow;
X_Y = fft(windowedNEW_acceldataBPpadded(:,1),hannsize); %complex discrete fourier transform of data
% Scale power spectrum of fourier transform and control for the end
% bands having half the width of the other bands to creat power
% spectral density = (EU^2/Hz)
X_Pyy = (2*(abs(X_Y))/hannsize); %*2 is because the hanning window cuts 1/2 the power from the signal therefore have to add that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes from)
X_Pyy(2:halfhannsizeplusone-1)=X_Pyy(2:halfhannsizeplusone-1)*2; %ends have 1/2 the bandwith of the other frequencies therefore they are not doubled
X_Pyy=X_Pyy.^2;
X_grtc(:,1)=X_Pyy(:);
X_DFTspectraldata_UNweighted(:,i+1)=X_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,1)=NEW_WacceldataBPpadded(k+1:k+hannsize,1).*hannwindow(:,1);
XW_Y = fft(windowedNEW_WacceldataBPpadded(:,1),hannsize);
XW_Pyy = (2*(abs(XW_Y))/hannsize);
XW_Pyy(2:halfhannsizeplusone-1)=XW_Pyy(2:halfhannsizeplusone-1)*2;
XW_Pyy=XW_Pyy.^2;
XW_grtc(:,1)=XW_Pyy(:);
X_DFTspectraldata_weighted(:,i+1)=XW_grtc(1:halfhannsizeplusone);

windowedNEW_acceldataBPpadded(:,2)=NEW_acceldataBPpadded(k+1:k+hannsize,2).*hannwindow(:,1);
Y_Y = fft(windowedNEW_acceldataBPpadded(:,2),hannsize);
Y_Pyy = (2*(abs(Y_Y))/hannsize);
Y_Pyy(2:halfhannsizeplusone-1)=Y_Pyy(2:halfhannsizeplusone-1)*2;
Y_Pyy=Y_Pyy.^2;
Y_grtc(:,1)=Y_Pyy(:);
Y_DFTspectraldata_UNweighted(:,i+1)=Y_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,2)=NEW_WacceldataBPpadded(k+1:k+hannsize,2).*hannwindow(:,1);
YW_Y = fft(windowedNEW_WacceldataBPpadded(:,2),hannsize);
YW_Pyy = (2*(abs(YW_Y))/hannsize);
YW_Pyy(2:halfhannsizeplusone-1)=YW_Pyy(2:halfhannsizeplusone-1)*2;
YW_Pyy=YW_Pyy.^2;
YW_grtc(:,1)=YW_Pyy(:);
Y_DFTspectraldata_weighted(:,i+1)=YW_grtc(1:halfhannsizeplusone);

windowedNEW_acceldataBPpadded(:,3)=NEW_acceldataBPpadded(k+1:k+hannsize,3).*hannwindow(:,1);
Z_Y = fft(windowedNEW_acceldataBPpadded(:,3),hannsize);
Z_Pyy = (2*(abs(Z_Y))/hannsize);
Z_Pyy(2:halfhannsizeplusone-1)=Z_Pyy(2:halfhannsizeplusone-1)*2;
Z_Pyy=Z_Pyy.^2;
Z_grtc(:,1)=Z_Pyy;
Z_DFTspectraldata_UNweighted(:,i+1)=Z_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,3)=NEW_WacceldataBPpadded(k+1:k+hannsize,3).*hannwindow(:,1);
ZW_Y = fft(windowedNEW_WacceldataBPpadded(:,3),hannsize);
ZW_Pyy = (2*(abs(ZW_Y))/hannsize);
ZW_Pyy(2:halfhannsizeplusone-1)=ZW_Pyy(2:halfhannsizeplusone-1)*2;
ZW_Pyy=ZW_Pyy.^2;
ZW_grtc(:,1)=ZW_Pyy;
ZW_DFTspectraldata_weighted(:,i+1)=ZW_grtc(1:halfhannsizeplusone);

windowedNEW_acceldataBPpadded(:,4)=NEW_acceldataBPpadded(k+1:k+hannsize,4).*hannwindow(:,1);
Roll_Y = fft(windowedNEW_acceldataBPpadded(:,4),hannsize);
Roll_Pyy = (2*(abs(Roll_Y))/hannsize);
Roll_Pyy(2:halfhannsizeplusone-1)=Roll_Pyy(2:halfhannsizeplusone-1)*2;
Roll_Pyy=Roll_Pyy.^2;
Roll_grtc(:,1)=Roll_Pyy;
Roll_DFTspectraldata_UNweighted(:,i+1)=Roll_grtc(1:halfhannsizeplusone);

windowedNEW_acceldataBPpadded(:,5)=NEW_acceldataBPpadded(k+1:k+hannsize,5).*hannwindow(:,1);
Pitch_Y = fft(windowedNEW_acceldataBPpadded(:,5),hannsize);
Pitch_Pyy = (2*(abs(Pitch_Y))/hannsize);
Pitch_Pyy(2:halfhannsizeplusone-1)=Pitch_Pyy(2:halfhannsizeplusone-1)*2;
Pitch_Pyy=Pitch_Pyy.^2;
Pitch_grtc(:,1)=Pitch_Pyy;
Pitch_DFTspectraldata_UNweighted(:,i+1)=Pitch_grtc(1:halfhannsizeplusone);

windowedNEW_WacceldataBPpadded(:,6)=NEW_WacceldataBPpadded(k+1:k+hannsize,6).*hannwindow(:,1);
Yaw_Y = fft(windowedNEW_WacceldataBPpadded(:,6),hannsize);
Yaw_Pyy = (2*(abs(Yaw_Y))/hannsize);
Yaw_Pyy(2:halfhannsizeplusone-1)=Yaw_Pyy(2:halfhannsizeplusone-1)*2;
Yaw_Pyy=Yaw_Pyy.^2;
Yaw_grtc(:,1)=Yaw_Pyy;
Yaw_DFTspectraldata_UNweighted(:,i+1)=Yaw_grtc(1:halfhannsizeplusone);
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YawW_Pyy = (2*(abs(YawW_Y))/hannsize);
YawW_Pyy(2:halfhannsizeplusone-1)=YawW_Pyy(2:halfhannsizeplusone-1)*2;
YawW_Pyy=YawW_Pyy.^2;
YawW_grtc(:,1)=YawW_Pyy(1:halfhannsizeplusone);

end
end

MTVV_UNweighted(1,1)=max(running_RMS_UNweighted(:,1));
MTVV_UNweighted(1,2)=max(running_RMS_UNweighted(:,2));
MTVV_UNweighted(1,3)=max(running_RMS_UNweighted(:,3));
MTVV_UNweighted(1,4)=max(running_RMS_UNweighted(:,4));
MTVV_UNweighted(1,5)=max(running_RMS_UNweighted(:,5));
MTVV_UNweighted(1,6)=max(running_RMS_UNweighted(:,6));

MTVV_weighted(1,1)=max(running_RMS_weighted(:,1));
MTVV_weighted(1,2)=max(running_RMS_weighted(:,2));
MTVV_weighted(1,3)=max(running_RMS_weighted(:,3));
MTVV_weighted(1,4)=max(running_RMS_weighted(:,4));
MTVV_weighted(1,5)=max(running_RMS_weighted(:,5));
MTVV_weighted(1,6)=max(running_RMS_weighted(:,6));

MTVV_aw_ratio_UNweighted=MTVV_UNweighted./RMS_UNweighted;
MTVV_aw_ratio_weighted=MTVV_weighted./RMS_weighted;

% calculate the mean stdev min and max of the moving average data

dataonly=running_RMS_UNweighted(:,);
clear running_RMS_UNweighted
running_RMS_UNweighted(1,:)=mean(dataonly);
running_RMS_UNweighted(2,:)=std(dataonly);
running_RMS_UNweighted(3,:)=min(dataonly);
running_RMS_UNweighted(4,:)=max(dataonly);
clear dataonly

dataonly=running_RMS_weighted(:,);
clear running_RMS_weighted
running_RMS_weighted(1,:)=mean(dataonly);
running_RMS_weighted(2,:)=std(dataonly);
running_RMS_weighted(3,:)=min(dataonly);
running_RMS_weighted(4,:)=max(dataonly);
clear dataonly

dataonly=running_RMS_X_third_octave_UNweighted(:,);
clear running_RMS_X_third_octave_UNWeighted
running_RMS_X_third_octave_UNWeighted(1,:)=third_octave_RMS_UNWeighted(:,1);
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dataonly=running_RMS_Y_third_octave_UNweighted(1,:);
clear running_RMS_Y_third_octave_UNweighted
running_RMS_Y_third_octave_UNweighted(1,:)=third_octave_RMS_UNweighted(:,1);
running_RMS_Y_third_octave_UNweighted(2,:)=mean(dataonly);
running_RMS_Y_third_octave_UNweighted(3,:)=std(dataonly);
running_RMS_Y_third_octave_UNweighted(4,:)=min(dataonly);
running_RMS_Y_third_octave_UNweighted(5,:)=max(dataonly);
clear dataonly
running_RMS_Y_third_octave_UNweighted=running_RMS_Y_third_octave_UNweighted;

running_RMS_Z_third_octave_UNweighted(1,:)=third_octave_RMS_UNweighted(:,1);
running_RMS_Z_third_octave_UNweighted(2,:)=mean(dataonly);
running_RMS_Z_third_octave_UNweighted(3,:)=std(dataonly);
running_RMS_Z_third_octave_UNweighted(4,:)=min(dataonly);
running_RMS_Z_third_octave_UNweighted(5,:)=max(dataonly);
clear dataonly
running_RMS_Z_third_octave_UNweighted=running_RMS_Z_third_octave_UNweighted;

running_RMS_Roll_third_octave_UNweighted(1,:)=third_octave_RMS_UNweighted(:,1);
running_RMS_Roll_third_octave_UNweighted(2,:)=mean(dataonly);
running_RMS_Roll_third_octave_UNweighted(3,:)=std(dataonly);
running_RMS_Roll_third_octave_UNweighted(4,:)=min(dataonly);
running_RMS_Roll_third_octave_UNweighted(5,:)=max(dataonly);
clear dataonly
running_RMS_Roll_third_octave_UNweighted=running_RMS_Roll_third_octave_UNweighted;

running_RMS_Pitch_third_octave_UNweighted(1,:)=third_octave_RMS_UNweighted(:,1);
running_RMS_Pitch_third_octave_UNweighted(2,:)=mean(dataonly);
running_RMS_Pitch_third_octave_UNweighted(3,:)=std(dataonly);
running_RMS_Pitch_third_octave_UNweighted(4,:)=min(dataonly);
running_RMS_Pitch_third_octave_UNweighted(5,:)=max(dataonly);
clear dataonly
running_RMS_Pitch_third_octave_UNweighted=running_RMS_Pitch_third_octave_UNweighted;

running_RMS_Yaw_third_octave_UNweighted(1,:)=third_octave_RMS_UNweighted(:,1);
running_RMS_Yaw_third_octave_UNweighted(2,:)=mean(dataonly);
running_RMS_Yaw_third_octave_UNweighted(3,:)=std(dataonly);
running_RMS_Yaw_third_octave_UNweighted(4,:)=min(dataonly);
running_RMS_Yaw_third_octave_UNweighted(5,:)=max(dataonly);
clear dataonly
running_RMS_Yaw_third_octave_UNweighted=running_RMS_Yaw_third_octave_UNweighted;

running_RMS_X_third_octave_weighted(1,:)=third_octave_RMS_weighted(:,1);
running_RMS_X_third_octave_weighted(2,:)=mean(dataonly);
running_RMS_X_third_octave_weighted(3,:)=std(dataonly);
APPENDIX H: Vibration Analysis MatLab Code

running_RMS_X_third_octave_weighted(4,:)=min(dataonly);
running_RMS_X_third_octave_weighted(5,:)=max(dataonly);
clear dataonly
running_RMS_X_third_octave_weighted=running_RMS_X_third_octave_weighted';

dataonly=running_RMS_Y_third_octave_weighted(:,);
clear running_RMS_Y_third_octave_weighted
running_RMS_Y_third_octave_weighted(1,:)=third_octave_RMS_weighted(:,1)';
running_RMS_Y_third_octave_weighted(2,:)=mean(dataonly);
running_RMS_Y_third_octave_weighted(3,:)=std(dataonly);
running_RMS_Y_third_octave_weighted(4,:)=min(dataonly);
running_RMS_Y_third_octave_weighted(5,:)=max(dataonly);
clear dataonly
running_RMS_Y_third_octave_weighted=running_RMS_Y_third_octave_weighted';

dataonly=running_RMS_Z_third_octave_weighted(:,);
clear running_RMS_Z_third_octave_weighted
running_RMS_Z_third_octave_weighted(1,:)=third_octave_RMS_weighted(:,1)';
running_RMS_Z_third_octave_weighted(2,:)=mean(dataonly);
running_RMS_Z_third_octave_weighted(3,:)=std(dataonly);
running_RMS_Z_third_octave_weighted(4,:)=min(dataonly);
running_RMS_Z_third_octave_weighted(5,:)=max(dataonly);
clear dataonly
running_RMS_Z_third_octave_weighted=running_RMS_Z_third_octave_weighted';

dataonly=running_RMS_Roll_third_octave_weighted(:,);
clear running_RMS_Roll_third_octave_weighted
running_RMS_Roll_third_octave_weighted(1,:)=third_octave_RMS_weighted(:,1)';
running_RMS_Roll_third_octave_weighted(2,:)=mean(dataonly);
running_RMS_Roll_third_octave_weighted(3,:)=std(dataonly);
running_RMS_Roll_third_octave_weighted(4,:)=min(dataonly);
running_RMS_Roll_third_octave_weighted(5,:)=max(dataonly);
clear dataonly
running_RMS_Roll_third_octave_weighted=running_RMS_Roll_third_octave_weighted';

dataonly=running_RMS_Pitch_third_octave_weighted(:,);
clear running_RMS_Pitch_third_octave_weighted
running_RMS_Pitch_third_octave_weighted(1,:)=third_octave_RMS_weighted(:,1)';
running_RMS_Pitch_third_octave_weighted(2,:)=mean(dataonly);
running_RMS_Pitch_third_octave_weighted(3,:)=std(dataonly);
running_RMS_Pitch_third_octave_weighted(4,:)=min(dataonly);
running_RMS_Pitch_third_octave_weighted(5,:)=max(dataonly);
clear dataonly
running_RMS_Pitch_third_octave_weighted=running_RMS_Pitch_third_octave_weighted';

dataonly=running_RMS_Yaw_third_octave_weighted(:,);
clear running_RMS_Yaw_third_octave_weighted
running_RMS_Yaw_third_octave_weighted(1,:)=third_octave_RMS_weighted(:,1)';
running_RMS_Yaw_third_octave_weighted(2,:)=mean(dataonly);
running_RMS_Yaw_third_octave_weighted(3,:)=std(dataonly);
running_RMS_Yaw_third_octave_weighted(4,:)=min(dataonly);
running_RMS_Yaw_third_octave_weighted(5,:)=max(dataonly);
clear dataonly
running_RMS_Yaw_third_octave_weighted=running_RMS_Yaw_third_octave_weighted';

dataonly=X_DFTspectraldata_UNweighted(:,2:totalnumberwindows);
clear X_DFTspectraldata_UNweighted
columnTOrOW=dataonly';
average=mean(columnTOrOW);
average=average';
stdev=std(columnTOrOW);
stdev=stdev';
minimum=min(columnTOrOW);
minimum=minimum';
maximum=max(columnTOrOW);
maximum=maximum';
X_DFTspectraldata_UNweighted(:,1)=DFTfreq(:,1);
X_DFTspectraldata_UNweighted(:,2)=average(:,1);
X_DFTspectraldata_UNweighted(:,3)=stdev(:,1);
X_DFTspectraldata_UNweighted(:,4)=minimum(:,1);
X_DFTspectraldata_UNweighted(:,5)=maximum(:,1);
dataonly=Y_DFTspectraldata_UNweighted(:,2:totalnumberwindows);
clear Y_DFTspectraldata_UNweighted
columnTOrOW=dataonly';
average=mean(columnTOrOW);
average=average';
stdev=std(columnTOrOW);
stdev=stdev';
minimum=min(columnTOrOW);
minimum=minimum';
maximum=max(columnTOrOW);
maximum=maximum';
Y_DFTspectraldata_UNweighted(:,1)=DFTfreq(:,1);
Y_DFTspectraldata_UNweighted(:,2)=average(:,1);
Y_DFTspectraldata_UNweighted(:,3)=stdev(:,1);
Y_DFTspectraldata_UNweighted(:,4)=minimum(:,1);
Y_DFTspectraldata_UNweighted(:,5)=maximum(:,1);
dataonly=Z_DFTspectraldata_UNweighted(:,2:totalnumberwindows);
clear Z_DFTspectraldata_UNweighted
columnTOrOW=dataonly';
average=mean(columnTOrOW);
average=average';
stdev=std(columnTOrOW);
stdev=stdev';
minimum=min(columnTOrOW);
minimum=minimum';
maximum=max(columnTOrOW);
maximum=maximum';
Z_DFTspectraldata_UNweighted(:,1)=DFTfreq(:,1);
Z_DFTspectraldata_UNweighted(:,2)=average(:,1);
Z_DFTspectraldata_UNweighted(:,3)=stdev(:,1);
Z_DFTspectraldata_UNweighted(:,4)=minimum(:,1);
Z_DFTspectraldata_UNweighted(:,5)=maximum(:,1);
dataonly=Roll_DFTspectraldata_UNweighted(:,2:totalnumberwindows);
clear Roll_DFTspectraldata_UNweighted
columnTOrOW=dataonly';
average=mean(columnTOrOW);
average=average';
stdev=std(columnTOrOW);
APPENDIX H: Vibration Analysis MatLab Code

```matlab
stdev=stdev';
minimum=min(columnTOrow);
minimum=minimum';
maximum=max(columnTOrow);
maximum=maximum';
Roll_DFTspectraldata_UNweighted(:,1)=DFTfreq(:);
Roll_DFTspectraldata_UNweighted(:,2)=average(:,1);
Roll_DFTspectraldata_UNweighted(:,3)=stdev(:,1);
Roll_DFTspectraldata_UNweighted(:,4)=minimum(:,1);
Roll_DFTspectraldata_UNweighted(:,5)=maximum(:,1);

dataonly=Pitch_DFTspectraldata_UNweighted(:,2:totalnumberwindows);
clear Pitch_DFTspectraldata_UNweighted
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stdev=std(columnTOrow);
stdev=stdev';
minimum=min(columnTOrow);
minimum=minimum';
maximum=max(columnTOrow);
maximum=maximum';
Pitch_DFTspectraldata_UNweighted(:,1)=DFTfreq(:);
Pitch_DFTspectraldata_UNweighted(:,2)=average(:,1);
Pitch_DFTspectraldata_UNweighted(:,3)=stdev(:,1);
Pitch_DFTspectraldata_UNweighted(:,4)=minimum(:,1);
Pitch_DFTspectraldata_UNweighted(:,5)=maximum(:,1);

dataonly=Yaw_DFTspectraldata_UNweighted(:,2:totalnumberwindows);
clear Yaw_DFTspectraldata_UNweighted
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stdev=std(columnTOrow);
stdev=stdev';
minimum=min(columnTOrow);
minimum=minimum';
maximum=max(columnTOrow);
maximum=maximum';
Yaw_DFTspectraldata_UNweighted(:,1)=DFTfreq(:);
Yaw_DFTspectraldata_UNweighted(:,2)=average(:,1);
Yaw_DFTspectraldata_UNweighted(:,3)=stdev(:,1);
Yaw_DFTspectraldata_UNweighted(:,4)=minimum(:,1);
Yaw_DFTspectraldata_UNweighted(:,5)=maximum(:,1);

dataonly=X_DFTspectraldata_weighted(:,2:totalnumberwindows);
clear X_DFTspectraldata_weighted
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stdev=std(columnTOrow);
stdev=stdev';
minimum=min(columnTOrow);
minimum=minimum';
maximum=max(columnTOrow);
```

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maximum=maximum';
X_DFTspectraldata_weighted(:,1)=DFTfreq();
X_DFTspectraldata_weighted(:,2)=average(:,1);
X_DFTspectraldata_weighted(:,3)=stdev(:,1);
X_DFTspectraldata_weighted(:,4)=minimum(:,1);
X_DFTspectraldata_weighted(:,5)=maximum(:,1);

dataonly=Y_DFTspectraldata_weighted(:,2:totalnumberwindows);
clear Y_DFTspectraldata_weighted
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stdev=std(columnTOrow);
stdev=stdev';
minimum=min(columnTOrow);
minimum=minimum';
maximum=max(columnTOrow);
maximum=maximum';
Y_DFTspectraldata_weighted(:,1)=DFTfreq();
Y_DFTspectraldata_weighted(:,2)=average(:,1);
Y_DFTspectraldata_weighted(:,3)=stdev(:,1);
Y_DFTspectraldata_weighted(:,4)=minimum(:,1);
Y_DFTspectraldata_weighted(:,5)=maximum(:,1);

dataonly=Z_DFTspectraldata_weighted(:,2:totalnumberwindows);
clear Z_DFTspectraldata_weighted
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stdev=std(columnTOrow);
stdev=stdev';
minimum=min(columnTOrow);
minimum=minimum';
maximum=max(columnTOrow);
maximum=maximum';
Z_DFTspectraldata_weighted(:,1)=DFTfreq();
Z_DFTspectraldata_weighted(:,2)=average(:,1);
Z_DFTspectraldata_weighted(:,3)=stdev(:,1);
Z_DFTspectraldata_weighted(:,4)=minimum(:,1);
Z_DFTspectraldata_weighted(:,5)=maximum(:,1);

dataonly=Roll_DFTspectraldata_weighted(:,2:totalnumberwindows);
clear Roll_DFTspectraldata_weighted
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stdev=std(columnTOrow);
stdev=stdev';
minimum=min(columnTOrow);
minimum=minimum';
maximum=max(columnTOrow);
maximum=maximum';
Roll_DFTspectraldata_weighted(:,1)=DFTfreq();
Roll_DFTspectraldata_weighted(:,2)=average(:,1);
Roll_DFTspectraldata_weighted(:,3)=stdev(:,1);
Roll_DFTspectraldata_weighted(:,4)=minimum(:,1);
APPENDIX H: Vibration Analysis MatLab Code

Roll_DFTspectraldata_weighted(:,5)=maximum(:,1);

dataonly=Pitch_DFTspectraldata_weighted(:,2:totalnumberwindows);
clear Pitch_DFTspectraldata_weighted
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stdev=std(columnTOrow);
stdev=stdev';
mimimum=min(columnTOrow);
mimimum=mimimum';
maximum=max(columnTOrow);
maximum=maximum';
Pitch_DFTspectraldata_weighted(:,1)=DFTfreq(:);
Pitch_DFTspectraldata_weighted(:,2)=average(:,1);
Pitch_DFTspectraldata_weighted(:,3)=stdev(:,1);
Pitch_DFTspectraldata_weighted(:,4)=mimimum(:,1);
Pitch_DFTspectraldata_weighted(:,5)=maximum(:,1);

dataonly=Yaw_DFTspectraldata_weighted(:,2:totalnumberwindows);
clear Yaw_DFTspectraldata_weighted
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stdev=std(columnTOrow);
stdev=stdev';
mimimum=min(columnTOrow);
mimimum=mimimum';
maximum=max(columnTOrow);
maximum=maximum';
Yaw_DFTspectraldata_weighted(:,1)=DFTfreq(:);
Yaw_DFTspectraldata_weighted(:,2)=average(:,1);
Yaw_DFTspectraldata_weighted(:,3)=stdev(:,1);
Yaw_DFTspectraldata_weighted(:,4)=mimimum(:,1);
Yaw_DFTspectraldata_weighted(:,5)=maximum(:,1);

kwd=1.4; %Currently kwd is for health analyses. Change it to 1 for comfort analyses
kwk=1;
kweRx=0.63;
kweRy=0.4;
kweRz=0.2;

VTV_translational_RMS_UNweighted=((RMS_UNweighted(1,1)*kwd)^2)+((RMS_UNweighted(1,2)*kwd)^2)+((RMS_UNweighted(1,3)*kwk)^2))^0.5;
VTV_translational_RMS_weighted=((RMS_weighted(1,1)*kwd)^2)+((RMS_weighted(1,2)*kwd)^2)+((RMS_weighted(1,3)*kwk)^2))^0.5;

% Calculate vibration total values --> summed across axes

% NOTE: multiplying factors k are in accordance with ISO 2631-1;1997
APPENDIX H: Vibration Analysis MatLab Code

VTV_6DOF_RMS_UNweighted=(((RMS_UNweighted(1,1)*kwd)^2)+((RMS_UNweighted(1,2)*kwd)^2)+((RMS_UNweighted(1,3)*kwk)^2)+((RMS_UNweighted(1,4)*kweRx)^2)+((RMS_UNweighted(1,5)*kweRy)^2)+((RMS_UNweighted(1,6)*kweRz)^2))^0.5;

VTV_6DOF_RMS_weighted=(((RMS_weighted(1,1)*kwd)^2)+((RMS_weighted(1,2)*kwd)^2)+((RMS_weighted(1,3)*kwk)^2)+((RMS_weighted(1,4)*kweRx)^2)+((RMS_weighted(1,5)*kweRy)^2)+((RMS_weighted(1,6)*kweRz)^2))^0.5;

VTV_translational_running_RMS_UNweighted=(((running_RMS_UNweighted(1,1)*kwd)^2)+((running_RMS_UNweighted(1,2)*kwd)^2)+((running_RMS_UNweighted(1,3)*kwk)^2))^0.5;

VTV_translational_running_RMS_weighted=(((running_RMS_weighted(1,1)*kwd)^2)+((running_RMS_weighted(1,2)*kwd)^2)+((running_RMS_weighted(1,3)*kwk)^2))^0.5;

VTV_6DOF_running_RMS_UNweighted=(((running_RMS_UNweighted(1,1)*kwd)^2)+((running_RMS_UNweighted(1,2)*kwd)^2)+((running_RMS_UNweighted(1,3)*kwk)^2)+((running_RMS_UNweighted(1,4)*kweRx)^2)+((running_RMS_UNweighted(1,5)*kweRy)^2)+((running_RMS_UNweighted(1,6)*kweRz)^2))^0.5;

VTV_6DOF_running_RMS_weighted=(((running_RMS_weighted(1,1)*kwd)^2)+((running_RMS_weighted(1,2)*kwd)^2)+((running_RMS_weighted(1,3)*kwk)^2)+((running_RMS_weighted(1,4)*kweRx)^2)+((running_RMS_weighted(1,5)*kweRy)^2)+((running_RMS_weighted(1,6)*kweRz)^2))^0.5;
APPENDIX I

CUSTOM MULTIPLE RESOLUTION CROSS-CORRELATION MATLAB CODE

The pages to follow contain the custom “Multi_Res_Xcorr” MatLabTM code used to align the goniometer and vibration exposure data collected in the field with the simultaneously collected time stamp data.
Function[aligned_data,shift_check]=Multi_Res_Xcorr(alignment_data,alignment_data_column,align_with_data,align_with_data_column,low_res_Fc,high_res_Fc,percent_from_start,sf)

--------------------------------------------- Multi_Res_Xcorr
---------------------------------------------

This code takes a selected column (alignment_data_column) from a dataset (alignment_data) and uses that data in a multiple resolution cross correlation outlined by Jack et al. (2008) to align that data with a selected column (align_with_data_column) from a reference dataset (align_with_data). The reference dataset must have shorter column lengths than the alignment_data

The code uses low and high resolution cut-off frequencies (low_res_Fc and high_res_Fc) selected by the user

Only a selected percentage of the total data length from the start of the data (percent_from_start) is used for the high resolution alignment

Note that both datasets must have the same sample rate (sf)

Once aligned the data_for_alignment is padded or windowed to match the length of the data_to_align_with and the two datasets are concatenated, i.e. [alignment_data,align_with_data]

A shift_check is performed to report how far off the final alignment is

Written by Robert J. Jack May 30th, 2011

---------------------------------------------
---------------------------------------------

determine the length of the datasets

arraysize=size(alignment_data);
alignment_data_length=arraysize;

arraysize=size(align_with_data);
align_with_data_length=arraysize;

Low resolution shift determination

filter and resample data to create low resolution data

nyq=sf/2;

[b1,a1]=butter(2,low_res_Fc/nyq,'low');
alignment_data_LP=filtfilt(b1,a1,alignment_data);
align_with_data_LP=filtfilt(b1,a1,align_with_data);

low_res_Hz=(2*low_res_Fc)+1;

alignment_data_resampled(:,::)=resample(alignment_data_LP,low_res_Hz,sf);
align_with_data_resampled(:,::)=resample(align_with_data_LP,low_res_Hz,sf);
APPENDIX I: Multiple Resolution Cross-Correlation MatLab Code

% determine shift

[c,lags]=xcorr(align_with_data_resampled(:,align_with_data_column),alignment_data_resampled(:,alignment_data_column));

searchvalue=max(c);

index_X = find(c == searchvalue);
shift_low=lags(index_X);

% Resample shift value to match the full resolution sampling rate

% sample rate conversion

src=low_res_Hz/sf;
corr_shift_low=round(shift_low/src);

% Shift the alignment_data to align with the align_with_data

if corr_shift_low == 0
    low_res_align_with_data(:,:,)=align_with_data;
    low_res_alignment_data(:,:,)=alignment_data(1:align_with_data_length(1,1),:);
    low_res_data_aligned_and_clipped=[low_res_alignment_data,low_res_align_with_data];
else if corr_shift_low >= 0
    padding=zeros(corr_shift_low,alignment_data_length(1,2));
    low_res_align_with_data(:,:,)=align_with_data;
    low_res_alignment_data(:,:,)=[padding;alignment_data(1:(align_with_data_length(1,1)-corr_shift_low),:)];
    low_res_data_aligned_and_clipped=[low_res_alignment_data,low_res_align_with_data];
    clear padding
else if corr_shift_low <= 0
    new_corr_shift_low=abs(corr_shift_low)+1;
    low_res_align_with_data(:,:,)=align_with_data;
    low_res_alignment_data(:,:,)=alignment_data(new_corr_shift_low:(align_with_data_length(1,1)+new_corr_shift_low-1),:);
    low_res_data_aligned_and_clipped=[low_res_alignment_data,low_res_align_with_data];
    clear new_corr_shift_low
end
end
end

clear c
clear lags
clear data_aligned
clear alignment_data_resampled
clear align_with_data_resampled

% High resolution shift determination

% filter and resample data to create high resolution data

nyq=sf/2;

[b1,a1]=butter(2,high_res_Fc/nyq,'low');

high_res_alignment_data_LP=filtfilt(b1,a1,low_res_alignment_data);
high_res_align_with_data_LP=filtfilt(b1,a1,low_res_align_with_data);

high_res_Hz=(2*high_res_Fc)+1;

alignment_data_resampled(:,:,1,:)=resample(high_res_alignment_data_LP,high_res_Hz,sf);
align_with_data_resampled(:,:,1,:)=resample(high_res_align_with_data_LP,high_res_Hz,sf);

% Use the first 10% of the data for the high resolution shift

arraysize=size(align_with_data_resampled);
align_with_data_resampled_length=arraysize(1,1);
new_end=round(align_with_data_resampled_length*(percent_from_start/100));

% determine shift

[c,lags]=xcorr(align_with_data_resampled(1:new_end,align_with_data_column),alignment_data_resampled(1:new_end,alignment_data_column));

searchvalue=max(c);

index_X = find(c == searchvalue);
shift_high=lags(index_X);

% Resample shift value to match the full resolution sampling rate

% sample rate conversion

src=high_res_Hz/sf;

corr_shift_high=round(shift_high/src);
shift_high=corr_shift_low+corr_shift_high;

% Shift the alignment_data to align with the align_with_data

if shift_high == 0

high_res_align_with_data(:,:,1,:)=align_with_data;
high_res_alignment_data(:,:,1,:)=alignment_data(1:align_with_data_length(1,1,:));
high_res_data_aligned_and_clipped=[high_res_alignment_data,high_res_align_with_data];

else if shift_high >= 0


padding=zeros(shift_high,alignment_data_length(1,2));

high_res_align_with_data(:,:,)=align_with_data;
high_res_alignment_data(:,:,)=padding;alignment_data(1:(align_with_data_length(1,1)-shift_high),:);
high_res_data_aligned_and_clipped=[high_res_alignment_data,high_res_align_with_data];

clear padding

else if shift_high <= 0

new_shift_high=abs(shift_high)+1;

high_res_align_with_data(:,:,)=align_with_data;
high_res_alignment_data(:,:,)=alignment_data(new_shift_high:(align_with_data_length(1,1)+new_shift_high-1),:);
high_res_data_aligned_and_clipped=[high_res_alignment_data,high_res_align_with_data];

clear new_shift_high
end
end
end

clear c
clear lags
clear data_aligned

clear alignment_data_resampled

clear align_with_data_resampled

clear shift_low

clear corr_shift_low

clear shift_high
clear corr_shift_high

clear low_res_align_with_data

clear low_res_data_aligned_and_clipped

% aligned data

aligned_data=high_res_data_aligned_and_clipped;

% shift check
APPENDIX I: Multiple Resolution Cross-Correlation MatLab Code

```matlab
[c, lags] = xcorr(high_res_align_with_data(:, align_with_data_column), high_res_alignment_data(:, alignment_data_column));

searchvalue = max(c);

index_X = find(c == searchvalue);
shift_check = lags(index_X);

clear high_res_align_with_data

clear high_res_data_aligned_and_clipped
```
APPENDIX J

CUSTOM WAVELET DE-NOISING MATLAB CODE

The pages to follow contain the an example of the custom “wavelet_de_noising” Matlab™ code used to de-noise the trunk posture data collected with the goniometers in the field.
function[de_noised_data]=wavelet_de_noising(noise_estimate_data,noisy_test_data,set_levels,set_threshold,sample_freq,upper_freq)

%%% wavelet_de_noising
%%
% This code loads a two time histories of data. One for noise estimation
% and one to be de-noised. The noise estimation data is graphed so that the
% noise can be windowed and the have denoising thresholds can be determined
% from that windowed dataset. A 3rd order Daubechies wavelet decomposition
% is used to denoise the signal. Users must enter the number of levels to
% be used for the deconstruction (set_levels). Users must also enter the
% threshold level in standard deviations (set_threshold) for the signal
% amplitudes above which will be considered good data. The thresholded data
% is then reconstructed to produce the denoised data. Users are also asked
% to enter the upper frequency of the signal being denoised. The code will
% then eliminate the signal found for the closet detail level above that
% set upper frequency.
%
%
% Created by Robert J. Jack          July 16, 2009
%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% 

% Determine the upper frequency limit for the detail wavelet levels
detail_freq(1,1)=sample_freq;
for i=1:set_levels
detail_freq(i+1,1)=detail_freq(i,1)*0.5;
end

% determine the level with which to attenuate all signal above its
% frequency
for i=1:set_levels
    if detail_freq(i,1)>=upper_freq;
        threshold_limit(i,1)=1000;
    else
        threshold_limit(i,1)=3;
    end
end

% Obtain noise estimates and wavelet thresholds

% Plot data
figure(1)
subplot(2,1,1); plot(noise_estimate_data);
title('Data for Noise Estimation')
subplot(2,1,2); plot(noisy_test_data);
title('Data to be De-noised')

% Select the section of noise desired for the noise estimate
points=2;
clear screen
fprintf 'Click the start and end of the data to be used for a noise estimate \n'
[X,Y]=ginput(points);
noiseST=(round(X(1,1)));
noiseEND=(round(X(2,1)));

noise=noise_estimate_data(noiseST:noiseEND,1);

% Perform a ith level decomposition of the signal (using the db3 wavelet)
for i=1:set_levels
    s=noise(:,1);
    [C,L] = wavedec(s,set_levels,'db3');
    % Reconstruct the level 15 approximation from C
    A = wrcoef('a',C,L,'db3',set_levels);
    % To reconstruct the details at the 15 levels from C
    D(:,i) = wrcoef('d',C,L,'db3',i);
    % Establish the threshold amplitudes for each detail level
    % based on Z-score calculations where Z=(x(i)-mean(x))/std(x)
    % if z=3 or 3 standard deviations and assuming a zero mean from the
    % details levels, then x(i)=3*std(x)
    threshold(i,1)=(threshold_limit(i,1)*(std(D(:,i))));
end

clear s
clear D
clear A

%Apply wavelet noise thresholds to the noise contaminated signal
s=noisy_test_data(:,1);
% Perform a ith level decomposition of the signal (using the db3 wavelet)
for i=1:set_levels
    [C,L] = wavedec(s,set_levels,'db3');
    % Reconstruct the level 15 approximation from C
    A = wrcoef('a',C,L,'db3',set_levels);
    % To reconstruct the details at the 15 levels from C
D(:,i) = wrcoef('d',C,L,'db3',i);
end

% Set thresholds for signal reconstruction

% N=decomposition level
for i=1:set_levels
    N(:,i)=i;
end

% T=decomposition level threshold
T=threshold';

% Calculate new wavelet coefficients
NC = wthcoef('t',C,L,N,T,'s');

% Reconstruct signal using the new coefficients
de_noised_data=waverec(NC,L,'db3');

figure(2)
subplot(2,1,1); plot(s(:,:)); title('Original')
subplot(2,1,2); plot(de_noised_data(:,:)); title('De-noised')
APPENDIX K

CUSTOM KISTLER FORCE PLATE MATLAB CODE

The pages to follow contain the custom “Kistler_force_plate_processing” MatLab™ code used to process the force plate data collected in the laboratory.
function[force_plate_data]=Kistler_force_plate_processing(FPLPFc,sf,raw_force_plate_data)

%%%%% Kistler_force_plate_processing
%%%%%%
%% This code takes raw kistler voltages (CH1 through CH8 has the following
%% order: FPX12, FPX34, FPY14, FPY23, FPZ1, FPZ2, FPZ3, FPZ4); low-pass
%% filters those voltages and then determines Fx, Fy, Fz, Mx, My, Mz, COPx, 
%% COPy and COPz (force_plate_data output order) using procedures and 
%% sensitivities provided by Kistler for a 9281B force plate with a 9865B
%% charge amplifier.
%%
% Created by Robert J. Jack                     June 4th, 2011
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %

% force plate low-pass filter

nyq=sf/2;

[b1,a1]=butter(2,FPLPFc/nyq,'low');
force_plate_data_LP=filtfilt(b1,a1,raw_force_plate_data);

% conversion of force plate data to N, Nm and m

% scaling factors for Kistler a force plate

xy_sensitivity=8;  %pC/N
z_sensitivity=3.8; %pC/N
range_pC=5000;  %+/- pC
range_V=10;  %+/- V
xy_range=500;  %+/- N
z_range=2000;  %+/- N

Fx=xy_range/(((xy_range*xy_sensitivity)/range_pC)*range_V);    %N/V
Fz=z_range/(((z_range*z_sensitivity)/range_pC)*range_V);    %N/V
a=0.12; %in m
b=0.2; %in m
z=-0.054;   %in m

force_plate_data(:,1)=(force_plate_data_LP(:,1)+force_plate_data_LP(:,2))*Fxy;  %Fx
force_plate_data(:,2)=(force_plate_data_LP(:,3) +force_plate_data_LP(:,4))*Fxy;  %Fy
force_plate_data(:,3)=(force_plate_data_LP(:,5) +force_plate_data_LP(:,6)+
force_plate_data_LP(:,7)+force_plate_data_LP(:,8))* Fz; %Fz
force_plate_data(:,7)=((a*(-force_plate_data_LP(:,5)+force_plate_data_LP(:,6)+
force_plate_data_LP(:,7)-force_plate_data_LP(:,8))*Fz)-(force_plate_data(:,1)*z))./force_plate_data(:,3);  %COPx
force_plate_data(:,8)=((b*(force_plate_data_LP(:,5)+force_plate_data_LP(:,6)-
force_plate_data_LP(:,7)-force_plate_data_LP(:,8))*Fz)+(force_plate_data(:,2)*z))./force_plate_data(:,3);  %COPy
force_plate_data(:,9)=0;  %COPz
force_plate_data(:,4)=(-force_plate_data(:,3).*force_plate_data(:,8))-(force_plate_data(:,2)*z);  %Mx
force_plate_data(:,5)=(-force_plate_data(:,3).*force_plate_data(:,7))+(force_plate_data(:,1)*z);  %My
force_plate_data(:,6)=((b*(-
force_plate_data_LP(:,1)+force_plate_data_LP(:,2))*Fxy)+(a*(force_plate_data_LP(:,3)-
force_plate_data_LP(:,4))*Fxy))-
(force_plate_data(:,2).*force_plate_data(:,7))+(force_plate_data(:,1).*force_plate_data(:,8));  %Mz
clear force_plate_data_LP

%Correct for divide by zero problems by only using forces and moments
%greater than 1.5 (the apparent noise floor) for the COP calculations

FP_length=size(force_plate_data);

for j=1:FP_length(1,1)
    if force_plate_data(j,1) < 1.5 & force_plate_data(j,2) < 1.5 & force_plate_data(j,3) < 1.5 &
        force_plate_data(j,4) < 1.5 & force_plate_data(j,5) < 1.5 & force_plate_data(j,6) < 1.5
        force_plate_data(j,7)=0;
        force_plate_data(j,8)=0;
    else
        force_plate_data(j,7)=force_plate_data(j,7);
        force_plate_data(j,8)=force_plate_data(j,8);
    end
end
APPENDIX L

CUSTOM ELECTROMYOGRAPHY MATLAB CODE

The pages to follow contain the custom “EMG_processing” MatLab™ code used to process the electromyography data collected in the laboratory.
function [rectified_EMG, linear_envelope, integrated_EMG, AEMG, reference_AEMG, normalized_AEMG, RMS_EMG, reference_RMS_EMG, normalized_RMS_EMG] = EMG_processing(EMGLPFc, EMGHPFc, raw_reference_EMG_data, raw_trial_EMG_data, sf)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% EMG_processing
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% This code band-pass filters the raw EMG reference and trial data. It then
% rectifies and low-pass filters raw EMG data with a cut-off frequency
% of 6Hz in accordance with Cholewicki and McGill (1996). The linear
% envelope created is then integrated and the integrated EMG is then
% divided by the duration of the dataset to provide the average EMG level
% or AEMG. The RMS EMG level is also calculated.
%
% The aformentioned is performed for both the trial and reference
% contractions. The trial data is then normalized to the reference data
%
% Created By Robert J. Jack       June 1st, 2011
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %%%%%

% Base filtering of all data

nyq = sf/2;

% EMG band-pass filter

[b1,a1] = butter(2, EMGLPFc/nyq, 'low');
reference_EMG_data = filtfilt(b1,a1, raw_reference_EMG_data);
[b1,a1] = butter(2, EMGHPFc/nyq, 'high');
reference_EMG_data = filtfilt(b1,a1, raw_reference_EMG_data);

[b1,a1] = butter(2, EMGLPFc/nyq, 'low');
trial_EMG_data = filtfilt(b1,a1, raw_trial_EMG_data);
[b1,a1] = butter(2, EMGHPFc/nyq, 'high');
trial_EMG_data = filtfilt(b1,a1, raw_trial_EMG_data);

% trial data

% rectify raw EMG data
rectified_EMG = abs(trial_EMG_data);

% create the linear envelope

[b1,a1] = butter(2, 6/nyq, 'low');
linear_envelope = filtfilt(b1,a1, rectified_EMG);

% integrate EMG

dt = 1/sf;
length = size(trial_EMG_data);
total_time = length(1,1)*dt;
duration = total_time - dt;
time=0:dt:duration;
time=time';

integrated_EMG=cumtrapz(time,linear_envelope);

% determine AEMG
AEMG=(max(integrated_EMG))/(max(time));
clear time

% determine RMS EMG
RMS_EMG=sqrt(mean(trial_EMG_data.^2));

% reference data
% rectify raw EMG data
rectified_reference_EMG=abs(reference_EMG_data);

% create the linear envelope
[b1,a1]=butter(2,6/nyq,'low');
reference_linear_envelope=filtfilt(b1,a1,rectified_reference_EMG);

% integrate EMG
dt=1/sf;
length=size(reference_EMG_data);
total_time=length(1,1)*dt;
duration=total_time-dt;
time=0:dt:duration;
time=time';

integrated_reference_EMG=cumtrapz(time,reference_linear_envelope);

% determine AEMG
reference_AEMG=(max(integrated_reference_EMG))/(max(time));

% determine RMS EMG
reference_RMS_EMG=sqrt(mean(reference_EMG_data.^2));

% normalized data
normalized_AEMG=(AEMG/reference_AEMG)*100;
normalized_RMS_EMG=(RMS_EMG/reference_RMS_EMG)*100;
APPENDIX M

CUSTOM ROTATION MATRIX MATLAB CODE

The pages to follow contain the custom “RTM_joint_angles” MatLab™ code used to determine the rotational motions of marker triads via the marker positional data collected in the laboratory with the Vicon™ 460 motion capture system.
Function[beta, alpha, gamma, displacement] = RTM_joint_angles(proximal_triad, distal_triad, order)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% % RTM_joint_angles
%%%%%%%%%%%%%%%%%%%%%%%%%%
% This code inputs the coordinates of 2 marker triads and calculates the
% 3D angles (in degrees) and the translation (in input units, i.e. likely
% mm if Vicon data) between them.
% The rotation order relative to the GCS is also input.
% 1 = xyz
% 2 = xzy
% 3 = yxz
% 4 = yzx
% 5 = zxy
% 6 = zyx
% The order should be flexion/extension, adduction/abduction, and then
% axial rotation.
% GSC - X Y Z coordinates, unit vectors i j k
% LCS - x y z coordinates, unit vectors i' j' k' (here ii jj kk)
% proximal_triad=(marker1x,marker1y,marker1z,marker2x,marker2y,marker2z,marker3x,
% marker3y,marker3z)
% distal_triad=(marker1x,marker1y,marker1z,marker2x,marker2y,marker2z,marker3x,
% marker3y,marker3z)
% Steps used: 1) Separate out the individual maker coordinates from the
% marker triads and determine the triad origin.
% 2) Calculated V (the translational component of the
% triad/segment origin relative to the GCS) for both
% triads in all frames.
% 3) Use V to align the origin of both triads with the GCS
% origin in all frames (shift all three marker positions in
% 3D space).
% 4) Define triad coordinate system (LCS or SCS)
% 5) Make the unit vectors Tp and Td. Triad 2 is the proximal
% segment and Triad 1 is the distal segment.
% 6) Create a rotation matrices Trp and Trd by multiplying Tp
% and Td by the identity matrix Tid.
% 7) Use Tr and Euler angle matrices to determine the angle
% between the Tp and Td with the GCS.
% 8) Determine the difference between the GCS and Tp, Td
% rotations to get the angles between Tp and Tp
% 9) Determine the difference between V2 and V1 to get the
% displacement of the distal triad from the proximal
% 10) Make the first frame in the trial the reference frame
% or use a previously defined/recorded posture as the
% reference).
% Formulas used outlined in Hamill and Selbie, In: Robertson, Caldwell,
% Hamill, Kamen and Whittlesey 2004. (The code assumes a Figure 2.7a
% marker setup).
NOTE: the proximal triad can also be thought of as the reference triad with which the distal triad is compared too

% Created by Robert J. Jack June 29, 2009

% Beta = angle about Y = flexion/extension of the knee for example
% Alpha = angle about X = abduction/adduction of the knee for example
% Gamma = angle about Z = axial rotation of the knee for example

% Assuming that X is the direction of travel

% calculate the trial length

trial_length = size(proximal_triad);

% proximal_triad
p11=proximal_triad(:,1:3); %origin position
p12=proximal_triad(:,4:6);
p13=proximal_triad(:,7:9);

V1=p11; % calculate V1 -- Linear transform (V) to align origins

% distal_triad
p21=distal_triad(:,1:3); %origin position
p22=distal_triad(:,4:6);
p23=distal_triad(:,7:9);

V2=p21; % calculate V2 -- Linear transform (V) to align origins

% align triad origins for the LCS with the GCS (shift all triad markers appropriately).

% proximal_triad
newp11=p11-V1;
newp12=p12-V1;
newp13=p13-V1;

% distal_triad
newp21=p21-V2;
newp22=p22-V2;
newp23=p23-V2;

% Determine the displacement between the two segments

displacement=V2-V1;
% Define segment/triad LCS vectors

% LCS1
a = newp12-newp11;
b = newp13-newp11;
c = newp12-newp11;

% LCS2

d = newp22-newp21;
e = newp23-newp21;
f = newp22-newp21;

for i = 1:trial_length

% LCS1
aa(i,:) = norm(a(i,:));
jj1(i,:) = a(i,:)/aa(i,:);
cbc(i,:) = cross(b(i,:),c(i,:));
nbc(i,:) = norm(cbc(i,:));
ii1(i,:) = cbc(i,:)/nbc(i,:);
kk1(i,:) = cross(ii1(i,:),jj1(i,:));

% LCS2
/dd(i,:) = norm(d(i,:));
jj2(i,:) = d(i,:)/dd(i,:);
cef(i,:) = cross(e(i,:),f(i,:));
nef(i,:) = norm(cef(i,:));
ii2(i,:) = cef(i,:)/nef(i,:);
kk2(i,:) = cross(ii2(i,:),jj2(i,:));

% determine the proximal & distal segment LCS and identity matrices
Tp = [ii1(i,1), ii1(i,2), ii1(i,3); jj1(i,1), jj1(i,2), jj1(i,3); kk1(i,1), kk1(i,2), kk1(i,3)];
Td = [ii2(i,1), ii2(i,2), ii2(i,3); jj2(i,1), jj2(i,2), jj2(i,3); kk2(i,1), kk2(i,2), kk2(i,3)];
Tid = [1,0,0;0,1,0;0,0,1];

% determine the rotation transformation matrix between the proximal segment and the GCS.
Trp = Tid*(Tp');

% determine the rotation transformation matrix between the distal segment and the GCS.
APPENDIX M: Rotation Matrix MatLab Code

Trd=Tid*(Td');

%%% Calculate the Cardan/Euler angles for Trp
if order==1
    betaTrp(i,1)=asin(Trp(3,1));  % = asin(R(3,1))
    alphaTrp(i,1)=asin((-Trp(3,2))/(cos(betaTrp(i))));   % = asin((-R(3,2))/cos(beta))
    gammaTrp(i,1)=asin((-Trp(2,1))/(cos(betaTrp(i))));   % = asin((-R(2,1))/cos(beta))
else if order==2
    gammaTrp(i,1)=asin(-Trp(2,1));   % = asin(-R(2, 1))
    betaTrp(i,1)=asin((Trp(3,1))/(cos(gammaTrp(i))) );  % = asin((R(3,1))/(cos(gamma))
    alphaTrp(i,1)=acos((Trp(2,2))/(cos(gammaTrp(i)) ));   % = acos((R(2,2))/(cos(gamma)))
else if order==3
    alphaTrp(i,1)=asin(-Trp(3,2));   % = asin(-R(3, 2))
    betaTrp(i,1)=asin((Trp(3,1))/(cos(alphaTrp(i)))));   % = asin((R(3,1))/(cos(alpha))
    gammaTrp(i,1)=acos((Trp(2,2))/(cos(alphaTrp(i)) ));   % = acos((R(2,2))/cos(alpha))
else if order==4
    gammaTrp(i,1)=asin(Trp(1,2));   % = asin(R(1,2))
    betaTrp(i,1)=asin((-Trp(1,3))/(cos(gammaTrp(i)) ));     % = asin((-R(1,3))/cos(gamma))
    alphaTrp(i,1)=acos((Trp(2,2))/(cos(gammaTrp(i)))));   % = acos((R(2,2))/cos(gamma))
else if order==5
    alphaTrp(i,1)=asin(Trp(2,3));   % = asin(R(2,3))
    betaTrp(i,1)=acos((Trp(3,3))/(cos(alphaTrp(i))));   % = acos((R(3,3))/cos(alpha))
    gammaTrp(i,1)=acos((Trp(2,2))/(cos(alphaTrp(i)) ));   % = acos((R(2,2))/cos(alpha))
else if order==6
    betaTrp(i,1)=asin(-Trp(1,3));  % = asin(-R(1,3))
    alphaTrp(i,1)=acos((Trp(3,3))/(cos(betaTrp(i))));   % = acos((R(3,3))/cos(gamma))
    gammaTrp(i,1)=asin((Trp(1,2))/(cos(betaTrp(i)))));   % = asin((R(1,2))/cos(beta))
end
end
end
end
end
end

% Convert the angles from rad to deg
beta2Trp(i,1)=betaTrp(i,1);
alpha2Trp(i,1)=alphaTrp(i,1);
gamma2Trp(i,1)=gammaTrp(i,1);
betaTrp(i,1) = rad2deg(beta2Trp(i,1));
alphaTrp(i,1) = rad2deg(alpha2Trp(i,1));
gammaTrp(i,1) = rad2deg(gamma2Trp(i,1));

%%%%%%%%%%%%%%%%%%%% %%%%%
%%%% Calculate the Cardan/Euler angles for Trd

if order==1

betaTrd(i,1) = asin(Trd(3,1));  % = asin(R(3,1))
alphaTrd(i,1) = asin((-Trd(3,2))/(cos(betaTrd(i))));   % = asin((-R(3,2))/cos(beta))
gammaTrd(i,1) = asin((-Trd(2,1))/(cos(betaTrd(i))));   % = asin((-R(2,1))/cos(beta))
endif

else if order==2

gammaTrd(i,1) = asin(-Trd(2,1));   % = asin(-R(2, 1))
betaTrd(i,1) = asin((Trd(3,1))/(cos(gammaTrd(i))) );  % = asin((R(3,1))/(cos(gamma)))
alphaTrd(i,1) = acos((Trd(2,2))/(cos(gammaTrd(i)) ));   % = acos((R(2,2))/(cos(gamma)))
endif

else if order==3

alphaTrd(i,1) = asin(-Trd(3,2));   % = asin(-R(3, 2))
betaTrd(i,1) = asin((Trd(3,1))/(cos(alphaTrd(i)))) ;  % = asin((R(3,1))/(cos(alpha)))
gammaTrd(i,1) = acos((Trd(2,2))/(cos(alphaTrd(i)))) ;   % = acos((-R(2,2))/cos(alpha))
endif

else if order==4

gammaTrd(i,1) = asin(Trd(1,2));   % = asin(R(1,2))
betaTrd(i,1) = asin((-Trd(1,3))/(cos(gammaTrd(i)))) ;  % = asin((-R(1,3))/cos(gamma))
alphaTrd(i,1) = acos((Trd(2,2))/(cos(gammaTrd(i)))) ;   % = acos((-R(2,2))/cos(gamma))
endif

else if order==5

alphaTrd(i,1) = asin(Trd(2,3));   % = asin(R(2,3))
betaTrd(i,1) = acos((Trd(3,3))/(cos(alphaTrd(i)))) ;  % = acos((R(3,3))/cos(alpha))
gammaTrd(i,1) = acos((Trd(2,2))/(cos(alphaTrd(i)))) ;   % = acos((R(2,2))/cos(alpha))
endif

else if order==6

betaTrd(i,1) = asin(-Trd(1,3));   % = asin(-R(1,3))
alphaTrd(i,1) = acos((Trd(3,3))/(cos(betaTrd(i)))) ;  % = acos((R(3,3))/cos(gamma))
gammaTrd(i,1) = asin((Trd(1,2))/(cos(betaTrd(i)))) ;   % = asin((R(1,2))/cos(beta))
end
end
end
end
end

% Convert the angles from rad to deg

beta2Trd(i,1) = betaTrd(i,1);
alpha2Trd(i,1)=alphaTrd(i,1);
gamma2Trd(i,1)=gammaTrd(i,1);

betaTrd(i,1)=rad2deg(beta2Trd(i,1));
alphaTrd(i,1)=rad2deg(alpha2Trd(i,1));
gammaTrd(i,1)=rad2deg(gamma2Trd(i,1));

end

% Subtract the two rotation angles to get the angle between the segments.

beta(:,1)=betaTrd(:,1)-betaTrp(:,1);
alpha(:,1)=alphaTrd(:,1)-alphaTrp(:,1);
gamma(:,1)=gammaTrd(:,1)-gammaTrp(:,1);

% rotation matrices

%Rx=[1,0,0;0,cos(alpha),sin(alpha);0,-sin(alpha),cos(alpha)];
%Ry=[cos(beta),0,-sin(beta);0,1,0;sin(beta),0,cos(beta)];
%Rz=[cos(gamma),sin(gamma),0;-sin(gamma),cos(gamma),0;0,0,1];

%Rxyz=Rz*Ry*Rx;
%Rxzy=Ry*Rz*Rx;
%Ryxz=Rz*Rx*Ry;
%Ryzx=Rx*Rz*Rx;
%Rzxy=Rx*Ry*Rz;
%Rzyx=Rx*Ry*Rx;
APPENDIX N

CUSTOM TRANSFER FUNCTION MATLAB CODE

The pages to follow contain the custom “transfer_function” MatLab™ code used to determine the translational and rotational transfer functions between the seat and T9, C7 and Occiptial marker triad motions measured in the laboratory.
function[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,phase_deg_unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpcflow,bpfcup,AT,overlap)

% transfer_function
% This code calculates (an estimate of) the magnitude, phase, and coherence
% of a transfer function using the cross-spectral density method (as
% outlined in Griffin 1990 and Mansfield 2005. This code also follows DFT
% procedures outline in Smith 1999.
% The code requires the user to input the sampling frequency (sf) of the
% data, the upper (bpfcup) and lower (bpcfclow) cut-off frequency of an
% initial band limiting filter, the size of a Hanning window to be used on
% the data (AT in seconds), and the amount of overlap used for each window
% prior to the calling of this function
% The code then outputs the input, output and cross-spectral densities, and
% the magnitude, phase (in degrees and detrended), and coherence of the
% transfer function for each hanning window by frequency. CH1 = frequency
% bins, CH2 and on = processed data. The code then averages the hanning
% windows together and adds the mean and standard deviations to the last
% two columns of the data variable.
% The last column of the coherence variable is the coherence to be used,
% and is calculated from the mean Gio, Goo, and Gii of the entire time
% histories averaging window data.
% Created by Robert J. Jack Sept. 1, 2010
% Band-pass filter the input and output data. ISO used 2nd order filters,
% so that is what was used here. The filter is Zero-lag so that no
% phase distortion occurs (results in 4th order zero-lag filtering).

nyq=sf/2;
[b1,a1]=butter(2,bpcfclow/nyq,'high');
outputHP=filtfilt(b1,a1,outputdata);
inputHP=filtfilt(b1,a1,inputdata);
[b1,a1]=butter(2,bpfcup/nyq,'low');
outputBP=filtfilt(b1,a1,outputHP);
inputBP=filtfilt(b1,a1,inputHP);

% If no filtering is desired then use the below for output and input data

%outputBP=outputdata;
%inputBP=inputdata;
% The following section of code creates the sliding hanning windows used in
% the transfer function analysis

% Calculate the hanning window size and create window

hannsize=AT*sf;
hannwindow=hann(hannsize);

% Calculate the amount of window overlap in data points

overlapdp=(overlap/100)*hannsize;

% Calculate the data point shift for the consecutive hanning windows based
% on the percent overlap selected

hannshift=(sf*AT)-overlapdp;

% Calculate the number of windows to fit into the data time history

arraysize=size(inputBP);
length=arraysize(:,1);

numberwindows=length/hannsize;

% If an interger number of windows can't fit into the data time history
% calculate how much padding is required to get an interger number of windows
% and then create a padded time history, using the mirror image of the last
% data points in the time history.

numberwindowsrounded=round(numberwindows);

if numberwindowsrounded < numberwindows
    newnumberwindows=numberwindowsrounded+1;
else
    newnumberwindows=numberwindowsrounded;
end

newlength=newnumberwindows*hannsize;

% Calculate the amount of padding need to make the data file the newlength

if newlength > length
    padding=newlength-length;
else
    padding=0;
end

% Create an inverted mirror image of the end of the data that is the
% necessary padding length and pad the data

initialoutputpadding=padarray(outputBP,padding+2,'symmetric','post');
invertedoutputpadding=(initialoutputpadding(length+1:newlength+2))*-1;
outputpadded=[outputBP,invertedoutputpadding(2:padding+1)];

initialinputpadding=padarray(inputBP,padding+2,'symmetric','post');
invertedinputpadding=(initialinputpadding(length+1:newlength+2))*-1;
Appendix N: Transfer Function MatLab Code

inputpadded=[inputBP;invertedinputpadding(2:padding+1)];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %%%%%
%%%%%%%%%%%%%%%%%%%
% Calculate the total number of windows to be used based on the overlap % selected
for i=1:newlength
    if (((i-1)*hannshift)+hannsize)<=newlength;
        windowsfitting(i,1)=1;
    else
        windowsfitting(i,1)=0;
    end
end

totalnumberwindows=sum(windowsfitting(:,1));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
% Calculate the power spectrum for the output
%Calculate frequency bins for DFT
halfhannsize=hannsize/2;
fh = sf*(0:halfhannsize)/hannsize;   %fh=(sample rate)*(0:0.5*hannsize)/hannsize
halfhannsizeplusone=halfhannsize+1;
DFTspectraldata_output(:,1)=fh(:);

%Calculate the power spectrum for each DFT frequency bin for each sliding %hanning window
for i=1:totalnumberwindows
    if i==1
        windoweddata(:,1)=outputpadded(i:hannsize,1).*hannwindow(:,1);
        Y = fft(windoweddata(:,1),hannsize);   % Complex discrete fourier transform of data
        Goo(:,i)=Y.* conj(Y);   % Power spectrum of fourier transform % Needs to be the power spectrum % Scale power spectrum of fourier transform and control for the end % bands having half the width of the other bands to creat power % spectral density = (EU^2/Hz)
        Pyy = (2*(abs(Y))/hannsize);   % *2 is because the hanning window cuts 1/2 the power from the signal therefore have to add that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes from)
        Pyy(2:halfhannsizeplusone-1)=Pyy(2:halfhannsizeplusone-1)*2;   % Ends have 1/2 the bandwith of the other frequencies therefore they are not doubled
        grtc(:,1)=Pyy.^2;
        DFTspectraldata_output(:,i+1)=grtc(1:halfhannsizeplusone);
    else
        k=(i-1)*hannshift;
        windoweddata(:,1)=outputpadded(k+1:k+hannsize,1).*hannwindow;
        Y = fft(windoweddata(:,1),hannsize);   % Complex discrete fourier transform of data
        Goo(:,i)=Y.* conj(Y);   % Power spectrum of fourier transform
    end
end
% Needs to be the power spectrum
% Scale power spectrum of fourier transform and control for the end
% bands having half the width of the other bands to creat power
% spectral density = (EU^2/Hz)
Pyy = (2*(abs(Y))/hannsize); % *2 is because the hanning window cuts 1/2 the power from the signal therefore
% have to add that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes from)
Pyy(2:halfhannsizeplusone-1)=Pyy(2:halfhannsizeplusone-1)*2; % Ends have 1/2 the bandwith of the other
% frequencies therefore they are not doubled
Pyy=Pyy.^2;

% Calculate the power spectrum for the input
% Calculate frequency bins for DFT
halfhannsize=hannsize/2;
f = sf*(0:halfhannsize)/hannsize; %f=(sample rate)*(0:0.5*hannsize)/hannsize
halfhannsizeplusone=halfhannsize+1;
DFTspectraldata_input(:,1)=f(:);

% Calculate the power spectrum for each DFT frequency bin for each sliding
% hanning window
for i=1:totalnumberwindows
    if i==1
        windoweddata(:,1)=inputpadded(i:hannsize,1).*hannwindow(:,1);
        Y = fft(windoweddata(:,1),hannsize);    % Complex discrete fourier transform of data
        Gii(:,i)=Y.* conj(Y);    % Power spectrum of fourier transform
        % Needs to be the power spectrum
        % Scale power spectrum of fourier transform and control for the end
        % bands having half the width of the other bands to creat power
        % spectral density = (EU^2/Hz)
Pyy = (2*(abs(Y))/hannsize); % *2 is because the hanning window cuts 1/2 the power from the signal therefore
        % have to add that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes from)
Pyy(2:halfhannsizeplusone-1)=Pyy(2:halfhannsizeplusone-1)*2; % Ends have 1/2 the bandwith of the other
        % frequencies therefore they are not doubled
        Pyy=Pyy.^2;
        grtc(:,1)=Pyy(:,);
        DFTspectraldata_output(:,i+1)=grtc(1:halfhannsizeplusone);
    else
        k=(i-1)*hannshift;
        windoweddata(:,1)=inputpadded(k+1:k+hannsize,1).*hannwindow(:,1);
        Y = fft(windoweddata(:,1),hannsize);    % Complex discrete fourier transform of data
        Gii(:,i)=Y.* conj(Y);    % Power spectrum of fourier transform
        % Needs to be the power spectrum
        % Scale power spectrum of fourier transform and control for the end
% bands having half the width of the other bands to create power
% spectral density = (EU^2/Hz)
Pyy = (2*(abs(Y))/hannsize); % *2 is because the hanning window cuts 1/2 the power from the signal therefore
% have to add that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes
% from)
Pyy(2:halfhannsizeplusone-1)=Pyy(2:halfhannsizeplusone-1)*2; % Ends have 1/2 the bandwidth of the other
% frequencies therefore they are not doubled
Pyy=Pyy.^2;

grtc(:,1)=Pyy(:);
DFTspectraldata_input(:,i+1)=grtc(1:halfhannsizeplusone);
end
end

% Calculate the cross spectrum for the output and input
% Calculate frequency bins for Xpsd

halfhannsize=hannsize/2;
f = sf*(0:halfhannsize)/hannsize; % f=(sample rate)*(0:0.5*hannsize)/hannsize
halfhannsizeplusone=halfhannsize+1;
XDFTspectraldata(:,1)=f(:);

% Calculate the Xcorr and power spectrum of the Xcorr for each DFT frequency bin for each sliding
% window that is the same size as the previous hanning windows
for i=1:totalnumberwindows
    if i==1
        windowedinputdata(:,1)=inputpadded(i:hannsize,1).*hannwindow(:,1);
        windowedoutputdata(:,1)=outputpadded(i:hannsize,1).*hannwindow(:,1);
        XXcorr=xcorr(windowedoutputdata(:,1),windowedinputdata(:,1));  % Xcov subtracts the average to give a Xcorr
% with zero mean, Xcorr leaves that mean in
        XXXcorr=[XXcorr;0];
        [m,n]=size(XXXcorr);
        Y = fft(XXXcorr,m); % Discrete fourier transform of data
% Downsample the XXcorr FFT data such that it is the same length as the
% original inputs to the Xcorr.
        newY=downsample(Y(:,2);
        Gio(:,i)=newY;  % Complex fourier transform
% Needs to be the complex power spectrum
% Scale power spectrum of fourier transform and control for the end
% bands having half the width of the other bands to create power
% spectral density = (EU^2/Hz)
Pyy = (2*(abs(Y))/hannsize); % *2 is because the hanning window cuts 1/2 the power from the signal therefore
% have to add that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes
% from)
Pyy(2:halfhannsizeplusone-1)=Pyy(2:halfhannsizeplusone-1)*2; % Ends have 1/2 the bandwidth of the other
% frequencies therefore they are not doubled
Pyy=Pyy.^2;

        grtc=Pyy(:);
        XDFTspectraldata(:,i+1)=grtc(1:halfhannsizeplusone);
    else
APPENDIX N: Transfer Function MatLab Code

\[ k = (i-1) \cdot \text{hannshift}; \]
windowed_input_data(:,1) = input_padded(k+1:k+hannsize,1) .* hann_window(:,1);
windowed_output_data(:,1) = output_padded(k+1:k+hannsize,1) .* hann_window(:,1);
XXcorr = xcorr(windowed_output_data(:,1), windowed_input_data(:,1));  % Xcov subtracts the average to give a Xcorr with zero mean, Xcorr leaves that mean in
XXXcorr = [XXcorr; 0];
[m, n] = size(XXXcorr);
Y = fft(XXXcorr, m);  % Discrete fourier transform of data
% Downsample the XXcorr FFT data such that it is the same length as the original inputs to the Xcorr.
newY = downsample(Y(:,2), 2);
Gio(:,i) = newY;  % Complex fourier transform
% Needs to be the complex power spectrum
% Scale power spectrum of fourier transform and control for the end bands having half the width of the other bands to creat power
% spectral density = (EU^2/Hz)
Pyy = (2 * (abs(Y))/hannsize);  % *2 is because the hanning window cuts 1/2 the power from the signal therefore have to add that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes from)
Pyy(2:halfhannsizeplusone-1) = Pyy(2:halfhannsizeplusone-1) * 2;  % Ends have 1/2 the bandwith of the other frequencies therefore they are not doubled
Pyy = Pyy.^2;

grtc = Pyy(:);
XDFTspectraldata(:,i+1) = grtc(1:halfhannsizeplusone);
end

% Calculate frequency bins for modulus, phase and coherence
halfhannsize = hannsize/2;
f = sf*(0:halfhannsize)/hannsize;
halfhannsizeplusone = halfhannsize+1;
modulus(:,1) = f(:,);
modulus_check(:,1) = f(:,);
modulus_PSDRatio(:,1) = f(:,);
modulus_Welch(:,1) = f(:,);
phase_rad(:,1) = f(:,);
phase_deg(:,1) = f(:,);
phase_rad_unwrapped(:,1) = f(:,);
phase_deg_unwrapped(:,1) = f(:,);
coherence(:,1) = f(:,);
for i = 1:total_number_windows
% Calculate the transfer function
H(:,i) = Gio(:,i) ./ Gii(:,i);  % Standard formula
% Calculate the transfer function modulus
APPENDIX N: Transfer Function MatLab Code

```matlab
a(:,i) = real(H(:,i));
b(:,i) = imag(H(:,i));

% Control for divide by zero error
for k = 1:hannsize
    if a(k,i) == 0
        a(k,i) = 0.00000000000000000001; % 1e-20
    else
    end
    if b(k,i) == 0
        b(k,i) = 0.00000000000000000001; % 1e-20
    else
    end
end

c(:,i) = a(:,i).^2;
d(:,i) = b(:,i).^2;
e(:,i) = c(:,i) + d(:,i);
modulus(:,i+1) = e(1:halfhannsizeplusone,i).^0.5;

% Method 2
check(:,i) = Goo(:,i) ./ Gii(:,i);
moduluscheck(:,i+1) = (check(1:halfhannsizeplusone,i)).^0.5;

% Method 3 - PSD ratio
modulusPSDratio(:,i+1) = (DFTspectraldata_output(:,i+1) ./ DFTspectraldata_input(:,i+1)).^0.5;

% Calculate the transfer function phase

g(:,i) = b(:,i) ./ a(:,i);
phase_rad(:,i+1) = atan(g(1:halfhannsizeplusone,i));

% Control for incorrect arctan
for k = 1:halfhannsizeplusone
    if (a(k,i) <= 0) & (b(k,i) <= 0)
        phase_rad(k,i+1) = phase_rad(k,i+1) - pi;
    else if (a(k,i) <= 0) & (b(k,i) >= 0)
        phase_rad(k,i+1) = phase_rad(k,i+1) + pi;
    end
end

% Determine the deviation from linear phase
```
linear_phase_rad(:,1)=(pi/(0.5*sf))*(f(:)');
phase_rad(:,i+1)=phase_rad(:,i+1)-linear_phase_rad(:,1);
phase_deg(:,i+1)=rad2deg(phase_rad(:,i+1));

phase_rad_unwrapped(:,i+1)=unwrap(phase_rad(:,i+1));
phase_deg_unwrapped(:,i+1)=rad2deg(phase_rad_unwrapped(:,i+1));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %%%%%
%%%%%%%%%%%%%%%%%%%
% Calculate the transfer function coherence for each window (should be a 1
% since there is only 1 window of data at a time)

h(:,i)=abs(Gio(:,i));
r(:,i)=h(:,i).^2;
s(:,i)=Gii(:,i).*Goo(:,i);
v(:,i)=r(:,i)./s(:,i);
coherence(:,i+1)=v(1:halfhannsizeplusone,i);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%

end

% Average the transfer function data windows (Stdev too)

[rows,columns]=size(modulus);

dataonly=XDFTspectraldata(:,2:columns);
columnTOrOW=dataonly';
average=mean(columnTOrOW);
average=average';
stdev=std(columnTOrOW);
stdev=stdev';
XDFTspectraldata(:,columns+1)=average(:,1);
XDFTspectraldata(:,columns+2)=stdev(:,1);

dataonly=DFTspectraldata_input(:,2:columns);
columnTOrOW=dataonly';
average=mean(columnTOrOW);
average=average';
stdev=std(columnTOrOW);
stdev=stdev';
DFTspectraldata_input(:,columns+1)=average(:,1);
DFTspectraldata_input(:,columns+2)=stdev(:,1);

dataonly=DFTspectraldata_output(:,2:columns);
columnTOrOW=dataonly';
average=mean(columnTOrOW);
average=average';
stdev=std(columnTOrOW);
stdev=stdev';
DFTspectraldata_output(:,columns+1)=average(:,1);
DFTspectraldata_output(:,columns+2)=stdev(:,1);
dataonly=Gio(:,1:columns-1);
columnTOrrow=dataonly';
average=mean(columnTOrrow);
average=average';
stdev=std(columnTOrrow);
stdev=stdev';
Gio(:,columns+1)=average(:,1);
Gio(:,columns+2)=stdev(:,1);

dataonly=Gii(:,1:columns-1);
columnTOrrow=dataonly';
average=mean(columnTOrrow);
average=average';
stdev=std(columnTOrrow);
stdev=stdev';
Gii(:,columns+1)=average(:,1);
Gii(:,columns+2)=stdev(:,1);

dataonly=Goo(:,1:columns-1);
columnTOrrow=dataonly';
average=mean(columnTOrrow);
average=average';
stdev=std(columnTOrrow);
stdev=stdev';
Goo(:,columns+1)=average(:,1);
Goo(:,columns+2)=stdev(:,1);

dataonly=modulus(:,2:columns);
columnTOrrow=dataonly';
average=mean(columnTOrrow);
average=average';
stdev=std(columnTOrrow);
stdev=stdev';
modulus(:,columns+1)=average(:,1);
modulus(:,columns+2)=stdev(:,1);

dataonly=modulusPSDratio(:,2:columns);
columnTOrrow=dataonly';
average=mean(columnTOrrow);
average=average';
stdev=std(columnTOrrow);
stdev=stdev';
modulusPSDratio(:,columns+1)=average(:,1);
modulusPSDratio(:,columns+2)=stdev(:,1);

dataonly=moduluscheck(:,2:columns);
columnTOrrow=dataonly';
average=mean(columnTOrrow);
average=average';
stdev=std(columnTOrrow);
stdev=stdev';
moduluscheck(:,columns+1)=average(:,1);
moduluscheck(:,columns+2)=stdev(:,1);

dataonly=phase_rad(:,2:columns);
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stddev=std(columnTOrow);
stddev=stddev';
phase_rad(:,columns+1)=average(:,1);
phase_rad(:,columns+2)=stddev(:,1);

dataonly=phase_rad_unwrapped(:,2:columns);
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stddev=std(columnTOrow);
stddev=stddev';
phase_rad_unwrapped(:,columns+1)=average(:,1);
phase_rad_unwrapped(:,columns+2)=stddev(:,1);

dataonly=phase_deg(:,2:columns);
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stddev=std(columnTOrow);
stddev=stddev';
phase_deg(:,columns+1)=average(:,1);
phase_deg(:,columns+2)=stddev(:,1);

dataonly=phase_deg_unwrapped(:,2:columns);
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stddev=std(columnTOrow);
stddev=stddev';
phase_deg_unwrapped(:,columns+1)=average(:,1);
phase_deg_unwrapped(:,columns+2)=stddev(:,1);

% Calculate the coherence from the average Gio, Gii, and Goo

meanGio=Gio(:,columns+1);
meanGii=Gii(:,columns+1);
meanGoo=Goo(:,columns+1);
h(:,1)=abs(meanGio(:,1));
r(:,1)=h(:,1).^2;
s(:,1)=meanGii(:,1).*meanGoo(:,1);
v(:,1)=r(:,1)./s(:,1);

coherence(:,columns+1)=v(1:halfhannsizeplusone,1);

%Checks with canned Welch's methods

[HH,FF]=tfestimate(inputpadded(:,1),outputpadded(:,1),hanning(hannsize),(hannsize-hannshift),hannsize, sf);
aa=real(HH);
bb=imag(HH);

% Control for divide by zero error

for k = 1:halfhannsizeplusone
    if aa(k,1)==0
        aa(k,1)=0.00000000000000000001; %1*E-20
    else
    end

    if bb(k,1)==0
        bb(k,1)=0.00000000000000000001; %1*E-20
    else
    end

end

cc=aa.^2;
dd=bb.^2;
ee=cc+dd;

modulus_Welch=ee(1:halfhannsizeplusone,1).^0.5;

phase_angle_Welch=angle(HH);

coherence_Welch=mscohere(inputpadded(:,1),outputpadded(:,1),hanning(hannsize),(hannsize-
hannshift),hannsize,sf);
APPENDIX O

CUSTOM DYNAMIC STIFFNESS MATLAB CODE

The pages to follow contain the custom “dynamic_stiffness” MatLab™ code used to determine the translational and rotational dynamic stiffness values between the seat and T9, C7 and Occipital marker triad motions measured in the laboratory.
function[DFTspectraldata_force,DFTspectraldata_disp,stiffness]=dynamic_stiffness(output_displacement,input_force,sf,bpfclow,bpfcup,AT,overlap)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%% dynamic_stiffness
%%%%%%%%%%%%%%%%%%%%%%%%%%%

% This code calculates (an estimate of) the dynamic stiffness of a body
% between and input_force and output_displacement locations, using the
% complex ratio of the input force/moment and the translational/rotational
% displacement (as outlined in Griffin 1990 and Pierson & Paez 2010). This
% code also follows DFT procedures outline in Smith 1999.
%
% The code requires the user to input the sampling frequency (sf) of the
% data, the upper (bpfcup) and lower (bpfclow) cut-off frequency of an
% initial band limiting filter, the size of a Hanning window to be used on
% the data (AT in seconds), and the amount of overlap used for each window
% prior to the calling of this function.
%
% The code then outputs the force and displacement spectral densities, and
% the dynamic stiffness for each hanning window by frequency. CH1 =
% frequency bins, CH2 and on = processed data. The code then averages the
% hanning windows together and adds the mean and standard deviations to the
% last two columns of the data variable.

% Created by Robert J. Jack June 6th, 2011
%
% Band-pass filter the output_displacement,input_force. ISO used 2nd order
% filters, so that is what was used here. The filter is Zero-lag so that no
% phase distortion occurs (results in 4th order zero-lag filtering).

nyq=sf/2;

[b1,a1]=butter(2,bpfclow/nyq,'high');
disp_HP=filtfilt(b1,a1,output_displacement);
force_HP=filtfilt(b1,a1,input_force);

[b1,a1]=butter(2,bpfcup/nyq,'low');
disp_BP=filtfilt(b1,a1,disp_HP);
force_BP=filtfilt(b1,a1,force_HP);

%%% If no filtering is desired then use the below for output_displacement
%%% and input_force data

%disp_BP=output_displacement;
%force_BP=input_force;

% The following section of code creates the sliding hanning windows used in
% the transfer function analysis
% Calculate the hanning window size and create window

hannsize=AT*sf;
hannwindow=hann(hannsize);

% Calculate the amount of window overlap in data points

overlapdp=(overlap/100)*hannsize;

% Calculate the data point shift for the consecutive hanning windows based
% on the percent overlap selected

hannshift=(sf*AT)-overlapdp;

% Calculate the number of windows to fit into the data time history

arraysize=size(force_BP);
length=arraysize(:,1);

numberwindows=length/hannsize;

% If an integer number of windows can't fit into the data time history
% calculate how much padding is required to get an integer number of windows
% and then create a padded time history, using the mirror image of the last
% data points in the time history.

numberwindowsrounded=round(numberwindows);

if numberwindowsrounded < numberwindows
    newnumberwindows=numberwindowsrounded+1;
else
    newnumberwindows=numberwindowsrounded;
end

newlength=newnumberwindows*hannsize;

% Calculate the amount of padding need to make the data file the newlength

if newlength > length
    padding=newlength-length;
else
    padding=0;
end

% Create an inverted mirror image of the end of the data that is the
% necessary padding length and pad the data

initial_disp_padding=padarray(disp_BP,padding+2,'symmetric','post');
inverted_disp_padding=(initial_disp_padding(length+1:newlength+2))*-1;
disp_padded=[disp_BP;inverted_disp_padding(2:padding+1)];

initial_force_padding=padarray(force_BP,padding+2,'symmetric','post');
inverted_force_padding=(initial_force_padding(length+1:newlength+2))*-1;
force_padded=[force_BP;inverted_force_padding(2:padding+1)];
% Calculate the total number of windows to be used based on the overlap
% selected
for i=1:newlength
    if (((i-1)*hannshift)+hannsize)<=newlength;
        windowsfitting(i,1)=1;
    else
        windowsfitting(i,1)=0;
    end
end
totalnumberwindows=sum(windowsfitting(:,1));

% Calculate the power spectrum for the output_displacement
% Calculate frequency bins for DFT
halfhannsize=hannsize/2;
f = sf*(0:halfhannsize)/hannsize; % f=(sample rate)*(0:0.5*hannsize)/hannsize
halfhannsizeplusone=halfhannsize+1;
DFTspectraldata_disp(:,1)=f(:);
% Calculate the power spectrum for each DFT frequency bin for each sliding hanning window
for i=1:totalnumberwindows
    if i==1
        windoweddata(:,1)=disp_padded(i:hannsize,1).*hannwindow(:,1);
        Y = fft(windoweddata(:,1),hannsize); % Complex discrete fourier transform of data
        Go0(:,i)=Y.* conj(Y); % Power spectrum of fourier transform
        % Needs to be the power spectrum
        % Scale power spectrum of fourier transform and control for the end
        % bands having half the width of the other bands to creat power
        % spectral density = (EU^2/Hz)
        Pyy = (2*(abs(Y))/hannsize); % *2 is because the hanning window cuts 1/2 the power from the signal therefore have to that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes from)
        Pyy(2:halfhannsizeplusone-1)=Pyy(2:halfhannsizeplusone-1)*2; % Ends have 1/2 the bandwith of the other frequencies therefore they are not doubled
        Pyy=Pyy.^2;
        grtc(:,1)=Pyy(:,);
        DFTspectraldata_disp(:,i+1)=grtc(1:halfhannsizeplusone);
    else
        k=(i-1)*hannshift;
        windoweddata(:,1)=disp_padded(k+1:k+hannsize,1).*hannwindow;
        Y = fft(windoweddata(:,1),hannsize); % Complex discrete fourier transform of data
        Go0(:,i)=Y.* conj(Y); % Power spectrum of fourier transform
        % Needs to be the power spectrum
        % Scale power spectrum of fourier transform and control for the end
% bands having half the width of the other bands to creat power
% spectral density = \((EU^2/Hz)\)

\(Pyy = (2*(abs(Y))/hannsize);\)  % *2 is because the hanning window cuts 1/2 the power from the signal therefore have to add that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes from)

\(Pyy(2:halfhannsizeplusone-1)=Pyy(2:halfhannsizeplusone-1)^2;\)  % Ends have 1/2 the bandwith of the other frequencies therefore they are not doubled

\(Pyy=Pyy.^2;\)

\(\text{grtc}(;1)\)=Pyy(;;);
\(\text{DFTspectraldata\_disp}(;1)+1=\text{grtc}(1:halfhannsizeplusone);\)  
end
end

% Calculate the power spectrum for the input_force

% Calculate frequency bins for DFT

\(\text{halfhannsize}=\text{hannsize}/2;\)
\(f = sf*(0:halfhannsize)/\text{hannsize};\)  %\(f=(\text{sample rate})*(0:0.5*\text{hannsize})/\text{hannsize}\)
\(\text{halfhannsizeplusone}=\text{halfhannsize}+1;\)
\(\text{DFTspectraldata\_force}(;1)=f(;;)\);

% Calculate the power spectrum for each DFT frequency bin for each sliding % hanning window

for i=1:totalnumberwindows
  if i==1
    \(\text{windoweddata}(;1)=\text{force\_padded}(i:\text{hannsize},1).*\text{hannwindow}(;1);\)
    \(Y = \text{fft}(\text{windoweddata}(;1),\text{hannsize});\)  % Complex discrete fourier transform of data
    \(\text{Gii}(;i)=Y.*\text{conj}(Y);\)  % Power spectrum of fourier transform
    % Needs to be the power spectrum
    % Scale power spectrum of fourier transform and control for the end
    % bands having half the width of the other bands to creat power
    % spectral density = \((EU^2/Hz)\)
    \(Pyy = (2*(abs(Y))/\text{hannsize});\)  % *2 is because the hanning window cuts 1/2 the power from the signal therefore have to add that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes from)
    \(Pyy(2:halfhannsizeplusone-1)=Pyy(2:halfhannsizeplusone-1)^2;\)  % Ends have 1/2 the bandwith of the other frequencies therefore they are not doubled
    \(Pyy=Pyy.^2;\)
  \text{grtc}(;1)=Pyy(;;);
  \text{DFTspectraldata\_force}(;1)+1=\text{grtc}(1:halfhannsizeplusone);
  else
    \(k=(i-1)*\text{hannshift};\)
    \(\text{windoweddata}(;1)=\text{force\_padded}(k+1:k+\text{hannsize},1).*\text{hannwindow}(;1);\)
    \(Y = \text{fft}(\text{windoweddata}(;1),\text{hannsize});\)  % Complex discrete fourier transform of data
    \(\text{Gii}(;i)=Y.*\text{conj}(Y);\)  % Power spectrum of fourier transform
    % Needs to be the power spectrum
    % Scale power spectrum of fourier transform and control for the end
    % bands having half the width of the other bands to creat power
    % spectral density = \((EU^2/Hz)\)
Pyy = (2*(abs(Y))/hannsize); % *2 is because the hanning window cuts 1/2 the power from the signal therefore have to add that back, /hannsize is to normalize the spectrum to the sample length or N (this is where the /Hz comes from)
Pyy(2:halfhannsizeplusone-1)=Pyy(2:halfhannsizeplusone-1)*2; % Ends have 1/2 the bandwidth of the other frequencies therefore they are not doubled
Pyy=Pyy.^2;
grtc(:,1)=Pyy(:);
DFTspectraldata_force(:,i+1)=grtc(1:halfhannsizeplusone);
end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %%%%%
%%%%%%%%%%%%%%%%%%%
% Calculate frequency bins
halfhannsize=hannsize/2;
f = sf*(0:halfhannsize)/hannsize;
halfhannsizeplusone=halfhannsize+1;
stiffness(:,1)=f(:);
for i=1:totalnumberwindows

% Calculate the dynamic stiffness
stiffness(:,i+1)=(DFTspectraldata_force(:,i+1)/DFTspectraldata_disp(:,i+1)).^0.5;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %%%%%
%%%%%%%%%%%%%%%%%%%
% Average the transfer function data windows (Stdev too)
[rows,columns]=size(stiffness);
dataonly=DFTspectraldata_force(:,2:columns);
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stdev=std(columnTOrow);
stdev=stdev';
DFTspectraldata_input_force(:,columns+1)=average(:,1);
DFTspectraldata_input_force(:,columns+2)=stdev(:,1);
dataonly=DFTspectraldata_disp(:,2:columns);
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stdev=std(columnTOrow);
stdev=stdev';
DFTspectraldata_output_disp(:,columns+1)=average(:,1);
DFTspectraldata_output_disp(:,columns+2)=stdev(:,1);
dataonly=stiffness(:,2:columns);
columnTOrow=dataonly';
average=mean(columnTOrow);
average=average';
stdev=std(columnTOrow);
stdev=stdev';
stiffness(:,columns+1)=average(:,1);
stiffness(:,columns+2)=stdev(:,1);
APPENDIX P

CUSTOM BINOMIAL PROBABILITY DISTRIBUTION MATLAB CODE

The pages to follow contain the custom “Binomial_Analysis” MatLab\textsuperscript{TM} code used to determine the significant trends in muscle activity, as well as translational and rotational dynamic stiffness, transmissibility and dominant transmission frequency between the seat and the T9, C7 spinal levels and the head in the laboratory.
function[total_num_cases,total_num_deviations,percent_deviations_w_dominant_trend,mean_change,prob_X,prob_outside_X]=Binomial_Analysis(reference_data,test_data,likelyhood_of_occurance)

% This code calculates the difference between a column of test data matched
% to a column of reference data. A count of the number of times the test
% data was greater and less than the reference data is performed. The
% dominant trend is then used for the remainder of the analysis. The
% binomial probability of seeing that many increases or decreases relative
% to the total number of deviations is determined as well as the
% cumulative probability of seeing a number of occurrences greater or less
% than the number seen. Finally the mean increase or decrease from
% reference is determined.

% Created by Robert J. Jack August 20th, 2011

% trend=test_data-reference_data;

increase=find(trend>=0.0000000000001);
decrease=find(trend<=-0.0000000000001);

a=size(increase);
num_increase=a(1,1);
b=size(decrease);
num_decrease=b(1,1);
c=size(trend);
total_num_cases=c(1,1);
total_num_deviations=num_increase(1,1)+num_decrease(1,1);

if num_increase==num_decrease
    prob_X=binopdf(num_increase,total_num_deviations,likelyhood_of_occurance);
    num_possibilities_above_X=total_num_deviations-num_increase;
    if num_increase==0
        prob_outside_X=1;
    else
        for i=num_increase:(num_increase+num_possibilities_above_X)
            Y(i,1)=binopdf(i,total_num_deviations,likelyhood_of_occurance);
        end
        prob_outside_X=sum(Y);
    end
    mean_change=0;
    percent_deviations_w_dominant_trend=0.5;
else if num_increase>=num_decrease
prob_X = binopdf(num_increase, total_num_deviations, likelyhood_of_occurance);

num_possibilities_above_X = total_num_deviations - num_increase;

for i = num_increase:(num_increase+num_possibilities_above_X)
    Y(i,1) = binopdf(i, total_num_deviations, likelyhood_of_occurance);
end

prob_outside_X = sum(Y);

for i = 1:total_num_cases
    if trend(i,1) >= 0.0000000000001
        increase_value(i,1) = trend(i,1);
    else
        increase_value(i,1) = 0;
    end
end

mean_change = (sum(increase_value))/num_increase;

percent_deviations_w_dominant_trend = num_increase/total_num_deviations;

else if num_increase <= num_decrease

    prob_X = binopdf(num_decrease, total_num_deviations, likelyhood_of_occurance);

    num_possibilities_below_X = total_num_deviations - num_increase;

    for i = num_decrease:(num_decrease+num_possibilities_below_X)
        Y(i,1) = binopdf(i, total_num_deviations, likelyhood_of_occurance);
    end

    prob_outside_X = sum(Y);

    for i = 1:total_num_cases
        if trend(i,1) <= -0.0000000000001
            decrease_value(i,1) = trend(i,1);
        else
            decrease_value(i,1) = 0;
        end
    end

    mean_change = (sum(decrease_value))/num_decrease;

    percent_deviations_w_dominant_trend = num_decrease/total_num_deviations;
end