SIX DEGREE OF FREEDOM WHOLE-BODY VIBRATION DURING FORESTRY SKIDDER OPERATIONS

A Thesis

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by

SARAH ELEANOR CATION

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ABSTRACT

SIX DEGREE OF FREEDOM WHOLE-BODY VIBRATION DURING FORESTRY SKIDDER OPERATIONS

Sarah Eleanor Cation

University of Guelph, 2007

Advisor:

Professor Michele Oliver

This thesis is an investigation of whole-body vibration exposures in forestry skidders. A six degree-of-freedom calibration procedure was developed to calibrate six degree-of-freedom motion sensors. This calibration was applied to the sensors used to simultaneously measure accelerations at the seat/operator interface and chassis of forestry skidders. The results of this study indicate that skidder seats amplify the whole body vibration accelerations at the seat/operator interface when compared to corresponding chassis values. The acceleration values outlined in this study are similar to those published over the past twenty years suggesting that little has changed with respect to the ability of the seat to attenuate harmful vibration. To our knowledge, this thesis represents the most comprehensive six degree-of-freedom field data set collected and analyzed to date for any type of off-road vehicle.

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Chapter 1: INTRODUCTION

This thesis deals with seated human whole-body vibration (WBV). Measurement techniques most often associated with seated WBV will be discussed. Discussion and applications focus predominantly on the health effects, exposures and comfort for seated vehicle operators of forestry skidders. This thesis was published in Ontario, Canada and thus uses the International Organization for Standardization (ISO) standards (ISO 2631-1) for the evaluation of the WBV exposure levels using the most current standard (ISO 2631-1:1997), although other standards are currently available.

1.1 Motivation

As a result of associative links between health effects, comfort and WBV exposure, the International Organization for Standardization has published a standard in regard to measuring WBV, health guidelines and comfort values. Some off-road vehicles have been reported to be associated with discomfort and WBV injuries (Griffin, 1990a; Griffin, 1990b). Skidder operators incur some of the most severe ride-induced vibration encountered in industrial machines (Golsse & Hope, 1987). Skidders drag trees between the location where they were cut to the location where further processing such as delimbing can be done.

Previous reports of skidder WBV accelerations (Golsse & Hope, 1987; Golsse 1989; Wegscheid, 1994; Neitzel & Yost, 2003) did not report vibration along all six degrees-of-freedom (6-DOF). In some instances the published WBV values used older versions of the ISO 2631-1 standard prior to the current 1997 publication (Golsse & Hope, 1987; Golsse 1989; Wegscheid, 1994). The goal of this study was to update the current literature by incorporating acceleration values for the rotational vibration axes at the operator/seat interface (OSI) and chassis (floor) of forestry skidders, in an effort to provide industry and researchers with the most up-to-date and complete field data set.

1.2 Project Definition

The purpose of this thesis was to outline an easy and reproducible calibration procedure which may be used for calibrating WBV transducers in 6-DOF. This calibration procedure was then used on two 6-DOF WBV transducers which were subsequently used to obtain field WBV accelerations at the OSI and chassis in forestry skidders. The skidder was investigated as it has been identified as an extreme WBV environment (Golse & Hope, 1987). Field data were then analyzed using current ISO standards (ISO 2631-1:1997) to evaluate the WBV exposures in conjunction with comfort and possible health effects outlined in the ISO 2631-1:1997.

1.3 Thesis Structure

This thesis is written in journal format. As a result, each chapter is written as a stand-alone article and as such includes a chapter reference list. The purpose of each chapter is outlined below.

Chapter 1: Chapter 1 is designed to provide the reader with an idea of why this research was carried out, the structure of the thesis and the definition of what will be contained within this thesis.

Chapter 2: This chapter is written to provide background information from the available literature such that the reader may understand the topics investigated in the subsequent sections.

Chapter 3: Chapter 3 provides a new methodology in which a 6-DOF sensor can be calibrated using a 6-DOF robot. Calibration validation methodology which allows for calibration through the range expected in field WBV investigations of forestry skidders was also included. This chapter outlines the preparatory steps required to then measure field WBV data.

Chapter 4: This chapter outlines the accelerations experienced by forestry skidders at the OSI and the chassis. The accelerations were measured in 6-DOF, expanding the currently available values in literature. The accelerations were evaluated using the most current publication of the

International Organization of Standardization ISO 2631-1:1997 standard. The values determined from this field study may be used by design firms, health organizations and future researchers.

Chapter 5: This chapter discusses the findings and contributions made by this thesis. In addition, future areas of related study are outlined and recommendations are presented which have surfaced as a result of the findings.

1.4 References

Golsse J.-M. 1989. Analysis of whole-body vibration levels during site preparation. Forest Engineering Research Institute of Canada (FERIC). Technical Report TR-90.

Golsse J.-M., Hope PA. 1987. Analysis of whole-body vibration levels during skidding. Forest Engineering Research Institute of Canada (FERIC). Technical Report TR-77.

Griffin, MJ. 1990a. Handbook of Human Vibration. Academic Press. NewYork.

Griffin MJ. 1990b. Measurement and evaluation of whole-body vibration at work. International Journal of Industrial Ergonomics, 6; 45-54.

ISO. 1997. ISO 2631-1: Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1: General requirements. International Organization for Standardization.

Neitzel R, Yost M. 2003. Forestry Vibration and Noise Exposure Project. University of Washington Department of Environmental Health. Seattle, Washington, USA.

Wegscheid E. 1994. Another look at skidder ride vibration. Journal of Forest Engineering, 5; 21-32.

Chapter 2: BACKGROUND

2.1 Whole-body Vibration

Whole-body vibration (WBV) occurs when the body is supported by a vibrating surface (Griffin, 1990a; Bovenzi, 2000). There are six axes in which WBV may occur: three translational and three rotational axes (Parsons *et al.*, 1979). The three translational axes are the fore-aft (X-), lateral (Y-) and vertical (Z-) axes and the three rotational axes are Roll, Pitch, and Yaw which are defined as rotation about the X-, Y- and Z-axes respectively (Parsons *et al.*, 1979; ISO, 1997; Griffin, 1990a). These axes have been defined for three measurement locations as shown in Figure 2-1 (ISO, 1997), wherein the X-axis is measured from the back-to-chest direction, Y-axis from right-to-left side and the Z-axis from the buttock-to-head direction for seated individuals (Griffin, 1990a).

Parsons *et al.* (1979) reported that when research has attempted to relate vehicle vibration to vehicle occupant comfort and health, the axes which have not been measured were often assumed to not be of significance in their contributions to the vibration total effects. However, vibration can occur in multiple DOFs in the environment (Griffin, 1990a). As a result, earlier literature may not be well translated into a variety of environments and vehicles, where the vertical axis may not always be the dominant axis (Bovenzi *et al.*, 2002; Rehn *et al.*, 2005a).

Figure 2-1: Measurement locations (chassis or floor surface, seat/operator interface (SOI) and seat-back) and basic axes as defined by ISO 2631-1:1997 (ISO, 1997). The rotations about the translational axes are also shown: Roll (r_x) measuring rotation about the X-axis, Pitch (r_y) measuring rotation about the Y-axis and Yaw (r_z) measuring rotation about the Z-axis.

WBV exposure has been linked to a variety of vehicles, including: road vehicles (Griffin, 1990a; Parsons *et al.*, 1979), trains (Griffin, 1990a; Johanning *et al.*, 2002; Johanning *et al.*, 2006), mining equipment (Eger *et al.*, 2006), military vehicles (Griffin, 1990a; Els, 2005) and forestry equipment (Griffin, 1990a; Golsse 1989; Golsse & Hope, 1987; Wegscheid, 1994; Rehn *et al.*, 2005a). Often in literature, vibration magnitude, frequency, direction/axis and duration (Griffin, 1990b; Kjellberg & Wikström, 1985) are the commonly measured variables. Although these variables are important considerations, they alone may not adequately define vibration severity (Griffin, 1990b).

In addition to the variables commonly measured, there are other factors which should be taken into consideration for WBV measurements. These factors include: road condition (Cann *et al.*, 2004; Smith & Kwak, 1978; Parsons *et al.*, 1979), terrain (Golsse & Hope, 1987), vehicle type (Cann *et al.*, 2004; Parsons *et al.*, 1979; Paddan & Griffin, 2002a), vehicle/seat suspension (Smith & Kwak, 1978) and speed of travel (Hansson, 1990; Parsons *et al.*, 1979). The effect of vibration on vehicle

occupants will also be dependent on several of these factors (Parsons *et al.*, 1979) and the WBV transmission as well. It is obvious that a single measurement from a vehicle should not be used to represent the vehicle across all operating conditions (Paddan & Griffin, 2002a); nor should a single vehicle be used to generalize a class of vehicle (Paddan & Griffin, 2002a). Variations in vibration magnitude occur across vehicle types (i.e., between types of cars, types of tractors, etc.) and wide vibration variation occurs as a result of operating conditions for a single vehicle (Paddan & Griffin, 2002a).

2.1.1 Comfort

The discomfort of WBV may be increased with the inclusion of shocks. These shocks have been reported to make the ride more uncomfortable at lower frequencies (Huston *et al.*, 2000), possibly due to the fact that they may be perceived by the individual as a larger disturbance to the ride comfort at the lower frequencies as they approach the vertical natural human frequency (Huston *et al.*, 2000). Comfort may be affected by rotational vibrations on the seat as well as vibrations induced through the backrest, or through the feet of a sitting person based on the environment (ISO, 1997).

Comfort is subjective, which results in measurement variability (Griffin, 1990a, Griffin, 1990b). This variability is introduced through intra-subject and inter-subject variability which are differences within and between individuals respectively (Griffin 1990a; Griffin, 1990b). The intra-subject variability occurs as subject posture and orientation may vary with respect to the vehicle which may result in different discomfort levels at different times (Griffin, 1990a). Subject size is a physical characteristic which has been reported to be an indicator of relative comfort between subjects (Griffin *et al.*, 1982). However, discomfort in a blanket sense cannot be determined by subject size, sex, or vibration transmissibility (Griffin *et al.*, 1982). Therefore, comfort data must be interpreted with caution. Subject variability may be partially addressed by an increase in the number of

subjects, as it may decrease the effect of one person having a very different sense of what is uncomfortable. It has also been noted that soldiers were less uncomfortable in off-road vehicle comfort tests when compared to those who were not frequently exposed to WBV from military vehicles, off-road terrain and off-road driving conditions (Els, 2005). Els (2005) suggested that this may be a result of the higher fitness levels or that they are used to the off-road conditions used in the test. This implies that comfort data should possibly be recorded for those individuals for whom the findings will be applied to. In some instances this may present issues; do those being tested in simulated environments adhere to the general physical characteristics of the population the findings will be applied to? Can the findings be accurately applied to a larger population set? Thus, for comfort studies, the average comfort ratings may be more representative if completed using a large data set containing subjects with varying physical characteristics throughout the range of those whom the comfort values are being applied.

There is no useful limit for discomfort (Seidel & Griffin, 1998) as there are environmental aspects which affect comfort measures and different environments have been associated with different levels of acceptable comfort (Seidel & Griffin, 1998). However, it has been reported that, for common vibration exposures, subject responses have provided enough information to set such limits (Griffin, 1990b). Comfort associated with vibration is also dependent on the direction (axis), duration and point of transmission (Seidel & Griffin, 1998).

2.1.1.1 Axis/Magnitude/Frequency

Magnitude, direction and frequency can provide a general indication of the human response to vibration (Griffin, 1990a). An increase in magnitude generally results in an increase in discomfort for WBV (Griffin, 1990a). Parsons *et al.* (1979) reported that translational vibration generally resulted in more discomfort than the rotational axes in which the Roll and Pitch axes produced more vibration discomfort than Yaw (Parsons *et al.*, 1979). More specifically, sensitivity to Roll vibration

was reported by Parsons & Griffin (1982) to be greatest, and least in Yaw at the seat, however, when vibrations in the rotational axes are present, translational vibrations result, except at the centre of the rotation (Griffin, 1990a). Although literature has demonstrated the order in which axes affect comfort, it is most important to understand that random multi-directional vibration has increased sensitivity in humans than unidirectional vertical or fore-aft random vibration (Demić *et al.*, 2002).

Rehn *et al.*, (2005a) reported the dominant vertical accelerations in off-road vehicles (snowgroomers); however, if measuring a single axis, incorrect conclusions may be drawn as multi-input is likely to be occurring (Wegscheid, 1994) which is common to off-road vehicles. For example, vibrations in the fore-aft and lateral directions may be dependent upon the seating type an individual is using.

Discomfort varies with vibration frequency (Griffin, 1990a). At low frequencies (1-2 Hz) the movement transmitted through the body is the same (Griffin, 1990a); however, when higher vibrations are reached, the body segments begin to amplify the vibration differently, based on the body segment resonances (Griffin, 1990a). The frequencies at which humans are most sensitive to vibration changes based on axis. In the lateral and fore-aft directions, the most sensitive range is between 0-2 Hz (Wegscheid, 1994). In the vertical direction, the most sensitive range is between 4-8 Hz (Wegscheid, 1994). The human is less sensitive at frequencies outside these ranges in each axis (Wegscheid, 1994).

2.1.1.2 Duration

Duration affects the human response to vibration as the vibration characteristics may alter over time, as in occupational settings where vibrations are often of various magnitudes, may contain shocks, and may be intermittent (Griffin, 1998). The effect of vibration on discomfort in man and the duration of vibration have resulted in two very different conclusions in literature. Some researchers have concluded that with an increased exposure time, the effect of vibration are reduced

(Clevenson et al., 1978 as cited by Kjellberg & Wikström, 1985) and some suggest that it is increased with increased exposure time (Miwa et al., 1973 as cited by Kjellberg & Wikström, 1985).

With variable vibration characteristics, operators may become more aware of the vibration as their bodies become tired. Their bodies may tire as a result of the continued muscle tension which was reported to occur in vehicle operators in an effort to maintain balance during driving exposure (Rehn *et al.*, 2002). It would make sense that with the variable terrain (Golsse & Hope, 1987) these stabilization muscles may become tired at a faster rate as they may be required in a variety of directions. Additionally, the experience level of the operator and the operator characteristics may also influence the results; those with less driving experience are more likely to incur more discomfort than those who are more seasoned at vehicle operation (Boshuizen *et al.*, 1998) or “terrain experienced” (Els, 2005).

2.1.1.3 Point of Transmission

Vibration can be transmitted from the vehicle to the operator through several points of contact. Transmission occurs at locations of contact between the vehicle and operator (Griffin, 1990a). The locations which have been highlighted for seated WBV transmission are the operator/seat interface (ISO, 1997) (OSI); (i.e., operator’s buttock in contact with the vehicle seat), the operator/seat-back interface (i.e., operator’s back and the vehicle back-rest) (Griffin, 1990a; ISO, 1997), the operator/floor interface (Parsons *et al.*, 1979) (i.e., operator’s feet contacting a foot-rest/floor). Each of these locations has various effects with regard to WBV and comfort, and may depend on a variety of confounding factors.

2.1.2 Health Effects

There is no definitive disease associated solely with WBV exposure (Rummer, 1986); however, literature reviews have linked WBV to a number of ailments, including increased risk of

lumbar spine disorders (Neitzel & Yost 2002; Seidel & Griffin, 1998; Griffin, 1990a), early degeneration of the spine (Magnusson *et al.*, 1998), herniated intervertebral discs (Magnusson *et al.*, 1998), and central nervous system disorders (Neitzel & Yost, 2002; Seidel & Griffin, 1998). It is also stated that WBV exposure is a contributor for various damage caused to the body's systems: circulatory (Seidel & Griffin, 1998; Griffin, 1990a), urinary and digestive (Neitzel & Yost, 2002; South, 2004; Griffin, 1990a). Discomfort, interference with perception (ability to sense vibration), as well as vision and motor skills, while not health risks, have also been stated to be attributed to WBV exposure (South, 2004). Most commonly, however, disorders of the back (including low-back pain (LBP)) have been associated with WBV exposure (Griffin, 1990b) during vehicle operation (Bongers and Boshuizen, 1992; Hoy *et al.*, 2005), especially with off-road vehicles (Griffin, 1990b).

Some researchers have suggested that epidemiological evidence between occupational WBV exposure and an increased risk of LBP is strong (Pope *et al.*, 2002), while others (Hoy *et al.*, 2005; Lings & Leboeuf-Yde, 2000) suggest WBV may act associatively with other factors to develop LBP. Rehn *et al.* (2002) reported that there was an increase in the risk of upper back pain possibly due to WBV exposure but no increased risk of LBP as a result of WBV exposure in all-terrain vehicle operators.

While operating most vehicles, the operator is seated putting the back in an 'extreme posture' (Wilder, 1993). The vibration may be amplified by the additional motion of the pelvis in a rocking motion due to a load from the spine along a moment arm occurring as a result of the anterior offset of the ischial tuberosities (Wilder, 1993). Others have suggested that the increased risk of LBP may simply be a secondary consequence of the adverse effects on the spine, specifically degeneration of the vertebrae and disks, resulting from many years of intense WBV exposure (Seidel & Griffin, 1998). It has also been suggested in literature reviews that WBV acts in combination with other factors such as posture (Hoy *et al.*, 2005; Bongers *et al.*, 1990; Griffin, 1990b), where the end

result may be LBP. When discussing the link between WBV exposures and an increased risk of neck, shoulder and thoracic symptoms (upper back), Rehn *et al.* (2002) suggested it may be attributed to the tensed muscles in the operators. These tense muscles occur as a result of the body's effort to maintain balance while simultaneously being exposed to WBV and handling the vehicle controls or continued arm elevation (Rehn *et al.*, 2002). In combination, these have been suggested as possibly inducing the neck and shoulder symptoms which result from the static overload of the muscles (Rehn *et al.*, 2002).

These adverse effects are not associated solely with WBV exposure (Pope *et al.*, 2002; Magnusson & Pope, 1998; Bovenzi, 2000), and as a result, controversy surrounds the association between WBV and health effects (Kjellberg & Wikström, 1985; Bovenzi, 2000). Although WBV related disorders have become more recognized, there is still no compensable disease which has been attributed solely to WBV in North America (Village & Morrison, 1989; Griffin, 1990b). In addition in epidemiological literature, exact cause and effect relationships have not been determined as there are incomplete or missing data in regards to exposure conditions (Seidel & Griffin, 1998) or confounding factors (Lings & Leboeuf-Yde, 2000) such as WBV magnitude, frequency and direction which may affect the relationship between WBV exposure and health effects (Ranganathan & Mohan, 1997). As a result, the determinations of safe limits are unsubstantiated, in regards to reliable prevention of spinal disease (Seidel & Griffin, 1998). The topic of LBP and WBV exposure is further confounded by intra-subject variability. For example, within the general public, there is a high incidence of degeneration regardless of WBV exposure (Griffin, 1990a; Griffin, 1990b). This is further complicated by "disc degeneration diagnosis" (Griffin, 1990b), as LBP can be present before degenerative changes are radiologically detectable (Griffin, 1990b).

There is even more confusion in epidemiological studies. Boshuizen *et al.* (1998) who reported that of a group of fork-lift and freight-container drivers with less than 5 years of driving

experience had a higher prevalence of back pain when compared to a reference group of similar age. This did not occur in drivers with more than 5 years driving experience (Boshuizen *et al.*, 1998). Boshuizen *et al.* (1998) suggested that this may be a result of health-based selection. This concern has also been noted by other investigators such as Rehn *et al.* (2002). Operators who are more susceptible to WBV or industry induced health effects or discomfort do not remain in the field, but those who have adapted or are not susceptible to the effects of their occupation may be more likely to continue working in the field (Rehn *et al.*, 2002).

The health effects are suggested to possibly depend on mechanical factors, such as vehicle design, more specifically whether the machine transmits vibrations to the tissue at the body's resonance frequencies (Kjellberg & Wikström, 1985). This will affect whether tissue is strained or compressed which will occur as a result of how the vibration is transmitted to the tissue (Kjellberg & Wikström, 1985). Vehicle designs in which the frames of the cab will obscure the operators view (Eklund, 1994) may induce the extreme and twisted postures associated with health effects as outlined previously.

The controversy surrounding WBV exposure and health effects is present throughout literature, however, it is important for the purpose of this thesis, to understand that exposure to WBV and shock can be assumed to be deleterious to health (Griffin, 1990a); thus, exposures should be minimized. In order to minimize these effects, whatever they may be, requires an understanding of the magnitudes of exposures.

2.2 Standardization of the Measurement of Whole-Body Vibration

2.2.1 Whole-body Vibration Measurement

Vibration may enter the seated human through the OSI, operator/backrest interface, or floor/feet interface (ISO, 1997) and, as a result, measurements should be taken at the WBV entrance

points between machine and operator (ISO, 1997). Measurements at the OSI must be made with a person sitting on the seat as the transmission through the seat will be affected by the body's impedance (Griffin, 1990b). The origin of the coordinate system should be located above the seat pad and beneath the ischial tuberosities (Griffin, 1990a; Seidel & Griffin, 1998) in the mid-sagittal plane (Griffin, 1990a). If measurements cannot be made at the OSI, then measurements at the floor beneath the seat may be used if the testing environment is free of rotational motion and the seat is rigid (Griffin, 1990b).

There are various aspects of measurement which should be carefully addressed such as calibration of the system used for measurement, measurement system capabilities, mounting techniques, frequency range (Thalheimer, 1996), expected vibration range and sampling rate.

2.2.2 Standards for Evaluating WBV

There are two WBV measurement standards which are predominantly applied in literature: The International Organization for Standardization' ISO263-1: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General Requirements, and the British Standards Institution's BS 6841: Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock. In North America, the ISO 2631-1 standard in its most recent publication (1997) is generally used.

The ISO 2631-1:1997 outlines the axes, general measurement locations and signal conditioning which should be applied to instances of WBV evaluation. The process for weighting the accelerations is outlined with a set of weights based on the frequency of the signals. It should be noted that when frequency content is evaluated, 1/3-octave band frequency bins are often used, as a standard octave band is too coarse (Griffin, 1990b).

The standard also provides health guidance caution zones. The health guidance caution zone describes the suggested relation between ISO 2631-1:1997 frequency-weighted accelerations in

m/s² to the exposure time in hours (ISO, 1997). The health guidance caution zone figure (ISO, 1997) provides the upper and lower limits of the health guidance caution zone. Accelerations remaining below the lower limit have not been shown to result in health effects (ISO, 1997). However, for accelerations exceeding the upper limit, health risks are likely to occur. Accelerations between the upper and lower health guidance caution zones are thought to have the potential for health risks (ISO, 1997). The upper and lower guidelines remain constant until 10 minutes of exposure is exceeded, at which point, the value of acceptable weighted acceleration levels for the upper and lower limits of the health guidance caution zone decrease with increasing time (ISO, 1997). Thus, the ISO 2631-1:1997 standard provides the means to determine acceptable accelerations (in weighted form) based on known exposure times. Alternatively the time of allowable exposure may be determined from the level of exposure (ISO, 1997).

General comfort reactions to environments with vibration are also outlined in the ISO 2631-1:1997 standard. Although the standard outlines that comfort is very dependent on a multitude of factors, the standard also presents a set of comfort levels ranging from not comfortable (<0.315 m/s²) to extremely uncomfortable (>2m/s²) (ISO, 1997) depending on the magnitude of the weighted accelerations.

There are a number of differences reported in literature between the standards which may be attributed to the various results which may be obtained as a result of using one standard over the other (Lewis & Griffin, 1998). The most obvious difference is that ISO 2631-1:1997 is based on the most severe axis which underestimates vibration severity and is contrary to BS 6841:1987 (Paddan & Griffin, 2002a). This difference in measurement axes, alongside different sets of frequency weightings and multiplying factors for the horizontal axis result in an underestimation of the ISO 2631-1:1997 values compared to the BS 6841:1987 standard (Paddan & Griffin, 2002a). The

use of RMS in the ISO 2631-1:1997 may also underestimate the influence of peak accelerations on health disorders (ISO, 1997).

WBV risk is generally underestimated when employing the ISO 2631-1:1997 standard in comparison to the processes outlined in BS 6841:1987 (Paddan & Griffin, 2002a). This may be related to the axes of measurement, as ISO 2631-1:1997 outlines measurement at the OSI in the translational axes, however the axis with the most severe vibration is only used to analyze the exposure (Paddan & Griffin, 2002a), however, the standard has made notes for vibration environments with multi-axis vibrations and rotational vibrations. The ISO 2631-1:1997 standard is further confounded by the encouragement of measurements at the back-rest which are not included in the measurement of vibration severity (Paddan & Griffin, 2002a).

There are three standards which are often referenced in literature, the ISO 2631-1 standard from different publication and the British Standard. The overall outcome of the 3 different standards (ISO 2631-1:1997, ISO 2631/1:1985, BS 6841:1987) for the duration of daily exposure to whole-body vibration and shock limits may be very different (Lewis & Griffin, 1998). This has been reported to be a result of the use of rms versus fourth power vibration dose values, and resulted in larger differences for the more severe motions (Lewis & Griffin, 1998). The current ISO standard (ISO 2631-1:1997) also fails to clearly illustrate when the rms or the vibration dose values should be used (Lewis & Griffin, 1998). When using the ISO 2631-1:1997 standard, the choice between these evaluation techniques may result in large differences (Lewis & Griffin, 1998); however, for the health guidance caution zone determination, there is less difference between the different evaluation techniques during the 4-8 hour window (Lewis & Griffin, 1998). At shorter durations, the difference may be a factor of 10 or greater (Lewis & Griffin, 1998).

2.3 Whole-Body Vibration in Industry

WBV exposure occurring in occupational environments has been attributed primarily to transport (Seidel & Griffin, 1998). Skidders have been reported to have rough rides (Golsse & Hope, 1987), which may be because off-road vehicles are exposed to severe vibrations and shock levels (Seidel & Griffin, 1998). These exposure levels among different models of vehicles used for the same purpose may vary greatly (Cann et al., 2004). This is as expected, as not only do the velocity (Hansson, 1990) and terrain (Cann et al., 2004) vary between machines, but mileage has also been suggested to affect WBV accelerations (Cann et al., 2004). Industrial WBV has been reported in a wide variety of off-road vehicles such as snowmobiles (Rehn *et al.*, 2005a), snowgroomers (Rehn *et al.*, 2005a) and forestry vehicles (Griffin, 1990a) including forwarders (Rehn *et al.*, 2005a) and skidders (Golsse & Hope, 1987, Golsse, 1989; Wegscheid, 1994; Neitzel & Yost, 2003).

Paddan and Griffin (2002a) reported a large variation in the magnitudes of vibration within and between the various vehicle categories tested. It is hypothesized that WBV may be minimized by an appropriate selection of vehicles under various operating conditions (Paddan & Griffin, 2002a). Intuitively, their findings also imply that variation due to operation is likely some function of terrain over which the task is completed and also the job for which the vehicle is operated. Some off-road vehicles have been reported to be associated with discomfort and WBV (Griffin, 1990b). This may be a function of off-road drivers being subjected to high acceleration levels as a result of roll, pitch, and Z-axis combined effects (Els, 2005). This suggests that standards should evaluate WBV exposure based on terrain type, occupation, vehicle job, vehicle type.

Road condition, mileage, driver experience and seat type (Cann *et al.*, 2004) have been investigated as possible influences on measured vibration levels. As a result, the comparison between vehicle types, vehicles of the same type, operators, operating locations etc. should be

carefully considered. More specifically, any generalization of specific vibration results should be made with care (Eger *et al.*, 2006).

2.3.1 Prevention and Minimization

The most obvious minimization technique is through improvements in seat dynamics. This has been shown by Paddan & Griffin (2002b) to decrease WBV exposure severity. This has been demonstrated in New York City subways where 'new-technology' trains were shown to be less severe in WBV than those normally operated in 1996 (Ozkaya *et al.*, 1996), thus a good example of how technology may be used to improve rider comfort and minimize WBV.

Prevention and minimization become increasingly difficult as a result of terrain in industries where the machines are operated on variable terrain in different locations. In industries such as forestry, the machines are operated at one location until the area is cleared of harvestable trees and then the operation is relocated. As a result of the relocations, the terrain may vary greatly which in turn may require very different operating machine characteristics and procedures in an effort to minimize WBV exposure. Intuitively for the forestry industry, where the terrain is usually not constant between site locations, there is little which can be done to alter the sites where the skidder is operated thus leaving design changes in the vehicle to be made in order to minimize WBV (de Silva, 2000).

Many mechanical and operator specific actions may be taken in order to minimize WBV without design changes. Tire inflation pressure may be able to moderate WBV exposure in timber harvesters (Sherwin *et al.*, 2004), and a reduction of vehicle speed (Seidel & Griffin, 1998) may also decrease WBV. The terrain type in which forwarders were operated while driving without a load (Rehn *et al.*, 2005b), and the way in which a forwarder is driven while driving loaded (Rehn *et al.*, 2005b) have been shown to have an effect on WBV. Some maintenance and design improvements have also been suggested: primary suspension at front and rear axles, cab and seat suspension, as

well as suitable tires for off-road vehicles (Boileau & Rakheja, 1990), new designs of seats for helicopter pilots (Harrer *et al.*, 2005), and adequate backrest designs (Boileau & Rakheja, 1990). It has also been suggested that backrests which provide lumbar support and correctly control seated posture may improve the operator comfort by supporting the spinal column and not the muscles (Boileau & Rakheja, 1990) be incorporated into designs.

Lab stands which vibrate seats in a test environment have replaced much of vehicle seat testing (Wegscheid, 1994), as it cheaper and has eliminated confounding variables such as vehicle weight, tire specification (type, size, pressure, etc.), vehicle wheelbase and travel speed (Wegscheid, 1994). The use of laboratory testing has resulted in improvements in repeatability and reliability of measurements (Wegscheid, 1994).

2.4 Whole-Body Vibration in Forestry

Seidel & Griffin (1998) included forestry machines in a list of environments which “may be most likely to be associated with a health risk” (Seidel & Griffin, 1998). Within the forestry industry, skidders, which move logs from one location to another, have been identified as having possibly the roughest ride of forestry machines (Wegscheid, 1994) and there have been several thousand of these working across Canada (Golsse & Hope, 1987). As a result of the extreme WBV environment, forestry skidders are a good example of extreme and variable conditions resulting from the movement between various locations over variable terrain. There are also differences which have been noted between front and rear mounted implements. Skidders (both cable and grapple) drag the load behind them. However, they will pile logs using their plow which is located at the front. Vehicles with front mounted implements were found to produce higher acceleration levels than their rear-mounted counterparts (Golsse, 1989) and tracked machines had higher acceleration levels than wheeled ones (Golsse, 1989), thus comparisons and grouping between tracked/wheeled and front/rear implemented skidders should be done with caution. Some of the most severe ride-

induced vibration encountered in industrial machines affects skidder operators (Golsse & Hope, 1987). Axelsson & Potén (1990) suggested that there is a need for improvements to the mechanization of tree harvesting in the areas of WBV and ergonomics.

The vibration amplitude which is experienced by seated operators in the forestry industry exceeds the levels proposed by various researchers and organizations, and as a result may pose a health risk and limits the speed at which the task may be completed (Boileau & Rakheja, 1990). Forestry machine operators are not only exposed to high levels of WBV (Hansson, 1990), but have a high incidence of reported unpleasant movements (Rehn *et al.*, 2002), particularly with high-speed travel on rough terrain (Golsse & Hope, 1987).

Skidders are not usually equipped with seats which isolate y-axis motions (Boileau & Rakheja, 1990) thus the incorporation of field acceleration profiles which include Y-axis accelerations aid seat designers in improving one aspect of skidder design. Previous studies do not provide the information required to isolate the characteristics required by seat designers to address the required suspension improvements (Wegscheid, 1994). As a result, further testing is required. To facilitate research and enable researchers to eliminate the need for expensive field tests, 6-DOF robots may be used to replicate field values. These laboratory tests will also allow for larger data sets and the inclusion of unskilled operators. This will allow for a larger range of acceptable limits to be determined once 6-DOF field profiles have been developed.

In order to be able to use simulations, representative ground (field) profiles are required that are specific to the terrain of interest (Rummer & Smith, 1989). Thus, a collection of various vehicles in various locations and conditions should be compiled such that it may be used in laboratory and simulation environments for future researchers. This should be done in the eventual aim to provide a relationship between health effects and forestry machinery, as it has not been completed to date by an occupational health unit in forestry (Hansson, 1990).

2.5 Summary

Although there is much controversy surrounding the details of discomfort and health effects associated with WBV, it is undeniable that these factors are issues with exposure to WBV. As a result, exposure to WBV would ideally be halted; however, this is not possible as modes of transportation and a variety of industries rely on mobile machines with human operators. Humans are exposed to WBV at work through the mechanization of tasks and this exposure should be minimized. To minimize the exposures, new designs are required as there is little which can be done to modify the environments that skidders are operated in. For these new designs to be properly developed, quantified field profiles and WBV accelerations are required such that appropriate laboratory tests may be developed to test new designs and to possibly develop new guidelines for extreme WBV work environments.

2.6 Conclusion

Based upon available literature, it is evident that there is a lack of 6-DOF information in regards to OSI and chassis measurements for skidders in forestry. Laboratory studies are not being done using data from field studies, leaving a larger number of questions unanswered.

2.7 References

- Axelsson S-Å, Potén B. 1990. New ergonomic problems in mechanized logging operations. *International Journal of Industrial Ergonomics*, 5; 267-73.
- Boileau P-E, Rakheja S. 1990. Vibration attenuation performance of suspension seats for off-road forestry vehicles. *International Journal of Industrial Ergonomics*, 5; 275-91.
- Bongers PM, Boshuizen HC. 1992. Back disorders and exposure to whole-body vibration: Thesis summary. *Clinical Biomechanics*, 7; 185-6.
- Bongers PM, Hulshof CTJ, Dijkstra L, Boshuizen HC, Groenhout HJM, Valken E. 1990. Back pain and exposure to whole body vibration in helicopter pilots. *Ergonomics*, 33; 1007-26.

Boshuizen HC, Bongers PM, Hulshof CT. 1998. Self-reported back pain in fork-lift truck and freight-container tractor drivers exposed to whole-body vibration. *Spine*, 17; 56-65.

Bovenzi M. 2000. Health disorders caused by occupational exposure to vibration. In: Violante F, Armstrong T, Kilbom A (Eds), *Occupational Ergonomics: Work related musculoskeletal disorders of the upper limb and back*. Taylor & Francis. New York, pp.88-104.

Bovenzi M, Pinto I, Stacchini N. 2002. Low back pain in port machine operators. *Journal of Sound and Vibration*, 253; 3-20.

BS. 1987. BS 6841: Measurement and evaluation of human exposure to whole-body mechanical vibration and shock. London: British Standards Institution.

Cann AP, Salmoni AW, Eger TR. 2004. Predictors of whole-body vibration exposure experienced by highway transport truck operators. *Ergonomics*, 47; 1432-53.

Clevenson SA, Dempsey TK, Leatherwood JD. 1978. Effects of vibration duration on human discomfort. NASA Technical Paper 1283.

de Silva CW. 2000. *Vibration – Fundamentals and practice*. CRC Press. New York. 2000. pp. 732-6.

Demić M, Likić J & Milić Ž. 2002. Some aspects of the investigation of random vibration influence on ride comfort. *Journal of Sound and Vibration*, 253; 109-29.

Eger T, Salmoni A, Cann A, Jack R. 2006. Whole-body vibration exposure experienced by mining equipment operators. *Occupational Ergonomics*, 6; 121-7.

Eklund J, Odenrick P, Zettergren S, Johansson H. 1994. Head posture measurements among work vehicle drivers and implications for work and workplace design. *Ergonomics*, 37; 623-39.

Els PS. 2005. The applicability of ride comfort standards to off-road vehicles. *Journal of Terramechanics*, 42; 47-64.

Golsse J-M. 1989. Analysis of whole-body vibration levels during site preparation. Forest Engineering Research Institute of Canada (FERIC). Technical Report TR-90.

Golsse J-M, Hope PA. 1987. Analysis of whole-body vibration levels during skidding. Forest Engineering Research Institute of Canada (FERIC). Technical Report TR-77.

Griffin, MJ. 1990a. *Handbook of Human Vibration*. Academic Press, New York.

Griffin MJ. 1990b. Measurement and evaluation of whole-body vibration at work. *International Journal of Industrial Ergonomics*, 6; 45-54.

Griffin MJ. 1998. Vibration. In: Stellman JM (Eds), *Encyclopedia of Occupational Health and Safety*, 4th edition Volume II. International Labour Office, Geneva, pp. 50.2

Griffin MJ, Whitham EM, Parsons KC. 1982. Vibration and comfort I. Translational seat vibration. *Ergonomics*, 25:603-30.

Hansson J-E. 1990. Ergonomic design of large forestry machines. *International Journal of Industrial Ergonomics*, 5; 255-66.

Harrer KL, Yniguez D, Majar M, Ellenbecker D, Estrada N, Geiger M. 2005. Whole-body vibration exposure for MH-60S pilots. *SAFE Association Annual Symposium Proceedings: 43rd annual SAFE Symposium*, Oct 24-26, Salt Lake City, UT, USA, 43; 303-13.

Hoy J, Mubarak N, Nelson S, Sweerts de Landas M, Magnusson M, Okunribido O, Pope M. 2005. Whole body vibration and posture among forklift truck drivers. *Journal of Sound and Vibration*, 284; 933-46.

Huston DR, Zhao X, Johnson CC. 2000. Whole-body shock and vibration: frequency and amplitude dependence on comfort. *Journal of Sound and Vibration*, 230; 964-70.

ISO. 1997. ISO 2631-1: Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1: General requirements. International Organization for Standardization.

Johanning E, Fischer S, Christ E, Göres B, Landsbergis P. 2002. Whole-body vibration exposure study in U.S. railroad locomotives – An ergonomic risk assessment. *American Industrial Hygiene Association Journal*, 63; 439-46.

Johanning E, Landsbergis P, Fischer S, Christ E, Göres B, Luhrman, R. 2006. Whole-body vibration and ergonomic study of US railroad locomotives. *Journal of Sound and Vibration*, 298; 594-600.

Kjellberg A, Wikström B-O. 1985. Whole-body vibration: exposure time and acute effects – a review. *Ergonomics*, 28; 535-44.

Lewis CH, Griffin MJ. 1998. A comparison of evaluations and assessments obtained using alternative standards for predicting the hazards of whole-body vibration and repeated shock. *Journal of Sound and Vibration*, 215; 915-26.

Lings S, Leboeuf-Yde C. 2000. Whole-body vibration and low back pain: a systematic, critical review of epidemiological literature 1992-1999. *International Archives of Occupational and Environmental Health*, 73; 290-97.

Magnusson ML, Pope MH. 1998. A review of the biomechanics and epidemiology of working postures (it isn't always vibration which is to blame!). *Journal of Sound and Vibration*, 215; 965-76.

Magnusson ML, Pope MH, Hulshof CTJ, Bovenzi M. 1998. Development of a protocol for epidemiological studies of whole-body vibration and musculoskeletal disorders of the lower back. *Journal of Sound and Vibration*, 215; 643-51.

Miwa T, Yonekawa Y, Kojima-Sudo A. 1973. Measurement and evaluation of environmental vibrations. Part 3: Vibration exposure criterion. *Industrial Health*, 11; 185-196.

Neitzel R, Yost M. 2002. Task-based assessment of occupational vibration and noise exposures in forestry workers. *American Industrial Hygiene Association Journal*, 63; 617-27.

Neitzel R, Yost M. 2003. Forestry Vibration and Noise Exposure Project. University of Washington Department of Environmental Health. Seattle, Washington, USA.

Ozkaya N, Willems B, Goldsheyder D. 1996. Whole-body vibration exposure studies on train operators. *Advances in Applied Ergonomics: Proceedings of the 1st International Conference on Applied Ergonomics (ICAE '96)*, Istanbul, Turkey, May 21-24, pp.695-700.

Paddan GS, Griffin MJ. 2002a. Evaluation of whole-body vibration in vehicles. *Journal of Sound and Vibration*, 253; 195-213.

Paddan GS, Griffin MJ. 2002b. Effects of seating on exposures to whole-body vibration in vehicles. *Journal of Sound and Vibration*, 253; 215-41.

Parsons KC, Griffin MJ. 1982. Vibration and comfort II. Rotational seat vibration. *Ergonomics*, 25; 631-44.

Parsons KC, Griffin MJ, Whitham EM. 1982. Vibration and comfort III. Translational vibration of the feet and back. *Ergonomics*, 25; 705-19.

Parsons KC, Whitham EM, Griffin MJ. 1979. Six axis vehicle vibration and its effects on comfort. *Ergonomics*, 22; 211-25.

Pope M, Magnusson M, Lundström R, Hulshof C, Verbeek J, Bovenzi M. 2002. Guidelines for whole-body vibration health surveillance. *Journal of Sound and Vibration*, 253; 131-67.

Ranganathan R, Mohan MV. 1997. A review of the general effects of whole-body vibration. *International Journal of Vehicle Design*, 4; 353-72.

Rehn B, Bergdahl IA, Ahlgren C, From C, Järvholm B, Lundström R, Nilsson T, Sundelin G. 2002. Musculoskeletal symptoms among drivers of all-terrain vehicles. *Journal of Sound and Vibration*, 253; 21-9.

Rehn B, Nilsson T, Olofsson B, Lundström R. 2005a. Whole-body vibration exposure and non-neutral neck postures during occupational use of all-terrain vehicles. *The Annals of Occupational Hygiene*, 49; 267-75.

Rehn B, Lundström R, Nilsson L, Liljelind I, Järvholm B. 2005b. Variation in exposure to whole-body vibration for operators of forwarder vehicles – aspects on measurement strategies and prevention. *International Journal of Industrial Ergonomics*, 35; 831-42.

Rummer RB, Smith LA. 1989. Reducing whole-body vibration of forest equipment operators through improved vehicle design. In: Mital A (Eds), *Advances in Ergonomic Safety I. Proceedings of the Annual International Industrial Ergonomics & Safety Conference*. Cincinnati, Ohio, USA, June 5-9. Taylor & Francis, NY, pp. 65-72.

Rummer RB. 1986. Whole-body vibration of forest equipment operators: A review of past research and present needs. In: Karwowski W (Eds), Trends in Ergonomics/Human Factors III, Proceedings of the Annual International Industrial Ergonomics and Safety Conference, June 12-14, Louisville, KY, USA, pp. 1131-9.

Seidel H, Griffin MJ. 1998. Whole-body Vibration. In: Stellman JM (Eds), Encyclopedia of Occupational Health and Safety, 4th edition Volume II. International Labour Office, Geneva, pp. 50.2-50.7

Sherwin LM, Owende PMO, Kanali CL, Lyons J, Ward SM. 2004. Influence of tyre inflation pressure on whole-body vibrations transmitted to the operator in a cut-to-length timber harvester. Applied Ergonomics, 35; 253-61.

Smith CC, Kwak YK. 1978. Identification of the dynamic characteristics of a bench-type automotive seat for the evaluation of ride quality. Transactions of the ASME. Journal of Dynamic Systems, Measurement, and Control, 100; 42-9.

South, T (2004). Managing Noise and Vibration at Work – A Practical Guide to Assessment, Measurement and Control. Elsevier Butterworth-Heinmann, Oxford.

Thalheimer E. 1996. Practical approach to measurement and evaluation of exposure to whole-body vibration in the workplace. Seminars in Perinatology, 20; 77-89.

Village J, Morrison J. 1989. Exposure of heavy equipment operators to whole body vibration and repeated shock. In: Proceedings of the Human Factors Association of Canada. 22nd Annual Conference, Toronto, Ontario, Canada, November 26-29.

Wegscheid E. 1994. Another look at skidder ride vibration. Journal of Forest Engineering, 5;21-32.

Wilder DG. 1993. The biomechanics of vibration and low back pain. American Journal of Industrial Medicine, 23; 577-88.

Chapter 3: WHOLE-BODY VIBRATION SENSOR CALIBRATION USING A SIX-DEGREE OF FREEDOM ROBOT

3.1 INTRODUCTION

With technological advancements, the detail and complexity of the measurements researchers are able to undertake has increased. This is exemplified in the field of whole-body vibration (WBV). The most recent publication of the ISO 2631-1 standard outlines the measurement of WBV in 6 degrees-of-freedom (DOF). Thus, measurements in translational axes X-, Y- and Z- as well as rotational axes roll, pitch and yaw (about X-, Y- and Z-axes respectively) are required. The movement to 6-DOF measurements has increased the complexity of the sensors used to measure WBV.

In some WBV environments, there may be transients (or shocks), which by definition are sudden changes in accelerations (Griffin, 1990). Off-road vehicles are likely often subjected to shocks as a result of the notably high speeds in rough terrain (Golsse & Hope, 1987). Based on skidder WBV literature, the transducer is required to record peak accelerations of no less than $7.08 \pm 3.48 \text{ m/s}^2$ (Golsse & Hope, 1987) or no less than $3.32 \pm 1.42 \text{ m/s}^2$ (Golsse, 1989) at the OSI in the translational axes. The reported dominant frequency band is 2.5 Hz at the chassis floor (Boileau & Rakheja, 1990). Heavy haul dump trucks on the other hand have reported acceleration at the OSI of up to 11.73 m/s^2 (Kumar, 2004). These published values have been weighted according to various versions of the ISO 2631-1 standard, thus an additional range should be allowed for in the calibration. This should be done to ensure that there has been no under estimation of the actual recorded field accelerations which may be attenuated at certain frequencies during the weighting process.

In the field of WBV, the literature outlining WBV accelerations rarely address the calibration technique/procedures used for WBV sensors to any depth, nor is there any detailed information regarding such procedures or calibration ranges for the sensors. This chapter will address these issues, outlining a simple 6-DOF calibration of a OSI transducer for WBV measurements using a 6-

DOF robot, and a separate technique used to verify the calibration outside the robot calibration range to include an acceptable calibration range for WBV environments.

3.2 METHODOLOGY

Calibration was completed in two phases on a seat-pad transducer (SPT) used for WBV measurements at the OSI both at a sampling rate of 500 Hz. The first phase was a calibration using a 6-DOF robot to generate the calibration equations for each DOF. The second phase was designed to verify the calibration equations determined using the 6-DOF robot at a larger acceleration range, throughout the expected field range. The SPT was designed to be compact and flat to remove pressure points as it was to be used at the operator/seat interface in the field to measure WBV. This sensor was built at the University of Guelph (Guelph, Ontario, Canada) using two Analog Devices™ (Analog Devices Inc., Norwood, Massachusetts, USA) ADXL320EB bi-axial accelerometers measuring the X, Y and Z axes and three Analog Devices™ ADXRS150EB rate gyroscopes to measure roll, pitch and yaw. The ADXL320EB accelerometers were rated for $\pm 5g$ and the ADXRS150EB gyroscopes were capable of recording $\pm 150^\circ/s$ velocities. The accelerometers and rate gyroscopes were orthogonally placed in a Delrin™ plastic casing to monitor the Roll, Pitch and Yaw axes. A 12-bit SOMAT™ Series 2001 Field computer (nCode International Inc., Southfield, Michigan, USA) collected raw device voltages at a sampling rate of 500 Hz.

3.2.1 Experimental Set-Up

The first phase was the low g (LG) calibration (peak values of: 1 to 8 m/s^2 and 10 to 100 $^\circ/s$) to determine the calibration equations using a 6-DOF robot. The second phase tested the sensors calibration previously determined in the LG calibration throughout the expected field range for WBV measurements of forestry skidders to validate the calibration values which were determined at low

g. The high g (HG) calibration used a vibration table and an optical motion capture system. The sensor was zeroed before each axis was tested to eliminate orientation bias.

3.2.1.1 Low g (LG) Calibration

The LG calibration was completed using a Parallel Robotics System Corporation (PRSCO) R2000 6-DOF robot (Parallel Robotic Systems Corporation, Hampton, New Hampshire, USA). The PRSCO was calibrated by PRSCO for repeatability and accuracy (within 24 μm), and accuracy (within +24/-38 μm) for travel in the X, Y and Z axes. Sinusoidal acceleration and velocity profiles were created as inputs to the PRSCO. The acceleration profiles were developed to achieve $\pm$ peak accelerations between 1 and 8 m/s^2 for the translational axes (X, Y, Z) at known frequencies (Table 3-1) and double integrated using the trapezoid rule. The profiles were integrated into displacement form as the robot requires displacement inputs. For pitch, roll and yaw, a single integration was required, since the sensors for these axes monitor angular velocity. Angular velocity profiles ranged between 10 and 100°/s at frequencies between 0.5 and 5 Hz as shown in Table 3-2. The sensors were placed in the centre of the PRSCO 6DOF robot platform which reproduced the known displacement profiles. The sensors were oriented such that the axis of interest was aligned such that the PRSCO robot would have the largest movement displacement allowing higher accelerations and angular velocities to be produced. The experimental set-up is shown in Figure 3-1.

Table 3-1: The peak sinusoidal accelerations and corresponding frequencies used to calibrate the translational (X, Y, Z) accelerometers using displacement profiles on a Parallel Robotics System Corporation Robot six-degree-of-freedom robot.

Acceleration (m/s^2)	1	2	3	4	5	6	7	8
Frequency (Hz)	1, 2, 5	1, 2, 5	2, 5	2, 5	2, 5	2, 5	2, 5	2, 5

Table 3-2: The peak sinusoidal velocities and corresponding frequencies used to calibrate the rotational (Roll, Pitch, Yaw) accelerometers using displacement profiles on a Parallel Robotics System Corporation Robot six-degree-of-freedom robot.

Velocity (°/s)	10	20	30	40	60	80	100
Frequency (Hz)	0.5, 1, 2, 5	0.5, 1, 2, 5	0.5, 1, 2, 5	0.5, 1, 2, 5	0.5, 1, 2, 5	0.5, 1, 2, 5	0.5, 1, 2

Figure 3-1: The experimental set-up for the low g (LG) calibration using a Parallel Robotics System Corporation (PRSCO) six-degree-of-freedom (6-DOF) robot shown here with the seat-pad transducer (SPT).

3.2.1.2 High g (HG) Calibration

The LG calibration calibrated up to 100°/s, which exceeded the expected field range of the gyroscopes, but did not calibrate the entire expected range of the accelerometers. Thus, a second stage was completed to calibrate the accelerometers up to and including approximately $\pm 4g$ at frequencies between 10 and 35 Hz.

An All-American™ vibration fatigue testing machine (VTM) (All American Tool & Mfg. Co., Illinois, USA) was used to calibrate at HGs. This vibration machine is able to only move in the Z-axis, thus the axis being tested was oriented with respect to the Z axis for each of the accelerometer axes as shown in Figure 3-2. The SPT movement on the VTM was recorded using three VICON M²m

cameras from a VICON™ 460 Motion Capture System (VICON Motion Systems, Centennial, CO, USA) and simultaneous data was recorded from the SPT. The experimental set-up is shown in Figure 3-3. The various accelerations were tested by changing the VTM using an analog frequency setting dial (between approximately 10Hz and 35 Hz) and peak-to-peak displacements (between approximately 1.27mm to 5.08 mm outlined in Table 3-3. The accelerations tested for HC calibration verification included and exceeded the accelerations determined at the LG acceleration which was used to generate the calibration equations. The VICON™ 460 M²m cameras were previously validated for vibration measurements of displacements greater than 1mm to contain less than 5% error for frequencies between 3 and 30 Hz (Jack *et al.*, 2005).

Figure 3-2: Sensor axis orientation and placement on the All-American vibration fatigue testing machine (VTM) which vibrated in the Z axis.

Figure 3-3: The experimental set-up for the high g (HG) calibration verification using an All-American vibration fatigue testing machine (VTM).

Table 3-3: The setting combination of peak-to-peak displacements and frequency manual settings used for the All-American vibration fatigue testing machine (VTM) and resulting approximate acceleration values determined by the manual settings on the VTM.

Peak-to-Peak Displacement (mm)	Frequency (Hz)	Approximate Acceleration (g)
5.08	10	1.02
1.27	20	1.01
3.81	15	1.72
2.54	20	2.03
3.81	20	3.04
2.54	25	3.17
1.27	35	3.08
5.08	20	4.06

Four, 14mm diameter spherical reflective markers were adhered to the sensor/vibration table using double sided tape such that all M²m cameras had full view of the markers. The cameras were oriented in an umbrella fashion (Figure 3-4) often used in gait analysis (Nigg *et al.*, 2007). The cameras recorded the X, Y, and Z lab coordinates of the reflective markers for each trial and were sampled at 500 Hz for 10 seconds. The VICON™ system was calibrated statically and dynamically in the measurement volume to minimize error due to the optical distortion phenomena (Chiari *et al.*, 2005). The calibration residuals (error) were less than 1mm during the calibration of the VICON motion capture system.

Figure 3-4: The umbrella (Nigg *et al.*, 2007) camera orientation.

3.2.2 Data Analysis

3.2.2.1 Calibration at Low *g* Values

The raw dynamic calibration data from the SPT were then second-order low pass Butterworth filtered at a cut-off frequency of 10 Hz (two times the highest expected signal frequency of 5 Hz as shown in Table 3-1 and Table 3-2) such that the Nyquist rate was exceeded. The acceleration and velocity known input profiles were then aligned with the sensor voltage output for

the translational and rotational axes respectively. The calibration equations were determined for each sensor and each axis independently. The calibration equations were determined to be of the form $y=mx$ for all 6-DOF for the SPT.

3.2.2.2 Translational Acceleration Data Validation at High g (HG) Values

The sensor voltages and raw digitized VICON™ 3D coordinates were second order zero lag low pass Butterworth filtered at a cutoff frequency of two times the frequency set on the VTM. The calibrations determined from the LG calibration were applied to the filtered sensor voltages and then compared to the double differentiated, filtered VICON™ displacement data for the three translational axes (X, Y, Z). Five individual cycles of double differentiated VICON™ displacement data and sensor data were manually aligned using peak acceleration values. The peak maximum and minimum accelerations as well as r^2 values were determined from the VICON™ and SPT data for five individual cycles at each VTM setting outlined in Table 3-3. In addition, the corresponding percent error was determined for the difference between the maximum sensor acceleration and maximum VICON™ acceleration, where the VICON™ data was taken to be the gold standard. The overall average ($n=5$) was reported using the five single cycle values. This was completed for each of the VTM settings listed in Table 3-3.

3.3 RESULTS

The SPT calibration equations are shown in Table 3-4. The calibration equations fit the LG calibration data with r^2 values of greater than 0.997 in all 6-DOF. When the LG calibration equations were applied to HG data and compared to VICON™ determined accelerations, the accuracy of the sensor was shown to generally produce less than 10% error. The largest error between the VICON™ and the system gold standard SPT data was approximately 12% (under 6 m/s^2). This error was less than 12% at both the maximum and minimum peaks. At the peak acceleration values, the SPT

recorded average peak accelerations of approximately $\pm 45.63 \text{ m/s}^2$ and VICON™ recorded an average acceleration of $\pm 51.58 \text{ m/s}^2$. The r^2 values exceeded 0.9 in all translational axes at all acceleration levels tested at the HG levels as shown in Table 3-5.

Table 3-4: Calibration equations for the seat-pad transducer developed using a low g acceleration values.

Axis	Calibration Equation	Unit of Measurement
X	$y = -52.02 x$	m/s^2
Y	$y = -52.18 x$	m/s^2
Z	$y = 51.13 x$	m/s^2
Roll	$y = 81.47 x$	$^\circ/\text{s}$
Pitch	$y = -84.34 x$	$^\circ/\text{s}$
Yaw	$y = 79.22 x$	$^\circ/\text{s}$

Table 3-5: Results of High g acceleration data verification for the seat-operator interface (SPT) transducers for the X, Y and Z axes at various displacement and frequency settings. The displacement and frequency settings were set on the vibration testing machine (VTM). Camera and SPT accelerations are shown for the various VTM settings.

X	Displacement (mm)	1.27	5.08	2.54	3.81	1.27	2.54	3.81	5.08
	Frequency	20	10	20	15	35	25	20	20
	r^2	0.97	0.98	0.95	0.96	0.92	0.97	0.95	0.98
	Maximum Camera Acceleration (m/s ²)	11.48	8.40	17.65	15.74	28.80	25.23	25.82	39.79
	Maximum Sensor Acceleration (m/s ²)	10.37	8.74	16.93	15.93	28.96	25.09	26.75	39.17
	Maximum Acceleration Percent Error (%)	9.61	4.01	4.01	3.21	3.81	2.62	3.62	2.95
	Minimum Camera Acceleration (m/s ²)	-11.48	-8.40	-17.65	-16.44	-28.80	-25.23	-25.82	-40.73
	Minimum Sensor Acceleration (m/s ²)	-10.37	-9.05	-16.93	-16.02	-28.96	-25.09	-26.50	-39.17
	Minimum Acceleration Percent Error (%)	9.61	7.77	4.01	2.54	3.81	2.62	3.30	3.77
Y	Displacement (mm)	1.27	5.08	2.54	3.81	1.27	2.54	3.81	5.08
	Frequency	20	10	20	15	35	25	20	20
	r^2	0.98	0.99	0.92	0.96	0.95	0.96	0.98	0.99
	Maximum Camera Acceleration (m/s ²)	10.42	9.90	20.33	15.38	29.49	32.30	27.88	40.40
	Maximum Sensor Acceleration (m/s ²)	10.54	9.47	18.76	17.00	29.00	29.06	28.21	36.69
	Maximum Acceleration Percent Error (%)	4.53	4.42	7.72	10.55	1.61	9.99	2.13	9.16
	Minimum Camera Acceleration (m/s ²)	-10.42	-9.90	-20.33	-15.48	-29.49	-32.30	-27.88	-40.40
	Minimum Sensor Acceleration (m/s ²)	-10.54	-9.58	-18.76	-17.18	-29.00	-29.06	-28.21	-36.69
	Minimum Acceleration Percent Error (%)	4.53	3.28	7.72	10.97	1.61	9.99	2.13	9.16
Z	Displacement (mm)	1.27	5.08	2.54	3.81	1.27	2.54	3.81	5.08
	Frequency	20	10	20	15	35	25	20	20
	r^2	0.92	1.00	0.99	0.99	0.98	0.94	0.99	0.98
	Maximum Camera Acceleration (m/s ²)	12.07	8.28	20.10	17.90	51.58	29.18	27.35	36.05
	Maximum Sensor Acceleration (m/s ²)	11.54	8.15	19.08	16.63	45.63	30.48	26.51	33.23
	Maximum Acceleration Percent Error (%)	4.37	4.20	5.07	7.09	11.46	4.77	3.07	7.82
	Minimum Camera Acceleration (m/s ²)	-12.07	-8.29	-20.10	-18.24	-51.58	-29.18	-27.35	-36.05
	Minimum Sensor Acceleration (m/s ²)	-11.54	-8.32	-19.08	-16.85	-45.63	-30.48	-26.51	-33.23
	Minimum Acceleration Percent Error (%)	4.37	5.01	5.07	7.62	11.46	4.77	3.07	7.82

The effects of using VICON™ in addition to the known VTM settings was visually assessed, an example of which is shown in Figure 3-5. As can be seen in the figure, there is a slight phase lag between the VTM and the SPT, while the SPT and VICON™ data are well aligned and no apparent phase lag.

Figure 3-5: Based on All-American vibration fatigue testing machine settings at a peak-to-peak displacement of 3.81mm and frequency setting of 15 Hz the expected acceleration profile is shown (VTM) alongside the accelerations determined using the seat-pad transducer (SPT) and VICON™.

There was minimal cross-talk encountered in the SPT (Figure 3-6). Similar results were found across the various translational accelerations and angular velocities used to calibrate the SPT and to verify the calibration.

Figure 3-6: A sample of raw voltages recorded for single axis excitement. The axis excited (X-axis, Y-axis, Z-axis, Pitch, Roll or Yaw) have been identified on the corresponding graph. Figures demonstrate that for peak translational accelerations of 4 m/s^2 at 5 Hz and angular velocities of $40^\circ/\text{s}$ at 2 Hz the sensor produced minimal cross-talk. The results demonstrated were consistent among other translational acceleration and angular velocity inputs tested for the SPT during calibration and verification steps.

3.4 DISCUSSION

The LG calibration method produced near perfect calibrations which held throughout the expected field range as shown through the HG data verification (Table 3-5). The errors encountered in the LG and HG acceleration values showed no apparent trends based on frequency or displacement (Table 3-5). The errors shown in Table 3-5 were minimized by the use of VICON™ double differentiated accelerations, as the VTM accelerations was shown (Figure 3-5) to introduce a phase lag between the VTM and the VICON™ and SPT accelerations. In the interest of keeping the required calibration time minimized, the VTM was not calibrated. The calibration method being developed is more widely applicable when requiring any vibration table alongside an optical measurement system. Because the VTM was not calibrated, the accuracy of analog frequency settings and displacements were not validated. This is likely the reason for part of the phase lag between the VTM and SPT data shown in Figure 3-5. The VTM data (Figure 3-5) was determined using the manual settings (peak-to-peak displacement and frequency) to determine the expected acceleration of the VTM. This is also why the VTM data was not included in the calibration verification process and why the VICON™ Motion Capture System was used.

The VICON™ motion capture system is not without issues. It has been noted that any measurement error in 3-D marker coordinates may propagate unpredictably (Chiari *et al.*, 2005). For example, the double differentiation may have also introduced high frequency errors which result from small errors in displacement data (Robertson & Caldwell, 2004). The data was low pass filtered so it is believed any error resulting from the double differentiation was minimized. The calibration data determined at LGs were applied to the SPT data, which were compared to the VICON™ data with good results. It was shown in Figure 3-5 that the VICON™ and SPT accelerations are aligned, and the results in Table 3-5 indicate that the calibration determined at the LGs was successfully applied to HG accelerations.

The findings of this study in the HG portion compare with previous literature which found the difference between the VICON™ measurements and accelerometer data to be less than 5% absolute error for displacements greater than 1 mm for frequencies between 3 and 30 Hz (Jack *et al.*, 2005). This error value does not seem unreasonable, as they are extremely small and fast motions (i.e., 1mm at 30 Hz). It is also possible that the errors reported by Jack *et al.* (2005) may have resulted from the double differentiation (Robertson & Caldwell, 2004).

The purpose of the work was to provide a simple and reasonably fast calibration procedure and the procedure presented adhered to both constraints. In the future a multiple resolution cross correlation technique (Jack *et al.*, 2007) could be used to ensure the data was lined up with the utmost accuracy and to quicken the data alignment portion of the procedure. Other studies which have utilized a robot to calibrate accelerometers have relied on complex mathematical analyses. Renk *et al.* (2005) developed a kinematic model which could be used by a 6-DOF robot arm to calibrate accelerometers. Kinematic model development required detailed math, whereas the PRSCO 6-DOF robot utilized in the current study requires simple sinusoidal equations and integration techniques. Others have reported instances where 6 (Padgaonkar *et al.*, 1975) or 9 (Mital & King, 1979; Padgaonkar *et al.*, 1975) linear accelerometer sensors to quantify 6-DOF movements in the field of biomechanics kinematic measurements. The calibration of these sensors requires the use of more complex mathematics than those required by the sensor and calibration procedure presented in this paper. The method outlined in the current paper can be used for WBV transducer calibration, as well as for almost any sensor measuring translational or rotational displacements, velocities, accelerations or jerk.

In addition to the ease at which this calibration can be completed, the incorporation of the VTM for validation allows for comparisons between the sensor and VICON™ at various frequencies and displacements exceeding those which the PRSCO robot is capable. The inclusion of a dynamic

calibration allows for more data points to be added to the data set. The increased number of data point is likely to increase the accuracy of the calibration equation when compared to a simple static calibration procedure alone. In this case, the calibration verification was quick with more emphasis being placed on the relationship of the results from the VICON™ double differentiated displacements and SPT accelerations. The intent of the inclusion of the HG data verification was included to confirm that the calibration determined easily at LG values did hold throughout the expected field testing range.

The methods outlined in this paper required little time, approximately three hours for the LG and five for the HG calibrations, including VICON™ set-up and calibration. The data processing took approximately 15 hours. Thus, a comprehensive calibration using a wide range of accelerations and angular rotations for a 6-DOF motion sensor may be performed in a reasonable amount of time by using the methods outlined in this paper.

3.5 CONCLUSIONS

This study described a method for calibrating multi-DOF sensors. The sensor calibrated in this study employed linear ($y=mx$) calibration equations with r^2 values greater than 0.97 for accelerations up to 8m/s^2 and velocities up to $100^\circ/\text{s}$. These calibrations in the translational axes were shown to hold for accelerations up to approximately 4 g. Thus, the calibration procedures have been shown to calibrate the SPT sensor through the expected range for 6-DOF WBV field measurements.

3.6 REFERENCES

Boileau P-E, Rakheja S. 1990. Vibration attenuation performance of suspension seats for off-road forestry vehicles. *International Journal of Industrial Ergonomics*, 5; 275-91.

Chiari L, Della Croce U, Leardini A, Cappozzo A. 2005. Human movement analysis using stereophotogrammetry Part 2: Instrumental errors. *Gait and Posture*, 21; 197-211.

Golsse J-M, Hope PA. 1987. Analysis of whole-body vibration levels during skidding. Forest Engineering Research Institute of Canada (FERIC). Technical Report No. TR-77.

Golsse J-M. 1989. Analysis of whole-body vibration levels during site preparation. Forest Engineering Research Institute of Canada (FERIC). Technical Report No. TR-90.

Griffin MJ. 1990. The handbook of human vibration. London: Academic Press.

ISO, 1997. ISO 2631-1: Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1: General requirements. International Organization for Standardization.

Jack RJ, Oliver M, Dony R. 2007. Alignment of 6-DOF Whole-Body Vibration Data. Proceedings of the 30th Canadian Medical and Biological Engineering Conference: Improving Medical Device Usability. June 16-19, Toronto, Ontario, Canada.

Jack, R., Oliver, M. and Hayward, G. 2005. Validation of the VICON™ 460 motion capture system for whole-body vibration acceleration determination. XXth Congress of the International Society of Biomechanics and 29th Annual Meeting of the American Society of Biomechanics. July 31 - Aug 5, Cleveland, Ohio.

Kumar S. 2004. Vibration in operating heavy haul trucks in overburden mining. Applied Ergonomics, 35; 509-20.

Mital NK, King AI. 1979. Computation of rigid-body rotation in three-dimensional space from body-fixed linear acceleration measurements. Journal of Applied Mechanics, 46; 925-30.

Nigg BM, Cole GK, Wright IC. 2007. Optical Methods, In: Nigg BM, Herzog W (Eds), Biomechanics of the musculo-skeletal system 3rd edition. John Wiley & Sons Inc., pp. 362-91.

Padgaonkar AJ, Krieger KW, King AI. 1975. Measurement of angular acceleration of a rigid body using linear accelerometers. Transactions of the ASME, SEPT; 552-6.

Renk EL, Collins W, Rizzo M, Lee F, Bernstein DS. 2005. Calibrating a triaxial accelerometer-magnetometer. IEEE Control Systems Magazine, DEC; 86-95.

Robertson GE, Caldwell GE. 2004. Planar Kinematics. In: Robertson GE, Caldwell GE, Hamill J, Kamen G, Whittlesey SN, Research Methods in Biomechanics. Human Kinetics, Windsor, Ontario, Canada.

Chapter 4: SIX DEGREE OF FREEDOM WHOLE-BODY VIBRATION DURING FORESTRY SKIDDER OPERATIONS

At the time of defence, this chapter has been submitted to the International Journal of Industrial Ergonomics and has undergone peer review.

The Author list appearing on the submitted article is as follows:

Sarah Cation¹, Robert Jack^{1,2}, Michele Oliver^{1,2}, James P. Dickey^{2,3}, Natasha K. Lee-Shee³

¹School of Engineering, University of Guelph, Ontario, Canada

²Biophysics Interdepartmental Group, University of Guelph, Ontario, Canada

³Human Health and Nutritional Sciences, University of Guelph, Ontario, Canada

4.1 INTRODUCTION

Whole-body vibration (WBV) exposure has been associated with a variety of ailments affecting a number of body systems and processes such as the spine, reproductive organs, digestive tract, vestibular system, circulatory system and nervous system (Griffin, 1990; Seidel, 1993; Seidel and Heide, 1986; Pope *et al.*, 2002). A number of factors are known to exacerbate the effects of WBV exposure such as long working hours, rough terrain, driving speed and vehicle design (Golsse, 1989; Golsse & Hope, 1987). Amongst mobile off-road forestry machines, skidder operators may be exposed to the most extreme WBV levels primarily as a result of relatively high speed travel along rough terrain (Golsse and Hope, 1987). The two most common skidders utilized in the forest industry are grapple and cable skidders. Grapple skidders use a grapple to secure and drag trees to a drop site whereas cable skidders require the operator to leave the skidder cab, attach a cable to the tree and then resume driving.

In skidders and other off-road mobile heavy equipment, WBV is transmitted to the operator through the chassis/feet, seat/buttock, seat/back (ISO, 1997) and controller/hand interfaces. Due to the widely reported association between WBV and spine related ailments, heavy equipment seats are designed to reduce WBV at the operator/seat interface (OSI). While on-road vehicle designers need to be concerned with primarily vertical or Z-axis WBV, off-road vehicles, and in particular, skidders, are exposed to six degree of freedom (6-DOF) vibration which includes the three translational (X, Y, Z) and three rotational (Roll, Pitch, Yaw) axes. Previous skidder studies have quantified field values for translational accelerations (Golsse and Hope, 1987; Golsse, 1989; Wegscheid, 1994; Neitzel and Yost, 2003). There are, however, no reports of rotational or 6-DOF acceleration levels. There are no skidder studies which involved simultaneous chassis and OSI acceleration measurements, with the exception of Golsse (1989) assessed concomitant triaxial (X, Y, Z) OSI and chassis Z-axis accelerations. To determine if the seat is attenuating the WBV, one needs

to have simultaneous measures of both the chassis and the seat accelerations for all vibration axes. Therefore, the first purpose of this chapter was to quantify OSI and chassis 6-DOF accelerations during driving tasks in Northern Ontario forestry skidders. The exposures were quantified using unweighted as well as ISO 2631-1:1997 standard weighted accelerations. The second purpose was to assess potential health risks as well as to predict comfort ratings using ISO 2631-1:1997. The third purpose of this study was to assess the influence of Driving Condition (Driving Loaded vs. Driving Unloaded), Measurement Location (Chassis vs. OSI) and Axis (X, Y, Z and Roll, Pitch, Yaw) on ISO weighted accelerations.

The data provided by this study will be useful to forest machine and heavy equipment seat designers. Field profiles developed from this data set are being used in 6-DOF robot laboratory studies to assess the ability of current and future seat designs to attenuate 6-DOF WBV as well as to develop new biodynamic measures of seat effectiveness.

4.2 METHODOLOGY

Simultaneous measures of 6-DOF acceleration from the OSI and the chassis were determined for seven skidders operating in Northern Ontario boreal forest conditions during the months of June and July 2006. The data were collected during skidder operations under actual working conditions.

4.2.1 Six Degree of Freedom Measurement

Data were collected using two separate transducers and data acquisition systems (details are provided in the sections below). One transducer was encased in a seat-pad and measured the vibration at the OSI while the other transducer simultaneously measured vibration at the skidder chassis.

4.2.1.1 The Seat-Pad Transducer

Two ADXL320EB dual axis accelerometers (Analog Devices Inc., MA, USA) and three ADXRS150EB gyroscopes (Analog Devices Inc., MA, USA) were orthogonally placed in a Delrin™ plastic casing. Electrical tape was used to protect the individual transducers while in the field (Figure 4-1a). A metal protective plate was used to keep the Delrin™ case in place during testing and to protect the transducer from the operator. The accelerometers were used to measure linear accelerations in the X, Y and Z axes, while the gyroscopes monitored angular velocity in Pitch (rotation about the Y-axis), Roll (rotation about the X-axis) and Yaw (rotation about the Z-axis). The seat-pad transducer, including the metal protective plate, Delrin™ and rubber casing and cables as used in the field weighed approximately 670 grams with a maximum thickness of 29.3 mm (Figure 4-1b). The assembled seat-pad transducer (Figure 4-2) was placed on the seat as it was designed for comfort and durability underneath the load of a person to capture accelerations at the OSI. Raw voltages were collected using a 12-bit SOMAT™ Series 2100 Field computer (nCode International Inc., Michigan, USA).

The data acquisition system was calibrated as outlined by Cation *et al.* (2006). The transducer was placed on a 6-DOF robot (Parallel Robotics System Corporation, NH, USA) and known sinusoidal displacement profiles were used to dictate the motion of the robot. Displacement profiles used for calibration of the accelerometers were between peak accelerations of 1 and 8 m/s² at frequencies between 1 and 5 Hz. The gyroscopes were calibrated using displacement profiles which produced peak velocities between 10 and 100 °/s at frequencies between 0.5 and 5 Hz. The linear calibration equations for the seat pad transducer provided r^2 values greater than 0.997 for all 6-DOF (Cation *et al.*, 2006).

Figure 4-1:a) The six degree of freedom seat-pad transducer without the rubber cushion measuring (A) 80.5mm by (B) 81.0mm with a thickness of (C) 26.2mm b) The seat-pad transducer has a minimum thickness of 17.2mm at the edge (D) and a constant thickness of 29.3mm across the centre metal protective plate (E). The metal protective plate has a radius of 58.8mm (F) while the radius of the seat-pad transducer is 125.1mm (G).

Figure 4-2: The six degree of freedom seat-pad transducer as used in the field. The transducer sat on the operator seat between the skidder seat and the operator measuring the accelerations present at the operator/seat interface (OSI).

4.2.1.2 The Chassis Transducer

A MEMSense 6-DOF sensor (MEMSense, SD, USA) 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. Including the casing, cabling and magnets, the chassis transducer weighed approximately 635 grams and was 47.0 mm thick (Figure 4-3). Raw voltages from the MEMSense transducer were collected using a 13-bit Biometrics Ltd. DataLOG No.P3X8 USB (Biometrics, VA, USA) data logger. The chassis transducer (Figure 4-4) was mounted such that it did not interfere with the skidder operator during his work activities. Using the calibration techniques described in section 4.2.1.1, the calibration equations of the chassis transducer were determined, with r^2 values greater than 0.999 for all 6-DOF.

Figure 4-3: The six degree of freedom chassis transducer measuring a) 119.5mm by b) 64.5mm with a thickness of c) 47.0mm which includes the magnets used to attach the sensor during testing.

Figure 4-4: The six degree of freedom chassis transducer affixed to a rigid portion of the chassis which supports the operator seat of a skidder during field testing.

4.3 Field Data Collection Methodology

Approval to conduct this study was obtained prior to data collection from the University of Guelph Ethics Committee. The seat-pad transducer (sampling frequency; $f_s = 500$ Hz) was placed on the skidder seats as shown in Figure 4-2. The chassis transducer ($f_s = 500$ Hz) was attached to the chassis, where the chassis was defined as the floor including the rigid seat mount, such as that shown in Figure 4-4. A Sony DCR-PC 109 digital video camera (Sony Corporation, Shinagawa, Tokyo, Japan) mounted in the skidder cabs (Figure 4-5) was used to determine when the skidder was being driven loaded (DL) or unloaded (DUL). Operators performed their normal daily activities during testing. Approximately 40 continuous minutes of data were collected from each skidder to be processed and further divided into DL or DUL tasks. Driving routes varied for each skidder with the exception of skidder 7 where the same route was repeated for each trial.

Figure 4-5: The Sony DCR-PC 109 digital video camera shown mounted in the skidder cab which was used to determine when the skidder was being driven loaded and unloaded during field testing.

4.3.1 Data Analysis Procedures

The calibration equations were applied to the data sets collected from the two 6-DOF transducers. The data sets from the two sensors were then aligned using a previously validated multiple resolution cross correlation technique (Jack *et al.*, 2007). The data were then categorized into DL and DUL operating conditions shown in Figure 4-6 and Figure 4-7 respectively.

Figure 4-6: A skidder driving unloaded (DUL) after dropping off a load at a pile

Figure 4-7: Skidder driving loaded (DL) about to drop its load at the drop site

4.3.1.1 Initial Data Analysis

The reported weighted values were determined using the Vibratools™ software package (Axiom EduTech, Ljusterö, Sweden) in Matlab™ (The Mathworks Inc., MA, USA). The weighted chassis and OSI accelerations were Butterworth band-pass filtered from 0.4-100 Hz in accordance

with ISO 2631-1:1997. Prior to acceleration weighting, the raw rotation velocities were band-pass filtered at 0.4 -100 Hz to remove high frequency noise before differentiating the velocities into the reported acceleration form.

Peak accelerations, running root mean squared (RMS) accelerations and crest factors (CFs) were then determined for each skidder trial recorded using a MATLAB™ routine. Peak accelerations were determined by full wave rectifying the data and determining the largest recorded weighted acceleration value. The running RMS accelerations were determined using 1-second central window averaging. The overall running RMS accelerations were determined for all skidders in all 6-DOF for both driving conditions. The crest factors were determined by dividing the peak weighted accelerations by the running RMS accelerations for each trial. Initial determination of the CFs using a simple RMS acceleration value generated some CFs which were considered high (i.e., exceeding 9.0), thus ISO 2631-1:1997 recommendations were adhered to in which a running RMS acceleration is suggested. The running RMS accelerations are reported and subsequently used for the calculation of the reported CFs. The averages for running RMS acceleration and peak acceleration were determined across all skidders for each driving condition at each measurement location to ensure that one trial did not have more influence than others. The number of trials recorded varied between skidders and driving conditions (skidder 1 DL n= 4, DUL n=4; skidder 2 DL n=2, DUL n=3; skidder 3 DL n=1, DUL n=2; skidder 4 DL n=10, DUL n=11; skidder 5 DL n=19, DUL n=11; skidder 6 DL n=6, DUL n=6; skidder 7 DL n=4, DUL n=3). Skidders which incurred running RMS accelerations in excess of three standard deviations above the overall average of all skidders were considered outliers and were not included in the averaging process. Accordingly, data from skidder 1 while DUL at the OSI were not included in the overall averaging for peak and running RMS accelerations as well as CFs.

The vibration total value (a_v) was calculated for the vector sum of the translational axes as outlined by ISO 2631-1:1997 as shown in Eq. 1:

$$a_v = (k_x^2 a_x^2 + k_y^2 a_y^2 + k_z^2 a_z^2)^{1/2} \quad \text{Eq. 1}$$

Where a is the weighted acceleration in the respective axis and k is the unitless multiplying factor (ISO, 1997). When quantifying a_v for comfort, $k=1$ for all translational axes whereas when quantifying a_v for health effects, $k=1.4$ for X- and Y-axes and $k=1$ for the Z-axis (ISO, 1997). The total vibration value shown in Eq. 1 was then expanded to include all 6-DOF as shown in Eq. 2:

$$a_v = (k_x^2 a_x^2 + k_y^2 a_y^2 + k_z^2 a_z^2 + k_{rx}^2 a_{rx}^2 + k_{ry}^2 a_{ry}^2 + k_{rz}^2 a_{rz}^2)^{1/2} \quad \text{Eq. 2}$$

Where a is the weighted accelerations in the various 6-DOF and the multiplying factor is one for the translational axes and 0.63 rad/m in Roll (k_{rx}), 0.4 rad/m in Pitch (k_{ry}) and 0.2 rad/m in Yaw (k_{rz}) (ISO,1997). The calculated vibration total values were then compared to the upper and lower exposure limits of the ISO 2631-1:1997 health guidance caution zones, to determine the potential health risks. The expected comfort ratings for the OSI alone were also determined from the translational vibration total value using the ISO 2631-1:1997 guide to comfort reactions due to vibration environments. The ISO comfort reaction guide is used to indicate the expected range of comfort for the vibration exposure. The ISO comfort guide is contained in Appendix C of the ISO 2631-1:1997 standard and states that in vibration environments, comfort reactions for accelerations between $0.8\text{-}1.6\text{m/s}^2$ are uncomfortable in nature while those between $1.25\text{-}2.5\text{ m/s}^2$ are very uncomfortable (ISO, 1997).

4.3.1.2 Frequency Analysis

Vibratools™ software in MATLAB™ was used to analyze the field profiles of seven skidders into 1/3- octave band frequency bins with centre frequencies ranging between 0.1 and 40 Hz. The frequency analyses were completed for both driving conditions and both measurement locations using only the ISO 2631-1:1997 weighted accelerations. The frequency bins contained the magnitude of the RMS accelerations presented for each frequency bin. The dominant frequency was determined by identifying the frequency bin at which the maximum weighted RMS acceleration occurred. The average exposures for each measurement location (OSI, Chassis) and each driving condition (DL, DUL) were then determined by averaging the weighted RMS accelerations for each frequency bin together. The frequency at which the maximum weighted RMS acceleration occurred for each axis of exposure was determined to be the dominant exposure frequency for that axis. This analysis was repeated for each of the seven skidders. The overall frequency analysis was completed for an average of all seven skidders by averaging the spectrum for each skidder at all frequency bins in the range and reported graphically.

4.3.1.3 Statistical Analyses

Statistical analyses were performed to determine how the four response (dependent) variables (translational dominant frequency ISO 2631-1:1997 weighted RMS acceleration (WRMSADF), rotational WRMSADF, translational running ISO 2631-1:1997 weighted RMS acceleration (RWRMSA), and rotational RWRMSA) changed with the independent variables (Driving Condition-DL, DUL; Measurement Location-Chassis, OSI; Axis-X, Y, Z or Roll, Pitch, Yaw). For each of the response variables the ANOVA model was as follows:

$$\begin{aligned} \text{Response} = & \text{Skidder} + \text{Driving Condition} + \text{Measurement Location} \\ & + \text{Axis} + \text{Two-way Interactions} + \text{Three-way Interactions} + \text{Error} \end{aligned}$$

Skidder was included in the statistical model as a random effect according to Oliver *et al.* (2006). Separate ANOVAs were run on the translational and rotational axes as a result of differing units in the response variables between the translational and rotational axes. The dependent variable Axis was comprised of X, Y, and Z for the WRMSADF and RWRMSA translational response variables, whereas Axis consisted of Roll, Pitch and Yaw for the rotational WRMSDF and rotational RWRMSA variables.

For the individual ANOVAs, when appropriate, differences between means were assessed using a Bonferroni (Dunn) t-test post-hoc procedure. The alpha level required to declare a significant difference between means was set at $p \leq 0.05$. All statistical analyses were performed using Minitab™ 15 (Minitab, State College, PA, USA).

4.3.2 Skidder and Operator Characteristics

Skidders varied in make and model. For each skidder, the operator (who completes the maintenance) reported tire pressure and maintenance history. The experimenters then measured and recorded seat height and orientation (Table 4-1). The chassis sensor was oriented with the direction of travel as shown in Figure 4-8a while the OSI sensor was placed on the seat in a basicentric orientation, in accordance with ISO 2631-1:1997, as shown in Figure 4-8b. The seat orientation offsets were measured in the X-Y plane.

Table 4-1: Skidder characteristics including seat orientation offset in the X-Y plane, grapple/cable design, operator reported maintenance histories and operator reported tire pressures.

Skidder Number	1	2	3	4	5	6	7
Grapple/Cable	Grapple	Grapple	Grapple	Grapple	Grapple	Grapple	Cable
Seat Orientation (degrees)	0	25	15	10	10	25	0
Seat Height (cm)	48.5	58	55	45	45	unknown	47
Operator Reported Maintenance History	Greased every other day, oil change every 500 hrs.	Greased every other day, oil change every 250 hrs.	Greased each day, oil changed each month	Lube each day, oil changed every 500 hrs.	Greased each day, oil changed every 200 hrs.	Greased at noon, oil changed every 150-200 hrs. and clean filters based on dust at location (either every other day or once per week)	Oil changed every month, fluid checked daily, greased every other day
Operator Reported Tire Pressure (psi)	35	45	33.5	25	32-35	45	30

Figure 4-8: The orientation of the chassis transducer a) and the orientation of the measurements recorded at the operator/seat interface (OSI) b).

Testing locations and terrain varied within and between skidders (Table 4-2). The locations were chosen based on available skidders and operators. The weather conditions were fairly similar for all testing dates and locations (sunny and hot with a slight wind).

Table 4-2: General terrain descriptions associated with each skidder included in the field testing

Skidder Number	Land Description	Ground Description	Tree Description
1 and 2	Large hills	Rocky with loose loam ground	Most trees already cleared
3	Flood bed with small rolling hills	Sandy loam	Most trees remained standing
4 to 6	Steep Rolling hills	Sandy soil with gravel	Most trees already cleared
7	Small rock outcrops on steep rolling hills	Clay soil with gravel and large rocks	Most trees already cleared

After providing informed consent, seven male subjects (mean $\pm$ standard deviation; age: 40.4 ± 10.3 years, mass: 97.8 ± 25.9 kg, height: 179.3 ± 6.0 cm) volunteered to participate. The skidder operators had an average of 19.5 ± 14.0 years experience operating skidders and 21.1 ± 11.9 years operating other forms of industrial mobile machinery such as delimbers, excavators and loaders. Prior to data collection, operator reported pain was recorded using severity weightings between 1 and 5, with 5 being the most severe pain (Table 4-3) through a questionnaire using an interview-style technique by one of the researchers. The same researcher conducted all of the operator interviews.

Table 4-3: Operator reported pain outlined by body region and last reported episode. The lack of a numerical value infers that there was no pain associated with that region for that skidder operator. The pain scale was reported within a range of “1-5”, with “5” being the most severe pain

Body Region	Skidder Number						
	1	2	3	4	5	6	7
Neck	2	-	-	1	1	-	-
Last Reported Episode	1-2 Weeks	-	-	Everyday	Everyday	-	-
Shoulder	-	-	2	-	-	-	-
Last Reported Episode	-	-	Everyday	-	-	-	-
Upper Back	-	-	-	-	-	-	-
Last Reported Episode	-	-	-	-	-	-	-
Elbows	-	-	-	-	-	-	-
Last Reported Episode	-	-	-	-	-	-	-
Lower Back	3	3	-	-	-	-	-
Last Reported Episode	1-6 Months	1-2 Weeks	-	-	-	-	-
Wrists/Hands	-	-	2	-	-	-	-
Last Reported Episode	-	-	Everyday	-	-	-	-
Hips/Thighs/Buttocks	-	-	-	1	-	-	-
Last Reported Episode	-	-	-	Everyday	-	-	-
Knees	-	-	2	-	-	2	-
Last Reported Episode	-	-	Everyday	-	-	Everyday	-
Ankles/Feet	-	-	2	-	2	2	-
Last Reported Episode	-	-	Everyday	-	Not Reported	Everyday	-

4.4 RESULTS

Tables 4-4 through 4-6 provide means and standard deviations for the ISO 2631-1:1997 weighted and unweighted running RMS accelerations, peak accelerations and CFs respectively. The dominant frequency bins and corresponding WRMSADF overall averages are shown in Table 4-7 alongside the overall RWRMSA averages. The vibration total values for the translational and 6-DOF are shown in Table 4-8 alongside the ISO 2631-1:1997 comfort reactions. Summaries of statistically significant effects for the ANOVAs are provided in Table 4-9 (main effects) and Table 4-10 (interactions). Figure 4-9 and Figure 4-10 provide an illustration of the weighted and unweighted running RMS accelerations while Figure 4-11 and Figure 4-12 show the average frequency spectra of weighted RMS accelerations at both the OSI and chassis while DUL and DL. Figure 4-13 and Figure

4-14 provide a graphical illustration of the significant two-way interactions determined from by the ANOVA procedures.

From Table 4-4, it is evident based on ISO 2631-1:1997, that RWRMSA for all 6-DOF are greater at the OSI than the Chassis. As well, the RWRMSA while DUL are greater than those while DL when comparing the OSI DUL to the OSI DL and Chassis DUL to Chassis DUL. This is not always the case when analyzing the unweighted running RMS accelerations also shown in Table 4-4. Skidder 1 incurred larger (in excess of 3 standard deviations) running unweighted RMS accelerations at the OSI while DUL (Figure 4-9 & Figure 4-10) and as a result was eliminated from the overall averaging for the running RMS accelerations, peak accelerations and CFs in both the weighted and unweighted form at the OSI while DUL. The ISO 2631-1:1997 weighted peak acceleration averages were greater at the OSI than the chassis in all 6-DOF except the Z-axis, however, this was not the case with each individual skidder or the averages in unweighted form (Table 4-5). The CFs did not display similar results to the peak and running weighted RMS accelerations (Table 4-6).

Table 4-4: The ISO 2631-1:1997 weighted running root mean squared (RMS) accelerations (RWRMSA) determined while driving loaded (DL) and driving unloaded (DUL) at the chassis and operator/seat interface (OSI) for each skidder as well as the overall averages while driving loaded for each skidder. The overall averages $\pm$ standard deviation (sd) across all skidders are reported also reported in weighted form as well as unweighted form

Skidder	Driving Condition	Measurement Location	Axis of Measurement					
			X (m/s ²)	Y (m/s ²)	Z (m/s ²)	Roll (rad/s ²)	Pitch (rad/s ²)	Yaw (rad/s ²)
1 WEIGHTED	DL	Chassis	0.65	0.70	0.41	0.28	0.20	0.21
		OSI	0.56	0.68	0.55	0.46	0.44	0.19
	DUL	Chassis	0.68	0.70	0.43	0.29	0.21	0.21
		OSI	0.66	0.84	0.65	0.56	0.45	0.23
2 WEIGHTED	DL	Chassis	0.52	0.56	0.42	0.20	0.15	0.27
		OSI	0.62	0.83	0.42	0.84	0.52	0.37
	DUL	Chassis	0.56	0.54	0.43	0.21	0.17	0.26
		OSI	0.71	0.74	0.46	0.77	0.62	0.31
3 WEIGHTED	DL	Chassis	0.43	0.58	0.29	0.21	0.16	0.20
		OSI	0.45	0.68	0.38	0.01	0.40	0.22
	DUL	Chassis	0.83	0.73	0.50	0.28	0.27	0.25
		OSI	0.86	0.83	0.61	0.01	0.73	0.29
4 WEIGHTED	DL	Chassis	0.94	1.29	0.91	0.60	0.35	0.39
		OSI	0.96	1.40	0.88	1.08	0.66	0.51
	DUL	Chassis	1.00	1.23	0.86	0.58	0.36	0.36
		OSI	1.02	1.32	0.82	1.05	0.70	0.49
5 WEIGHTED	DL	Chassis	0.66	0.76	0.73	0.35	0.27	0.24
		OSI	0.70	0.91	0.81	0.71	0.43	0.32
	DUL	Chassis	0.84	1.11	0.83	0.52	0.35	0.30
		OSI	0.89	1.28	0.88	0.99	0.55	0.39
6 WEIGHTED	DL	Chassis	0.53	0.78	0.54	0.31	0.28	0.24
		OSI	0.75	0.86	0.69	0.49	0.39	0.25
	DUL	Chassis	0.60	0.98	0.63	0.43	0.38	0.26
		OSI	0.93	1.10	0.79	0.60	0.53	0.27
7 WEIGHTED	DL	Chassis	0.54	0.74	0.52	0.36	0.25	0.24
		OSI	0.58	0.92	0.47	0.44	0.42	0.21
	DUL	Chassis	0.60	0.93	0.60	0.43	0.29	0.26
		OSI	0.67	1.14	0.53	0.52	0.50	0.22
Average $\pm$ sd WEIGHTED	DL	Chassis	0.68	0.86	0.68	0.38	0.28	0.27
			± 0.18	± 0.27	± 0.20	± 0.14	± 0.07	± 0.07
		OSI	0.72	0.96	0.72	0.69	0.47	0.33
			± 0.21	± 0.32	± 0.22	± 0.30	± 0.14	± 0.13
	DUL	Chassis	0.79	1.01	0.71	0.46	0.32	0.29
			± 0.24	± 0.33	± 0.21	± 0.17	± 0.10	± 0.08
		OSI	0.86	1.12	0.73	0.79	0.57	0.36
			± 0.27	± 0.39	± 0.23	± 0.37	± 0.17	± 0.15
Average $\pm$ sd UNWEIGHTED	DL	Chassis	1.61	1.53	1.21	3.74	3.68	3.21
			± 0.38	± 0.29	± 0.35	± 0.42	± 0.55	± 0.28
		OSI	1.62	1.89	1.29	1.81	1.61	1.41
			± 0.26	± 0.32	± 0.36	± 0.59	± 0.44	± 0.36
	DUL	Chassis	1.55	1.62	1.22	3.78	3.75	3.26
			± 0.47	± 0.43	± 0.37	± 0.43	± 0.57	± 0.39
		OSI	1.68	1.91	1.29	1.99	1.86	1.52
			± 0.30	± 0.49	± 0.35	± 0.69	± 0.45	± 0.43

Table 4-5: The ISO 2631-1:1997 weighted peak accelerations determined while driving loaded (DL) and driving unloaded (DUL) at the chassis and operator/seat interface (OSI) for each skidder as well as the overall averages while driving loaded for each skidder. The overall averages $\pm$ standard deviation (sd) across all skidders are reported also reported in weighted form as well as unweighted form.

Skidder	Driving Condition	Measurement Location	Axis of Measurement					
			X (m/s ²)	Y (m/s ²)	Z (m/s ²)	Roll (rad/s ²)	Pitch (rad/s ²)	Yaw (rad/s ²)
1 WEIGHTED	DL	Chassis	3.36	3.65	3.70	1.77	1.26	1.21
		OSI	2.59	3.09	3.84	1.84	2.41	0.97
	DUL	Chassis	4.24	4.20	5.11	2.23	1.82	1.27
		OSI	4.05	4.85	6.56	3.71	3.11	1.58
2 WEIGHTED	DL	Chassis	2.44	2.26	4.53	1.33	0.67	1.39
		OSI	2.74	3.63	2.96	3.51	2.96	2.50
	DUL	Chassis	2.76	2.57	4.22	1.24	0.97	1.20
		OSI	4.20	3.78	3.24	5.45	3.72	1.69
3 WEIGHTED	DL	Chassis	2.67	2.97	2.81	2.06	1.08	1.18
		OSI	2.80	3.98	5.85	0.03	3.20	1.33
	DUL	Chassis	3.72	4.21	7.34	1.83	1.64	1.32
		OSI	3.73	5.56	5.64	0.03	4.06	1.44
4 WEIGHTED	DL	Chassis	5.20	6.94	8.77	4.48	3.59	2.60
		OSI	6.57	7.32	6.84	6.32	5.06	3.19
	DUL	Chassis	5.26	6.38	7.33	3.69	3.19	2.42
		OSI	5.78	7.17	5.37	5.50	4.07	3.20
5 WEIGHTED	DL	Chassis	3.51	3.83	6.69	2.34	1.83	1.70
		OSI	3.47	4.37	5.02	3.75	2.56	2.17
	DUL	Chassis	4.05	5.37	6.53	3.02	2.30	1.89
		OSI	4.07	6.06	4.96	4.60	2.78	2.45
6 WEIGHTED	DL	Chassis	3.42	4.48	4.16	2.03	1.71	1.47
		OSI	3.85	5.05	6.90	2.78	2.35	1.64
	DUL	Chassis	3.72	5.30	5.28	2.92	3.01	1.64
		OSI	5.61	6.01	5.96	3.34	3.56	1.62
7 WEIGHTED	DL	Chassis	3.70	4.57	7.02	2.72	2.00	1.51
		OSI	3.92	5.11	5.03	3.04	3.40	1.27
	DUL	Chassis	4.12	5.73	12.92	3.17	2.42	1.66
		OSI	4.81	6.74	7.33	3.04	3.76	1.74
Average $\pm$ sd WEIGHTED	DL	Chassis	3.80	4.55	6.40	2.70	2.09	1.78
			± 1.13	± 1.68	± 2.40	± 1.28	± 1.03	± 0.63
		OSI	4.11	5.02	5.49	3.86	3.17	2.14
			± 1.89	± 1.84	± 2.20	± 1.83	± 1.56	± 0.85
	DUL	Chassis	4.24	5.28	6.77	2.93	2.48	1.84
			± 1.39	± 2.04	± 3.19	± 1.24	± 1.19	± 0.72
		OSI	4.90	6.23	5.34	4.35	3.54	2.36
			± 1.63	± 2.33	± 1.64	± 2.18	± 1.11	± 1.06
Average $\pm$ sd UNWEIGHTED	DL	Chassis	13.94	13.16	13.25	59.43	54.78	39.46
			± 6.09	± 6.19	± 6.04	± 36.91	± 32.37	± 23.35
		OSI	10.90	10.74	8.97	14.27	15.42	16.99
			± 5.41	± 2.99	± 3.40	± 6.74	± 6.67	± 8.67
	DUL	Chassis	13.00	14.14	13.52	60.26	63.87	44.46
			± 6.93	± 7.54	± 5.98	± 32.75	± 52.05	± 37.30
		OSI	11.73	12.26	8.75	16.14	17.83	16.63
			± 4.45	± 4.78	± 3.16	± 8.32	± 6.95	± 8.73

Table 4-6: Crest factors determined while driving loaded (DL) and driving unloaded (DUL) at the chassis and operator/seat interface (OSI) for each skidder as well as the overall averages while driving loaded for each skidder. The overall averages $\pm$ standard deviation (sd) across all skidders are reported also reported in weighted form

Skidder	Driving Condition	Measurement		Axis of Measurement				
		Location	X	Y	Z	Roll	Pitch	Yaw
1 WEIGHTED	DL	Chassis	5.16	5.29	8.94	6.58	6.25	5.68
		OSI	4.35	4.66	5.99	4.09	5.28	4.53
	DUL	Chassis	6.23	5.97	11.64	7.70	8.50	5.99
		OSI	6.12	5.76	9.69	6.54	6.85	6.81
2 WEIGHTED	DL	Chassis	4.73	4.13	10.88	6.60	4.36	5.43
		OSI	4.41	4.50	7.01	4.26	5.87	7.16
	DUL	Chassis	4.68	4.63	9.29	5.69	5.33	4.69
		OSI	5.51	4.99	6.85	6.61	5.69	5.08
3 WEIGHTED	DL	Chassis	6.19	5.09	9.65	9.70	6.70	5.86
		OSI	6.23	5.83	15.44	4.88	8.01	6.20
	DUL	Chassis	4.67	5.66	14.98	6.21	6.10	5.42
		OSI	4.54	6.58	8.88	4.49	5.63	4.97
4 WEIGHTED	DL	Chassis	5.59	5.39	9.68	7.53	10.13	6.64
		OSI	6.81	5.23	7.85	5.82	7.57	6.28
	DUL	Chassis	5.40	5.28	8.48	6.45	8.95	6.87
		OSI	5.78	5.45	6.60	5.29	5.87	6.72
5 WEIGHTED	DL	Chassis	5.40	5.14	9.28	6.99	6.94	7.17
		OSI	4.99	4.88	6.27	5.44	6.09	6.90
	DUL	Chassis	4.77	4.67	7.79	5.66	6.48	6.07
		OSI	4.56	4.59	5.63	4.50	4.99	5.95
6 WEIGHTED	DL	Chassis	6.52	5.68	7.58	6.43	6.09	6.04
		OSI	5.15	5.84	9.79	5.66	5.98	6.45
	DUL	Chassis	6.04	5.32	8.46	6.60	7.58	6.18
		OSI	5.89	5.40	7.52	5.53	6.69	5.91
7 WEIGHTED	DL	Chassis	6.86	6.16	13.37	7.67	7.89	6.22
		OSI	6.75	5.57	10.66	6.94	8.02	6.03
	DUL	Chassis	6.93	6.21	21.72	7.32	8.22	6.41
		OSI	7.15	5.93	13.97	5.83	7.56	7.88
Average ± sd WEIGHTED	DL	Chassis	5.68	5.32	9.55	7.10	7.43	6.59
			± 1.35	± 1.19	± 2.49	± 2.16	± 2.52	± 1.58
		OSI	5.50	5.13	7.66	5.50	6.53	6.42
			± 1.68	± 1.22	± 3.11	± 1.46	± 2.24	± 1.61
	DUL	Chassis	5.43	5.23	9.98	6.38	7.55	6.19
			± 1.30	± 1.29	± 5.11	± 1.53	± 2.86	± 1.51
		OSI	5.45	5.24	7.22	5.20	5.85	6.21
			± 1.46	± 1.33	± 2.68	± 1.43	± 1.48	± 1.81
Average ± sd UNWEIGHTED	DL	Chassis	8.54	8.70	10.92	15.43	14.23	12.05
			± 3.01	± 3.92	± 4.21	± 8.96	± 6.97	± 6.81
		OSI	6.77	5.63	6.90	7.81	9.53	11.70
			± 3.40	± 1.28	± 2.06	± 2.01	± 2.67	± 4.99
	DUL	Chassis	8.28	8.41	11.25	15.50	16.38	13.10
			± 3.41	± 3.46	± 4.54	± 7.28	± 11.85	± 9.93
		OSI	7.07	6.33	6.77	7.99	9.52	10.46
			± 2.56	± 1.70	± 1.85	± 2.82	± 2.94	± 3.62

Figure 4-9: The running RMS acceleration determined using a 1-second central running root mean squared (RMS) window. Values were determined at the Chassis and operator/seat interface (OSI) while driving loaded (DL) and driving unloaded (DUL). The ISO 2631-1:1997 standard weighted acceleration values are also shown at the OSI. Data for translational accelerations are contained in the following graphs: a) X-axis, b) Y-axis, and c) Z-axis

Figure 4-10: The running root mean squared (RMS) acceleration determined using a 1-second central running RMS window. Values were determined at the Chassis and operator/seat interface (OSI) while driving loaded (DL) and driving unloaded (DUL). The ISO 2631-1:1997 standard weighted acceleration values are also shown at the OSI. Data for rotational accelerations are contained in the following graphs: a) Roll, b) Pitch and c) Yaw.

The dominant bin centre frequency for both the OSI and chassis was 1 Hz in the X- and Y-axes, and 2 Hz in the Z-axis (Table 4-7 and Figure 4-11-Figure 4-12). Table 7 identifies the WRMSADF values for each Axis, Driving Condition and Measurement Location while Figure 4-11 and Figure 4-12 provide an illustration of the Z-axis frequency shift. In the rotational axes, the dominant bin centre frequency was determined to be between 1-1.25 Hz at the chassis and between 1-2 Hz at the OSI (Table 4-7).

Table 4-7: ISO 2631-1:1997 weighted running root mean squared (RMS) accelerations and weighted RMS accelerations at the dominant frequency bin for all six degrees of freedom (6-DOF) while driving loaded (DL) and driving unloaded (DUL) at both the chassis and the operator/seat interface (OSI) are reported as averages $\pm$ standard deviations (sd). Averages were calculated by taking the mean of the average for all seven skidders at each driving condition and measurement location for all 6-DOF. The values presented in this table were used for statistical analysis of the data collected in this study.

Axis	Driving Condition	Measurement Location	Running RMS Acceleration m/s^2 (average $\pm$ sd)	Frequency Analysis	
				Maximum Acceleration m/s^2	Frequency Bin (Hz)
X	DL	Chassis	0.61 $\pm$ 0.17	0.29 $\pm$ 0.10	1
		OSI	0.66 $\pm$ 0.17	0.29 $\pm$ 0.70	1
	DUL	Chassis	0.73 $\pm$ 0.16	0.35 $\pm$ 0.08	1
		OSI	0.82 $\pm$ 0.14	0.38 $\pm$ 0.06	1
Y	DL	Chassis	0.77 $\pm$ 0.24	0.33 $\pm$ 0.14	1
		OSI	0.90 $\pm$ 0.24	0.38 $\pm$ 0.16	1
	DUL	Chassis	0.89 $\pm$ 0.24	0.44 $\pm$ 0.13	1
		OSI	1.04 $\pm$ 0.23	0.51 $\pm$ 0.15	1
Z	DL	Chassis	0.55 $\pm$ 0.21	0.24 $\pm$ 0.10	2
		OSI	0.60 $\pm$ 0.20	0.28 $\pm$ 0.10	2
	DUL	Chassis	0.61 $\pm$ 0.18	0.25 $\pm$ 0.08	2
		OSI	0.68 $\pm$ 0.16	0.31 $\pm$ 0.07	2
Axis	Driving Condition	Measurement Location	Running RMS Acceleration rad/s^2 (average $\pm$ sd)	Frequency Analysis	
				Maximum Acceleration rad/s^2	Frequency Bin (Hz)
Roll	DL	Chassis	0.33 $\pm$ 0.13	0.15 $\pm$ 0.08	1
		OSI	0.57 $\pm$ 0.34	0.26 $\pm$ 0.15	1.25
	DUL	Chassis	0.39 $\pm$ 0.13	0.20 $\pm$ 0.07	1
		OSI	0.64 $\pm$ 0.35	0.30 $\pm$ 0.15	1
Pitch	DL	Chassis	0.24 $\pm$ 0.07	0.12 $\pm$ 0.04	1
		OSI	0.47 $\pm$ 0.10	0.21 $\pm$ 0.03	2
	DUL	Chassis	0.29 $\pm$ 0.08	0.14 $\pm$ 0.04	1.25
		OSI	0.58 $\pm$ 0.11	0.27 $\pm$ 0.04	1.25
Yaw	DL	Chassis	0.26 $\pm$ 0.06	0.11 $\pm$ 0.03	1
		OSI	0.30 $\pm$ 0.11	0.12 $\pm$ 0.05	2
	DUL	Chassis	0.27 $\pm$ 0.05	0.12 $\pm$ 0.02	1
		OSI	0.32 $\pm$ 0.10	0.14 $\pm$ 0.04	1.25

Figure 4-11: 1/3-octave band spectra for translational weighted root mean squared (RMS) accelerations for a) X-axis, b) Y-axis and c) Z-axis in frequency bins with centre frequencies between 0.1 and 40 Hz

Figure 4-12: 1/3-octave band spectrums for rotational weighted root mean squared (RMS) accelerations for a) Roll, b) Pitch and c) Yaw in frequency bins with centre frequencies between 0.1 and 40 Hz.

While DL and DUL, the vibration total value at the OSI was determined to be $1.27 \pm 0.33 \text{ m/s}^2$ and $1.53 \pm 0.28 \text{ m/s}^2$ respectively when considering only the translational axes. The expanded vibration total value, which included all 6-DOF, was $1.35 \pm 0.37 \text{ m/s}^2$ and $1.62 \pm 0.30 \text{ m/s}^2$ for DL and DUL respectively. The corresponding predicted comfort reactions (ISO, 1997) are shown in Table 4-8.

Table 4-8: Vibration total value and comfort reaction including translational axes and all six degrees of freedom (6-DOF) according to ISO 2631-1:1997 (average $\pm$ standard deviation) determined at the operator/seat interface (OSI) while driving loaded (DL) and driving unloaded (DUL).

Driving Condition	Translational a_v ($m/s^2 \pm sd$)	ISO 2631-1 (1997) Comfort Reaction	6-DOF a_v ($m/s^2 \pm sd$)	ISO 2631-1 (1997) Comfort Reaction
DUL	1.53 ± 0.28	Uncomfortable / Very Uncomfortable	1.62 ± 0.30	Very Uncomfortable
DL	1.27 ± 0.33	Uncomfortable / Very Uncomfortable	1.35 ± 0.37	Uncomfortable / Very Uncomfortable

All seven skidders were included in the ANOVA procedures with each of the four ANOVAs having r^2 values in excess of 0.99 indicating that the statistical model fit the data very well. This is somewhat surprising given that this was a field investigation conducted under normal skidder operating conditions and not in a tightly controlled laboratory or test track environment.

For each of the four response variables (Translational WRMSADF, Translational RWRMSA, Rotational WRMSADF and Rotational RWRMSA), significant main effects were observed for Driving Condition (Translational WRMSADF $p=0.012$; Translational RWRMSA $p=0.026$; Rotational WRMSADF $p=0.016$; Rotational RWRMSA $p=0.033$), Measurement Location (Translational WRMSADF $p=0.008$; Translational RWRMSA $p=0.003$; Rotational WRMSADF $p=0.011$; Rotational RWRMSA $p=0.007$), and Axis (Translational WRMSADF $p=0.001$; Translational RWRMSA $p=0.000$; Rotational WRMSADF $p=0.004$; Rotational RWRMSA $p=0.009$).

As summarized in Table 4-9, for the translational WRMSADF and RWRMSA variables, DUL resulted in significantly higher values than DL. For these same response variables, the OSI values were significantly higher than the Chassis. With respect to the Axes, Y was significantly higher than X which was significantly higher than Z.

The results obtained for the rotational axes echoed those found in the translational ones with the exception of the Axis main effect where Roll was significantly higher than Pitch which was significantly higher than Yaw for the rotational WRMSADF and RWRMSA response variables.

Table 4-9: Statistically significant results ($p \leq 0.05$) summary based on statistics calculated using dominant frequency ISO 2631-1: 1997 weighted root mean squared accelerations (WRMSADF) in the translational and rotational axes as well as using the running ISO 2631-1: 1997 weighted root mean squared accelerations (RWRMSA) also in the translational and rotational axes. The significant differences were reported for driving loaded (DL) and driving unloaded (DUL), chassis measurements and operator/seat interface (OSI) measurements as well as translational (X, Y, Z) and rotational (Roll, Pitch, Yaw) axes.

Dependant (Response) Variable	Independent Variable	Difference
Translational RWRMSA	Driving Condition	(DUL) > (DL)
	Measurement Location	(OSI) > (Chassis)
	Axis	(Y) > (X) > (Z)
Rotational RWRMSA	Driving Condition	(DUL) > (DL)
	Measurement Location	(OSI) > (Chassis)
	Axis	(Roll) > (Pitch) > (Yaw)
Translational WRMSADF	Driving Condition	(DUL) > (DL)
	Measurement Location	(OSI) > (Chassis)
	Axis	(Y) > (X) > (Z)
Rotational WRMSADF	Driving Condition	(DUL) > (DL)
	Measurement Location	(OSI) > (Chassis)
	Axis	(Roll) > (Pitch) > (Yaw)

Two significant two-way interactions were obtained from the ANOVA procedures (Table 4-10). For the translational WRMSADF response variable, a significant interaction was obtained between Driving Condition and Axis ($p=0.043$) (Figure 4-13). The second significant interaction ($p=0.041$) occurred between Measurement Location and Axis (Figure 4-14) for the rotational RWRMSA response variable.

For the translational WRMSADF response variable, DUL in the Y-Axis was greater than DL in the X- and Z- axes as well as DUL in the Z-axis. DL in the Y-axis was greater than DL in the Z-axis (Table 4-10). For the rotational RWRMSA response variable, the OSI for the Roll axis was greater than RWRMSA values for the Chassis in the Roll, Pitch and Yaw axes as well as at the OSI in the Yaw axis. In addition, RWRMSA values were greater for the OSI in the Pitch axis than at the Chassis about the Pitch and Yaw axes as well as at the OSI in the Yaw axis (Table 4-10).

Figure 4-13: ($p \leq 0.05$) Driving Condition*Axis interaction plot resulting from ANOVA procedures for translational dominant frequency weighted root mean squared (RMS) acceleration.

Figure 4-14: Significant ($p \leq 0.05$) Measurement Location*Axis interaction plot resulting from ANOVA procedures for rotational running weighted root mean squared (RMS) acceleration

Table 4-10: Interaction variable summary table ($p \leq 0.05$) showing significant differences. Including those at the Chassis and operator/seat interface (OSI), driving loaded (DL) and driving unloaded (DUL), calculated for dominant frequency ISO 2631-1: 1997 weighted root mean squared accelerations (WRMSADF) in the translational axes as well as using the running ISO 2631-1: 1997 weighted root mean squared accelerations (RWRMSA) in the rotational axes.

Dependant (Response) Variable	Interaction Variables	Differences
RWRMSA	Measurement Location*Rotational Axis	Roll (Chassis) < Roll (OSI)
		Pitch (Chassis) < Roll (OSI)
		Pitch (Chassis) < Pitch (OSI)
		Yaw (Chassis) < Roll (OSI)
		Yaw (Chassis) < Pitch (OSI)
		Yaw (OSI) < Roll (OSI)
		Yaw (OSI) < Pitch (OSI)
WRMSADF	Driving Condition*Translational Axis	X (DL) < Y (DUL)
		Z (DL) < Y (DL)
		Z (DL) < Y (DUL)
		Z (DUL) < Y (DUL)

4.5 DISCUSSION

4.5.1 Whole-Body Vibration Exposure

A number of studies have assessed translational OSI accelerations for a variety of vehicles.

Various studies of mobile machines reporting accelerations weighed according to the 1997 version of the ISO 2631-1 standard are shown in Table 4-11.

The only vehicle which exceeds the acceleration values determined in this study are those of garbage trucks while DL and DUL on a rough road (Maeda and Morioka, 1998). These previous results may be a function of operator speed (Parsons *et al.*, 1979), terrain (Smith and Kwak, 1978) or possibly the way the load is carried inside the garbage truck. Higher accelerations were also reported in load haul dump trucks (Eger *et al.*, 2006) in the X-axis when compared to those reported in this paper for forestry skidders. This may be also a result of the terrain these vehicles are subjected to or the processes they conduct during normal operation.

Table 4-11: Translational operator/seat interface (OSI) acceleration levels for selected mobile machines weighted according to ISO 2631-1:1997 in the fore-aft (X), lateral (Y) and vertical axes (Z) and the vibration total value (a_v).

Authors	Standard	Vehicle Type	Driving Conditions	X (m/s^2)	Y (m/s^2)	Z (m/s^2)	a_v (m/s^2)
Maeda & Morioka (1998)	ISO 2631-1 (1997)	Garbage Trucks (n=3)	DUL (rough road) DL (rough road)	1.09 * 1.23 *	1.07 * 1.16 *	1.56 * 1.49 *	2.64 * 2.80 * ++++
Bovenzi et al. (2002)	ISO 2631-1 (1997)	Straddle carriers (n=7) Fork-lift trucks (n=7) Mobile cranes (n=2)	transportation of loads transportation of loads and loading loading & unloading	0.23 0.35 0.21	0.08 0.18 0.37	0.33 0.64 0.32	0.48 † 0.90 ††† 0.53 †
Johanning et al. (2002)	ISO 2631-1 (1997)	U.S. Railroad Locomotives (n=22)	routine locomotive operation	0.18	0.28	0.32	0.59 †
Cann et al. (2004)	ISO 2631-1 (1997)	Transport Trucks (n=4)	driving on major highways	0.19	0.19	0.47 *	0.60 †
Rehn et al. (2005)	ISO 2631-1 (1997)	Snow groomers (n=7) Snowmobiles (n=6) Forest machines (n=6)	uphill & downhill driving (ski hills) uphill & downhill driving (ski hills) DUL, DL, loading & unloading	0.29 0.71 0.50	0.29 0.71 0.79	0.80 0.80 0.60	0.90 ††† 1.70 †††† 1.50 ††††
Burström et al. (2006)	ISO 2631-1 (1997)	Airplane Crew Seats (Front) Airplane Crew Seats (Rear) Grader (n=1)	airplane landing airplane landing typical operating conditions	0.30 0.20 0.38	0.10 0.40 0.45	0.60 0.90 0.79	0.74 * †† 1.10 * ††† 1.14 * †††
Eger et al. (2006)	ISO 2631-1 (1997)	Seated Locomotive (n=1) Personal Tractor (n=1) Load Haul Dump Truck (n=2)	typical operating conditions typical operating conditions typical operating conditions	0.20 0.55 0.81 *	0.38 0.68 0.49 *	0.58 1.09 1.57 *	0.84 * ††† 1.63 * †††† 1.93 * ††††
Johanning et al. (2006)	ISO 2631-1 (1997)	U.S. Railroad Locomotives (n=51)	routine locomotive operation	0.13	0.23	0.29	0.48 †
Cation et al.	ISO 2631-1 (1997)	Skidder (n=6) Skidder (n=7)	DUL typical operating condition DL typical operating conditions	0.86 0.72	1.12 0.96	0.73 0.72	2.10 †††† 1.83 ††††

* determined from published values

† exceeds ISO 2631-1:1997 health caution zone lower limit for a 8-hour day

†† exceeds ISO 2631-1:1997 health caution zone lower limit for a 4-hour day

††† exceeds ISO 2631-1:1997 health caution zone upper limit for a 8-hour day

†††† exceeds ISO 2631-1:1997 health caution zone upper limit for a 4-hour day

NOTE: † and †† indicates potential health risks while ††† and †††† indicates likely health risk as outlined in ISO 2631-1 (1997) using a_v

Eight vehicle types have reported Z-axis accelerations which exceed the OSI RWRMSA of the present study (Table 4-11). As a general comment, the accelerations from the current study likely differ from the vehicles included in Table 11 because of differences in testing terrain, vehicle seating systems and suspensions (Smith and Kwak, 1978), speed of travel, road conditions and most obviously, the type of vehicle (Parsons *et al.*, 1979).

Few studies have reported rotational acceleration values at the chassis. Chassis rotational RMS acceleration measurements were determined for landmine protected military vehicles on various terrains (Roll-0.10 rad/s², Pitch-0.05 rad/s², Yaw-0.10 rad/s²); (Els, 2005). These off-road vehicles show Pitch being the predominant axis of chassis rotational acceleration whereas Roll was found to be the predominant axis in the current investigation. Nonetheless, the values determined by Els (2005) are substantially smaller than those presented in this paper.

Undoubtedly variability in acceleration values occurred as a result of the terrain as the skidders included in this paper were observed during actual working conditions and operating procedures. The skidders did not always follow the same path for each trial as the piles of trees were placed throughout their working areas. Skidders were measured simply as they operated with no input from the researchers. It was noted during testing, however, that operators did not operate on one track but travelled through the logging site as required. Although this may result in larger standard deviations, it is also useful in attaining a representative average, as well as range, of the operating condition acceleration values at the Chassis and OSI. This does not explain why skidder 1 incurred larger acceleration values for all 6-DOF measured at the OSI while DUL compared to the other skidders (Figure 4-9 & Figure 4-10). It is believed that these elevated values are possibly a result of operator induced motion and/or the terrain or possibly a loosely fastened seat belt. Although these data are presented in the figures, they were not used to calculate the overall averages since they appeared to be outliers and did not represent the same vibration patterns as the other skidders.

A few studies have reported skidder exposure at the OSI and are shown in Table 4-12. Similar findings to those presented in this paper are shown by Golsse and Hope (1987) using the ISO 2631-1;1978 where the same trend for higher translational accelerations while DUL compared to DL were observed. Unlike the present study, however, Golsse and Hope (1987) observed larger Z-axis accelerations compared to the other translational axes. This may result from the fact that Golsse and Hope (1987) obtained their data from a test track. In contrast, Neitzel and Yost (2003), using ISO 2631-1:1997, and Golsse (1989) using ISO 2631-1;1978, reported similar trends as the current study; they did not obtain higher average RMS accelerations in the Z-axis. Neitzel and Yost (2003) used the ISO-2631-1;1997 standard which was used in this paper; however, their reported accelerations are notably higher than the present study. Different testing site locations, skidders, and operators were used which may have resulted in the variability between the various published values and the current study. Current and past (Golsse and Hope 1987, Golsse 1989, Neitzel and Yost, 2003) studies show similar exposures with no evident improvement in the accelerations that operators are subjected to through the OSI. This suggests that there is little evidence of improved skidder seat vibration attenuation between 1987 and 2006.

Table 4-12: ISO 2631-1:1997 weighted overall accelerations and peak accelerations $\pm$ standard deviation (sd) previously reported in literature for forestry skidders at the operator/seat interface (OSI) under various driving conditions.

Authors	Standard Year	Measurement Location	Driving Conditions (n=Number of Vehicles)	Average/Peak Acceleration	Axis of Measurement		
					X (m/s ²)	Y (m/s ²)	Z (m/s ²)
Golsse & Hope (1987)	1978	SOI	DUL (n=22)	peak $\pm$ sd	5.66 $\pm$ 1.97	6.27 $\pm$ 1.98	7.08 $\pm$ 3.48
				average $\pm$ sd	0.75 $\pm$ 0.21	0.82 $\pm$ 0.29	1.15 $\pm$ 0.43
			DL (n=17)	peak $\pm$ sd	4.41 $\pm$ 2.08	5.38 $\pm$ 2.11	6.80 $\pm$ 2.74
				average $\pm$ sd	0.54 $\pm$ 0.22	0.67 $\pm$ 0.31	0.95 $\pm$ 0.43
			pilling (n=8)	peak $\pm$ sd	4.28 $\pm$ 2.67	3.93 $\pm$ 1.70	4.74 $\pm$ 2.44
				average $\pm$ sd	0.54 $\pm$ 0.33	0.49 $\pm$ 0.27	0.80 $\pm$ 0.62
Golsse (1989)	1978	SOI	site preparation (n=6)	average $\pm$ sd	0.85 $\pm$ 0.25†	0.79 $\pm$ 0.25†	0.74 $\pm$ 0.26†
				peak $\pm$ sd	3.16 $\pm$ 1.51†	3.32 $\pm$ 1.42†	3.12 $\pm$ 1.23†
Wegscheid (1994)	1978	SOI	normal operation (n=4)	average range	*	0.75-1.43 [‡]	0.83-2.0 [‡]
Neitzel & Yost (2003)	1997	SOI	idle/driving loaded	average	1.6	1.4	1.4
Cation et al.	1997	SOI	DUL (n=6)	peak $\pm$ sd	4.90 $\pm$ 1.63	6.23 $\pm$ 2.33	5.34 $\pm$ 1.64
				average $\pm$ sd	0.86 $\pm$ 0.27	1.12 $\pm$ 0.39	0.73 $\pm$ 0.23
			DL (n=7)	peak $\pm$ sd	4.11 $\pm$ 1.89	5.02 $\pm$ 1.84	5.49 $\pm$ 2.20
				average $\pm$ sd	0.72 $\pm$ 0.21	0.96 $\pm$ 0.32	0.72 $\pm$ 0.22

* Unable to determine

[‡] Determined from figures

† Calculated from published values

The peak values show a large variance, which is as expected given that the study was conducted under actual field operating conditions. It is unlikely that during each trial the operator would incur the same peaks as the terrain was variable and the operators did not follow one specific path for each trial. The peak accelerations recorded are likely a result of transients or shock as the instantaneous acceleration would be larger than for sustained accelerations. Similar to the exposure to WBV, the effects of shocks are known to be harmful (Ranganathan and Mohan, 1997); however, the specific health risks associated with exposure to shocks and transients are not well established. The large peaks associated with these skidders have been downplayed in importance through the use of CFs.

The CFs, as defined by ISO 2631-1:1997, are the ratio between the peak and RMS accelerations. CFs which exceed 9.0 infer that alternative methods, specifically employing a running RMS acceleration, must be used. This results in a lowered acceleration value as each peak is attenuated due to the RMS

averaging in each window. Therefore, transients and instantaneous shocks are less of an influence on the overall reported value.

The magnitudes of the translational crest factors outlined in Table 4-6 are similar to those reported by Golsse (1989) and Wegscheid (1994) as shown in Table 4-13. The range reported here is lower than the range reported by Wegscheid (1994). As pointed out in by Wegscheid (1994) these CFs may be misconstrued since a large peak with a similarly high RMS acceleration but which may in fact result in the same CF as a low peak and low RMS acceleration. However, the high CF comprised of a moderate peak and low RMS acceleration is intuitively more desirable than a low CF comprised of a high peak and RMS acceleration. This was noted in a study of off-road vehicles by Els (2005) where an increase in the terrain roughness the crest factor decreased.

Table 4-13: factors (CFs) $\pm$ standard deviation and ranges reported in literature for forestry skidders at the operator/seat interface (OSI).

Authors	Measurement Location	Standard Year	Skidder Type	Axis of Measurement		
				X	Y	Z
Wegscheid (1978)	SOI	1978	Grapple (n=1)	5.88-9.76	6.11-12.25	5.95-15.31
			Grapple (n=1)	6.26-10.01	6.26-12.31	7.15-14.9
			Grapple (n=1)	5.61-10.78	5.18-11.86	6.62-10.77
			Grapple (n=1)	5.87-11.19	5.77-9.30	8.07-20.48
Golsse (1989)	SOI	1978	Grapple (n=1)	6.35	7.46	7.18
			Cable with no suspension (n=1)	7.73	6.95	5.05
			Cable with suspension (n=1)	8.33	8.79	7.43
Cation et al.	SOI	1997	Grapple & Cable DUL (n=6)	5.45 $\pm$ 1.49	5.24 $\pm$ 1.33	7.22 $\pm$ 2.68
			Grapple & Cable DL (n=7)	5.50 $\pm$ 1.68	5.13 $\pm$ 1.22	7.66 $\pm$ 3.11

The dominant frequency was determined to be higher in the Z-axis when compared to those in the X- and Y-axes. This may also be a function of the terrain. It is likely due to the terrain or machine, as the average for each axis is the same even at different measurement locations (OSI or Chassis) or driving condition (DL or DUL). This study found the dominant vertical (Z-axis) vibration occurred in the 2 Hz frequency band, which is lower than the 2.5 Hz dominant frequency bin reported by Boileau and Rakheja (1990) on the cab floor of skidders under normal operating conditions. The difference between

dominant frequency reported in this study and previous literature may also be a function of the terrain, skidders tested or standard used for testing.

It is also important to note that in this study the orientation of the axes of measurement for the chassis and OSI were not always perfectly aligned. There was an offset present as outlined in Table 4-1 and Figure 4-8. This angle of offset was less than or equal to 25° (for 5 skidders it was less than or equal to 15°). This was not optimal; however, the variation between skidder designs does allow for a more generalizable set of results. For future studies, the orientation could be standardized and aligned.

4.5.2 Potential Health Risks and Comfort Rating Predictions

Based on the overall weighted accelerations (a_w) determined for the skidders in this study at the OSI, the skidder operators exceed the ISO 2361-1:1997 health caution upper limit for a 4-hour day, and thus are likely to incur health risks as a result (ISO 2631-1:1997). When comparing the vibration total value of various reported values (using translational accelerations), a number of vehicles exceeded the upper limits of the health caution for a 4-hour day, including: garbage trucks, snow mobiles and forest machines, personal tractors, load haul dump trucks and skidders (Table 4-11). Also, based on the vibration total value for the skidders in this study, the acceleration is considered uncomfortable/very uncomfortable for both driving conditions when considering only the translational acceleration values according to the ISO 2631-1:1997 predicted vibration comfort reactions. When including all 6-DOF in the vibration total calculations, DL was still considered an uncomfortable/very uncomfortable condition, while DUL became a very uncomfortable condition (Table 4-7). Parsons *et al.* (1979) determined that translational vibration produced greater discomfort than the rotational axes in which Roll and Pitch caused increased discomfort over Yaw vibrations with the most predominant discomfort in the Z-axis. Parsons and Griffin (1978) showed that it may be adequate to measure the total vibration discomfort by the dominant axis in some conditions of combined translational and rotational environments. Although it is suggested that translational accelerations may be more indicative of discomfort in certain

situations, the rotational axes should not be ignored as discomfort is associated with vibration in these axes (Parsons *et al.*, 1979).

4.5.3 Influence of Driving Condition, Measurement Location and Axis on ISO Weighted Accelerations

DUL accelerations were determined to be significantly higher than DL. This follows with previous published values. There was one exception determined in this study (Figure 4-13); the translational WRMSADF was not significantly difference between driving conditions (DL, DUL) in the Z-axis. This makes sense as seats are generally designed to attenuate Z-axis accelerations (Donati, 2002). This result was expected as the lower accelerations present while DL in the case of skidders (Table 4-12) and other vehicles which may also carry loads is likely a function of the reduced travelling speed or the stabilizing effect of the load (Golsse and Hope, 1987). The accelerations at the OSI were also determined to be significantly greater than those measured at the chassis. There was one exception determined in this study; between rotational RWRMSA and measurement location in the Yaw axis where there was not a significant difference between the measurement locations (OSI, Chassis) in that axis. Again, this is likely a function of the distance between the OSI and the location of the centre of rotation. The rotations in Pitch and Roll would theoretically increase at the OSI when compared to the chassis as the OSI is further from the centre of rotation in these axes. This is not the case in the Yaw axis as the centre of rotation is in the vertical axis so the vertical distance from the centre of rotation does not matter. The significant difference between Measurement Location (OSI, chassis) in the other axes, further supports the notion that currently used seat designs are ineffective in dampening accelerations at the OSI and are in fact amplifying them. From this study, however, it is unclear if these findings are a result of improper operator seat adjustment or if the seat designs are simply lacking effective terrain appropriate WBV attenuation properties.

In addition to significant differences in Driving Condition and Measurement Location, for all response variables, there were significant differences with respect to Axis (translational and rotational). The vibration magnitude along the Y-axis was significantly larger than the X-axis, and the Z-axis was significantly smaller than both the X- and Y- axes. The predominance of the X- and Y-axis compared to the Z-axis may be a function of the off-road terrain, operator driving techniques, skidder tire pressure and/or skidder design. From Table 4-11, the vibration magnitude along the Z-axis has generally been reported to have higher accelerations for vehicles not operating on similar terrain to skidders. Golsse and Hope (1987) however also reported larger Z-axis accelerations when compared to the X- and Y- axes. Other reports (Table 4-12) on skidders have reported larger X- or Y- axis acceleration when compared corresponding Z-axis values they reported. It is not evident why there is so much variability in the data; however, the study methodologies do differ greatly as discussed in section 4.5.1. In the rotational axes, Roll vibration was significantly greater than Pitch and both were significantly greater than Yaw. Based on basic driving knowledge, even in extreme terrain conditions, rotation about the vertical (Yaw) axis is not very pronounced, unlike the movements in Pitch and Roll which occur more often, for example when driving over terrain irregularities.

Significant interactions were observed between Driving Condition and Axis for translational WRMSADF as well as for Measurement Location and Axis for rotational RWRMSA. The significant interaction observed between Driving condition and the X-, Y- and Z- axes was as expected, in that the increase observed while DUL compared to DL was not the same for each axis. This is as expected, as the load may have a dampening effect on the motion (Golsse and Hope, 1987) in some axes more than others while DL as well as the accelerations due to speed of travel may on each axis differently based on the impacts with the terrain. In addition the interaction between Measurement Location and Rotational Axis may be a function of the seat-belt, operator motion at the OSI, or seat-design

characteristics. It was seen that Chassis WRMSADF values about the OSI Yaw axis were not amplified to the same extent as Roll and Pitch at the OSI.

4.6 CONCLUSIONS

Skidder operators exceed WBV exposure levels outlined in ISO 2631-1:1997 health caution guidelines for a 4-hour work day and would be considered uncomfortable/very uncomfortable working conditions according to the ISO 2631-1:1997 comfort guide. Based upon the overall weighted acceleration averages reported in this study, there is no evidence that skidder seats have improved, and in fact we have shown that the seats result in significant amplification of the vibration along or about each of the six axes with the translational acceleration values being similar to studies conducted decades ago.

This study is by no means exhaustive and future studies should expand upon the data set collected here to include quantification of WBV at the seat/back, chassis/feet and controller/hand interfaces as they may act as a conduit for WBV transmission. Moreover, when assessing discomfort, the seat/back area may be of particular interest in an effort to identify which portions of the seat may be related to various discomfort levels and is subsequently indicated as a measurement location for discomfort in ISO 2631-1:1997. The current paper explores the OSI with the exclusion of the seat backrest and reveals that skidder seats are amplifying WBV under both Driving Conditions when compared to the Chassis. Nonetheless, this article is indeed a step towards providing the numerical values which may allow for modification of current seat designs as well as for the development of new innovative designs. To our knowledge, this data represents the most comprehensive 6-DOF field data set collected to date for any type of vehicle. Field profiles developed from this data set are currently being used in 6-DOF robot laboratory studies to assess the ability of current and future seat designs to attenuate 6-DOF WBV as well as to develop new biodynamic measures of seat effectiveness.

4.7 Acknowledgements

This project would not have been completed without the time and resources provided by subjects and forestry companies in Northern Ontario. Financial support was provided by the Workplace Safety and Insurance Board of Ontario Research Advisory Council, Natural Sciences and Engineering Research Council of Canada, Canadian Foundation for Innovation and the Ontario Innovation Trust.

4.8 References

- Boileau P-E, Rakheja S. 1990. Vibration attenuation performance of suspension seats for off-road forestry vehicles. *International Journal of Industrial Ergonomics*, 5; 275-91.
- Bovenzi M, Pinto I, Stacchini N. 2002. Low back pain in port machine operators. *Journal of Sound and Vibration*, 253; 3-20.
- Burström L, Lindberg L, Lindgren T. 2006. Cabin attendants' exposure to vibration and shocks during landing. *Journal of Sound and Vibration*, 298; 601-5.
- Cann AP, Salmoni AW, Eger TR. 2004. Predictors of whole-body vibration exposure experienced by highway transport truck operators. *Ergonomics*, 47; 1432-53.
- Cation S, Jack RJ, Dickey JP, Lee-Shee N, Oliver M. 2006. Calibration of a six-degree of freedom device for whole-body vibration determination, *Proceedings of the 14th Biennial Conference of the Canadian Society for Biomechanics*. Aug 16-19. Waterloo, Ontario, Canada.
- Donati P. 2002. Survey of Technical Preventative Measures to reduce whole-body vibration affects when designing mobile machinery. *Journal of Sound and Vibration*, 253;169-83.
- Eger T, Salmoni A, Cann A, Jack R. 2006. Whole-body vibration exposure experienced by mining equipment operators. *Occupational Ergonomics*, 6; 121-7.
- Els PS. 2005. The applicability of ride comfort standards to off-road vehicles. *Journal of Terramechanics*, 42; 47-64.
- Golse J-M, Hope PA. 1987. Analysis of whole-body vibration levels during skidding. Forest Engineering Research Institute of Canada (FERIC). Technical Report No. TR-77.
- Golse J-M. 1989. Analysis of whole-body vibration levels during site preparation. Forest Engineering Research Institute of Canada (FERIC). Technical Report No. TR-90.
- Griffin MJ. 1990. *The handbook of human vibration*. London: Academic Press.

ISO. 1997. ISO 2631-1: Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1: General requirements. International Organization for Standardization.

Jack RJ, Oliver M, Dony R. 2007. Alignment of 6-DOF Whole-Body Vibration Data. Proceedings of the 30th Canadian Medical and Biological Engineering Conference: Improving Medical Device Usability. June 16-19, Toronto, Ontario, Canada.

Johanning E, Fischer S, Christ E, Göres B, Landsbergis P. 2002. Whole-body vibration exposure study in U.S. railroad locomotives – An ergonomic risk assessment. American Industrial Hygiene Association Journal, 63; 439-46.

Johanning E, Landsbergis P, Fischer S, Christ E, Göres B, Luhrman, R. 2006. Whole-body vibration and ergonomic study of US railroad locomotives. Journal of Sound and Vibration, 298; 594-600.

Maeda S, Morioka M. Measurement of whole-body vibration exposure from garbage trucks. 1998. Journal of Sound and Vibration, 215; 959-64.

Neitzel R, Yost M. 2003. Forestry Vibration and Noise Exposure Project. University of Washington Department of Environmental Health. Seattle, Washington, USA.

Oliver M, Rogers R, Rickards J, Tingley M, Biden E. 2006. Effect of stiffness and movement speed on selected dynamic torque characteristics of hydraulic-actuation joystick controls for heavy vehicles. Ergonomics, 49; 249-68.

Parsons KC, Griffin MJ. 1978. The effect of the position of the axis of rotation on the discomfort caused by whole-body Roll and Pitch vibrations of a seated persons. Journal of Sound and Vibration, 58; 127-41.

Parsons KC, Whitham EM, Griffin MJ. 1979. Six axis vehicle vibration and its effects on comfort. Ergonomics, 22; 211-25.

Pope M, Magnusson M, Lundström R, Hulshof C, Verbeek J, Bovenzi M. 2002. Guidelines for whole-body vibration health surveillance. Journal of Sound and Vibration, 253; 131-67.

Ranganathan R, Mohan MV. 1997. A review of the general effects of whole-body vibration. International Journal of Vehicle Design, 4; 353-72.

Rehn B, Nilsson T, Olofsson B, Lundström R. 2005. Whole-body vibration exposure and non-neutral neck postures during occupational use of all-terrain vehicles. The Annals of Occupational Hygiene, 49; 267-75.

Seidel H. 1993. Selected health risks caused by long-term, whole-body vibration. American Journal of Industrial Medicine, 23; 589-604.

Seidel H, Heide R. 1986. Long-term effects of whole-body vibration: a critical survey of the literature. International Archives of Occupational and Environmental Health, 58; 1-26.

Smith CC, Kwak YK. 1978. Identification of the dynamic characteristics of a bench-type automotive seat for the evaluation of ride quality. *Journal of Dynamic Systems, Measurement, and Control*, 100; 42-9.

Wegscheid, E. 1994. Another look at skidder ride vibration. *Journal of Forest Engineering*, 5; 21-32.

Chapter 5: DISCUSSION, CONTRIBUTIONS, CONCLUSIONS & RECOMMENDATIONS

5.1 Introduction

This chapter will provide a brief discussion of the previous chapters and will also provide overall conclusions from the work presented in this thesis. Finally, this chapter will outline the contributions this work has made to literature and will outline the recommendations for future work.

5.2 Discussion

The calibration of a measurement system is very important (Thalheimer, 1996) and when complex transducers are being used, the simpler and less time consuming the calibration, the better. The calibration outlined in this thesis was shown to be quick and simple and was completed in two phases (i.e., the low g (LG) calibration and high g (HG) verification). The seat-pad transducer (SPT) calibrations yielded linear calibration equations with r^2 values greater than 0.97. When this method was applied to the chassis transducer (CT) the equations generated had r^2 values exceeding 0.99. These calibration equations were similarly validated using the HG verification of calibration procedure, with similar outcomes to the SPT at HG values. Thus, the methodology outlined in Chapter 3 may be applied to various transducers, although it is important to understand the capabilities of the entire measurement system such that the dynamic levels and frequency ranges are properly recorded (Thalheimer, 1996).

The calibrated range of the SPT has been shown to have been adequate for the acceleration values encountered in the field. Comparisons with various vehicle types presented in literature have shown that skidders have some of the highest rms accelerations at the operator/seat interface (OSI). The differences noted between skidders may be related to the vehicle speed (Parsons *et al.*, 1979), terrain (Smith and Kwak, 1978; Parsons *et al.*, 1979) or possibly the way the load stabilizes the

skidder (Golsse & Hope, 1987). Few studies have reported rotational acceleration values at the OSI or chassis.

It has been shown that skidders may not have dominant Z-axis acceleration in the translational axes, which is supported by current literature (Neitzel & Yost, 2003; Golsse, 1989). The dominant axis was reported as the X-axis in skidders by Neitzel & Yost (2003) and Golsse (1989), however, this current investigation found larger RWRMSA in the Y-axis. This was contrary to the findings reported by Golsse & Hope (1987) who found the Z-axis to have larger average accelerations; however, they used a test track. This further indicates that the terrain may influence the shift between dominant average acceleration axes. Terrain has been previously identified as one of the contributing factors to the higher WBV accelerations found in skidders (Golsse & Hope, 1987). Within the study presented in Chapter 4, the skidder operators accelerations were variable as a result of the use of actual working conditions, under which the same path was not always used, nor was the test site location the same throughout skidders being tested. In addition to differences in terrain, different makes and models of skidders were used, with a different operator for each skidder, which may have served to further increase the variability between skidders especially in regards to peak accelerations. The translational accelerations were also significantly ($p \leq 0.05$) larger while driving unloaded (DUL) than driving loaded (DL), which intuitively makes sense, as the operator was free to drive faster over rough terrain if they wished and did not have the stabilizing effect of the load (Golsse & Hope, 1987).

OSI accelerations were determined to be significantly greater than those measured at the chassis, indicating that currently used seat designs are in fact amplifying accelerations showing that seats are ineffective in dampening accelerations at the OSI. It cannot be determined in this case whether this was a result of improper operator seat adjustment or if the seat designs are simply lacking effective terrain appropriate whole-body vibration (WBV) attenuation properties.

5.3 Conclusions

The purpose of this work was to update the currently available acceleration measurements for forestry skidders to incorporate 6-DOF measurements at the OSI and chassis. The research has illustrated that seats currently used by skidder operators in Northern Ontario amplify WBV accelerations at the OSI when compared to the Chassis and that skidder operators are putting themselves at a likely health risk according to ISO 2631-1:1997 based on the acceleration levels and duration of exposure. Skidder operators exceed WBV exposure levels outlined in ISO 2631-1:1997 health caution guidelines for a 4-hour work day. The ride experienced by skidder operators would be considered uncomfortable/very uncomfortable according to the ISO 2631-1:1997 comfort guide.

As a result of the OSI overall weighted acceleration averages determined in this study, skidder seats result in significant amplification of the vibration along or about each of the six axes when compared to simultaneously collected chassis overall weighted accelerations.

5.3.1 Contributions

Field profiles developed from this data are being used in 6-DOF robot laboratory studies to assess WBV attenuation capabilities of current and future seat designs and to develop new biodynamic measures of seat effectiveness.

The work presented in this thesis has resulted in the following previously unavailable contributions:

1. Updated WBV acceleration values at the OSI and chassis in the translational axes of skidders alongside
2. WBV acceleration values at the OSI and chassis in the rotational axes of skidders
3. Indication for industry that the currently employed techniques need to be re-evaluated/redesigned such that the seats dampen, not amplify, the WBV accelerations at the OSI compared to the chassis
4. This is the most comprehensive description and analysis of 6-DOF WBV yet provided

5.3.2 Future Work

As a result of the work presented in this thesis, a number of concerns and avenues for future study have been raised:

1. The data set collected should be expanded to include the quantification of WBV at the seat/back, chassis/feet and controller/hand interfaces as they also act as a conduit for WBV transmission
2. In a field environment, how much effect does the seat/back interface have on the discomfort experienced by the skidder operator?
3. Should the working schedule of skidder operators be altered such that they are exposed to shorter durations of WBV more frequently as opposed to the constant exposure over a shorter day?
4. Should industrial seat designs for rough terrain vehicles be altered to minimize fore-aft and lateral vibrations more?
5. How can vehicle seat designs be altered for the various driving conditions the machines are exposed to in a working day, such that WBV exposure is minimized for all circumstances?
6. Can generalized design changes adhere to all skidders on the various driving terrains?
7. Do current guidelines adequately analyze extreme WBV environments such as skidders?

5.4 References

Golse J-M, Hope PA. 1987. Analysis of whole-body vibration levels during skidding. Forest Engineering Research Institute of Canada (FERIC). Technical Report No. TR-77.

Golse J-M. 1989. Analysis of whole-body vibration levels during site preparation. Forest Engineering Research Institute of Canada (FERIC). Technical Report No. TR-90.

Neitzel R, Yost M. 2003. Forestry Vibration and Noise Exposure Project. University of Washington Department of Environmental Health. Seattle, Washington, USA.

Parsons KC, Whitham EM, Griffin MJ. 1979. Six axis vehicle vibration and its effects on comfort. *Ergonomics*, 22; 211-25.

Smith CC, Kwak YK. 1978. Identification of the dynamic characteristics of a bench-type automotive seat for the evaluation of ride quality. *Journal of Dynamic Systems, Measurement, and Control*, 100; 42-9.

Thalheimer E. 1996. Practical approach to measurement and evaluation of exposure to whole-body vibration in the workplace. *Seminars in Perinatology*, 20; 77-89.

Appendix A – MATLAB™ CODE

MATLAB™ Code Table of Contents

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Description: This program is designed to filter at 2 times the theoretical cut-off frequency for the initial calibration files using a dual-pass zero-lag Butterworth filter.	
6.2 filtering2fc_highG.m	94
Description: This program is designed to filter at 2 the theoretical cut-off frequency for the High G data verification files for both the SPT and the VICON™ displacement data using a dual-pass zero- lag Butterworth filter.	
6.3 freq_analysis.m	96
Description: This program is designed to output frequency components of WBV signals, using third-octave bands.	
6.4 peak_determination.m	97
Description: This program is designed to output maximum acceleration from each of the files selected	
6.5 skidder_eval_running_rms_sk1.m	98
Description: This program is designed to determine the overall raw (unweighted) rms peak and average acceleration values for each skidder under each driving condition for each trial. Skidder 1 is shown as an example.	
6.6 runningrms.m.....	103
Description: This function calculates the running RMS of a signal	

Low g Calibration Filtering

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Written By: Sarah Cation 2006, edited 2006-2007
% Name: filtering2fc_lowG.m
%Description: This program is designed to filter at 2 times the theoretical cut-off frequency for the
% initial calibration files using a dual-pass zero-lag Butterworth filter.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
data=load('C:\SchoolWork\MYTHESIS\PAPER2\calibrationSPT\HighG cal\VICON\xaxis\testxaxis33c.txt');
%data(:,1)=x(:,1);
%data(:,2)=x(:,2);
%data(:,3)=x(:,3);
%data(:,4)=x(:,4);
%data(:,5)=x(:,5);
%data(:,6)=x(:,6);
%data(:,7)=x(:,7);
%data(:,8)=x(:,8);
%data(:,9)=x(:,9);
%data(:,10)=x(:,10);
%data(:,11)=x(:,11);
%data(:,12)=x(:,12);
%data(:,13)=x(:,13);
%data(:,14)=x(:,14);
%data(:,15)=x(:,15);
%data(:,16)=x(:,16);
%data(:,17)=x(:,17);
%data(:,18)=x(:,18);
%data(:,19)=x(:,19);
%data(:,20)=x(:,20);
%data(:,21)=x(:,21);
%data(:,22)=x(:,22);
%data(:,23)=x(:,23);
%data(:,24)=x(:,24);
%data(:,25)=x(:,25);
%data(:,26)=x(:,26);
%data(:,27)=x(:,27);
%data(:,28)=x(:,28);
%data(:,29)=x(:,29);
%data(:,30)=x(:,30);

%The sampling frequency was 500 Hz, and tried the fc=1.5*5 (max freq input); however, didn't work, so used fc=2*max
%freq of low g cal (5 Hz)=10Hz, Butterworth filter

f=500/2;
[B,A]=butter(2, 10/f,'low');
filtereddata(:,:)=(filtfilt(B,A,data(:,:)));

save x_33_VICON_filtered.txt filtereddata -ASCII -TABS;
clear all;
```

This Program Filters the Data from the High G Data Verification Process

%%%

% Written By: Sarah Cation 2006, edited 2006-2007

% Name: filtering2fc_highG.m

%Description: This program is designed to filter at 2 times the theoretical cut-off frequency for the
% High G data verification files for both the SPT and the VICON™ displacement data using a
% dual-pass zero-lag Butterworth filter.

%%%

data1=load('C:\SchoolWork\MYTHESIS\PAPER2\CalibrationFancyDay2\filteringfiles\x_raw_CAMERA_fancy_day2.txt');

data2=load('C:\SchoolWork\MYTHESIS\PAPER2\CalibrationFancyDay2\filteringfiles\x_raw_SENSOR_fancy_day2.txt');

data3=load('C:\SchoolWork\MYTHESIS\PAPER2\CalibrationFancyDay2\filteringfiles\y_raw_CAMERA_fancy_day2.txt');

data4=load('C:\SchoolWork\MYTHESIS\PAPER2\CalibrationFancyDay2\filteringfiles\y_raw_SENSOR_fancy_day2.txt');

data5=load('C:\SchoolWork\MYTHESIS\PAPER2\CalibrationFancyDay2\filteringfiles\z_raw_CAMERA_fancy_day2.txt');

data6=load('C:\SchoolWork\MYTHESIS\PAPER2\CalibrationFancyDay2\filteringfiles\z_raw_SENSOR_fancy_day2.txt');

%chosen as maximum value which was 5hz. Fs=500hz (sampling frequency), so

% went up to fc=70 as a result of the high G calibrations since we went up to 35 Hz max, chose 2 times the expected

%frequency as there was ambiguity in the VTM settings

%write it like [B,A]=butter(2,80/f,'low');

%filtereddata(:,:)=(filtfilt(B,A,data(:,:)));%

f=500/2;

%for 5 Hz%

[B,A]=butter(2,10/f,'low');

%for 10Hz%

[D,C]=butter(2,20/f,'low');

%for 15 Hz%

[F,E]=butter(2,30/f,'low');

%for 20 Hz%

[H,G]=butter(2,40/f,'low');

%for 25 Hz%

[L,K]=butter(2,50/f,'low');

%for 30 Hz%

[N,M]=butter(2,60/f,'low');

%for 35 Hz%

[Q,P]=butter(2,70/f,'low');

filtereddata1(:,1:4)=(filtfilt(D,C,data1(:,1:4)));

filtereddata1(:,5:8)=(filtfilt(H,G,data1(:,5:8)));

filtereddata1(:,9:12)=(filtfilt(F,E,data1(:,9:12)));

filtereddata1(:,13:16)=(filtfilt(H,G,data1(:,13:16)));

filtereddata1(:,17:20)=(filtfilt(H,G,data1(:,17:20)));

filtereddata1(:,21:24)=(filtfilt(L,K,data1(:,21:24)));

filtereddata1(:,25:28)=(filtfilt(Q,P,data1(:,25:28)));

filtereddata1(:,29:32)=(filtfilt(H,G,data1(:,29:32)));

```
save X_axis_VICON_fancy_highG_day2_FILTERED_fc_is_2x_Hz.txt filtereddata1 -ASCII -TABS;
```

```
filtereddata2(:,1)=(filtfilt(D,C,data2(:,1)));  
filtereddata2(:,2)=(filtfilt(H,G,data2(:,2)));  
filtereddata2(:,3)=(filtfilt(F,E,data2(:,3)));  
filtereddata2(:,4)=(filtfilt(H,G,data2(:,4)));  
filtereddata2(:,5)=(filtfilt(H,G,data2(:,5)));  
filtereddata2(:,6)=(filtfilt(L,K,data2(:,6)));  
filtereddata2(:,7)=(filtfilt(Q,P,data2(:,7)));  
filtereddata2(:,8)=(filtfilt(H,G,data2(:,8)));
```

```
save X_axis_SENSOR_fancy_highG_day2_FILTERED_fc_is_2x_Hz.txt filtereddata2 -ASCII -TABS;
```

```
filtereddata3(:,1:4)=(filtfilt(D,C,data3(:,1:4)));  
filtereddata3(:,5:8)=(filtfilt(H,G,data3(:,5:8)));  
filtereddata3(:,9:12)=(filtfilt(F,E,data3(:,9:12)));  
filtereddata3(:,13:16)=(filtfilt(H,G,data3(:,13:16)));  
filtereddata3(:,17:20)=(filtfilt(H,G,data3(:,17:20)));  
filtereddata3(:,21:24)=(filtfilt(L,K,data3(:,21:24)));  
filtereddata3(:,25:28)=(filtfilt(Q,P,data3(:,25:28)));  
filtereddata3(:,29:32)=(filtfilt(H,G,data3(:,29:32)));
```

```
save Y_axis_VICON_fancy_highG_day2_FILTERED_fc_is_2x_Hz.txt filtereddata3 -ASCII -TABS;
```

```
filtereddata4(:,1)=(filtfilt(D,C,data4(:,1)));  
filtereddata4(:,2)=(filtfilt(H,G,data4(:,2)));  
filtereddata4(:,3)=(filtfilt(F,E,data4(:,3)));  
filtereddata4(:,4)=(filtfilt(H,G,data4(:,4)));  
filtereddata4(:,5)=(filtfilt(H,G,data4(:,5)));  
filtereddata4(:,6)=(filtfilt(L,K,data4(:,6)));  
filtereddata4(:,7)=(filtfilt(Q,P,data4(:,7)));  
filtereddata4(:,8)=(filtfilt(H,G,data4(:,8)));
```

```
save Y_axis_SENSOR_fancy_highG_day2_FILTERED_fc_is_2x_Hz.txt filtereddata4 -ASCII -TABS;
```

```
filtereddata5(:,1:4)=(filtfilt(D,C,data5(:,1:4)));  
filtereddata5(:,5:8)=(filtfilt(H,G,data5(:,5:8)));  
filtereddata5(:,9:12)=(filtfilt(F,E,data5(:,9:12)));  
filtereddata5(:,13:16)=(filtfilt(H,G,data5(:,13:16)));  
filtereddata5(:,17:20)=(filtfilt(H,G,data5(:,17:20)));  
filtereddata5(:,21:24)=(filtfilt(L,K,data5(:,21:24)));  
filtereddata5(:,25:28)=(filtfilt(Q,P,data5(:,25:28)));  
filtereddata5(:,29:32)=(filtfilt(H,G,data5(:,29:32)));
```

```
save Z_axis_VICON_fancy_highG_day2_FILTERED_fc_is_2x_Hz.txt filtereddata5 -ASCII -TABS;
```

```
filtereddata6(:,1)=(filtfilt(D,C,data6(:,1)));  
filtereddata6(:,2)=(filtfilt(H,G,data6(:,2)));  
filtereddata6(:,3)=(filtfilt(F,E,data6(:,3)));  
filtereddata6(:,4)=(filtfilt(H,G,data6(:,4)));  
filtereddata6(:,5)=(filtfilt(H,G,data6(:,5)));  
filtereddata6(:,6)=(filtfilt(L,K,data6(:,6)));  
filtereddata6(:,7)=(filtfilt(Q,P,data6(:,7)));  
filtereddata6(:,8)=(filtfilt(H,G,data6(:,8)));
```

```
save Z_axis_SENSOR_fancy_day2_highG_FILTERED_fc_is_2x_Hz.txt filtereddata6 -ASCII -TABS;  
clear all;
```

Frequency Analysis – Third-Octave Band Breakdown

%%%

% Written By: Natasha Lee-Shee 2007

% Name: freq_analysis.m

%Description: This program is designed to output frequency components of WBV signals, using
% third-octave bands.

% NOTE: fanter2 is a modified version of fanter which was contained in the Vibratools™ MATLAB™
%software used.

%%%

```
fs=input('\n\n Please enter sampling frequency [Hz]: ');
fmin=input(' Please enter min freq band [Hz]: ');
fmax=input(' Please enter max fre band [Hz]: ');
%
[fname,fpath]=uigetfile('*.txt','Please select file(s)','MultiSelect','on');
[r,numfiles]=size(cellstr(fname));
clear r;
filename=char(fname);
%
for i=1:numfiles
    file=deblank(filename(i,:));
    fprintf(1,['Processing file ' file '\n']);
    data=load([fpath file]);
    data=data(:,2:7); %removing time column from data
    for k=1:6
        try
            [Oct(:,k),freq2(:,k)] = fanter2(data(:,k),fs,fmin,fmax);
        catch
            err=msgbox('Problem with fanter2 function','ERROR','error');
        end
    end
    outfile=[fpath 'third_' file];
    outdata=[freq2(:,1) Oct];
    dlmwrite(outfile,outdata,'\t');
    clear data Oct freq2;
end
fprintf(1,'\n\n ----Third Octave Bands DONE!----\n\n');
clear;
```

Peak Acceleration Determination

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Written By: Natahsa Lee-Shee 2007
% Name: peak_determination.m
%Description: This program is designed to output maximum acceleration from each of the files
%             selected
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
[filename,path]=uigetfile('*.txt','Select file(s) to be processed','MultiSelect','on');
[ro,numfiles]=size(cellstr(filename)); %get # of rows and columns of filename
clear ro;
infile =char(filename); %create filename variable
%
for i = 1:numfiles
    fname = deblank(infile(i,:)); %remove any trailing blanks
    file=[path fname];
    data=load(file);
    data=abs(data(:,2:7));
    y=max(data);
    clear data;
    box=msgbox(['Saving file ' num2str(i) ' of ' num2str(numfiles)'.'],'SAVING','help');
    outfile=['C:\FILES\peak\PEAK_' fname];
    dlmwrite(outfile,y,'delimiter','\t');
    delete(box);

    clear y;
    clear peak;

end
%
clear %clear memory
```

RMS peak and overall average running RMS average accelerations in raw (unweighted) form

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Written By: Sarah Cation 2006
% Name: skidder_eval_running_rms_sk1.m
%Description: This program is designed to determine the overall raw (unweighted) rms peak and
%             average acceleration values for each skidder under each driving condition for each
%             trial. Shown here for Skidder 1 as an example.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%SKIDDER 1 SEAT UNLOADED RAW%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%trial 1
```

```
%load the running rms file
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\UL\Rsk1_S_UL_rawrms_1.txt;

%read in the values for the columns of data getting rid of the time column
rms1=Rsk1_S_UL_rawrms_1(:,2:7);

%getting the overall average from each of the 6 columns, will give 6
%columnsn, the average of each column
a_rms1=mean(rms1)

%saving the file into the folder you are working with now as a .txt
save overallrms_sk1_S_UL_raw_1.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_UL_raw_1.txt peakrms_1 -ASCII -TABS;
```

```
%trial 2
```

```
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\UL\Rsk1_S_UL_rawrms_2.txt;
rms1=Rsk1_S_UL_rawrms_2(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_UL_raw_2.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_UL_raw_2.txt peakrms_1 -ASCII -TABS;
```

```
%trial 3
```

```
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\UL\Rsk1_S_UL_rawrms_3.txt;
rms1=Rsk1_S_UL_rawrms_3(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_UL_raw_3.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_UL_raw_3.txt peakrms_1 -ASCII -TABS;
```

```
%trial 4
```

```
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\UL\Rsk1_S_UL_rawrms_4.txt;
rms1=Rsk1_S_UL_rawrms_4(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_UL_raw_4.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_UL_raw_4.txt peakrms_1 -ASCII -TABS;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%SKIDDER 1 FLOOR UNLOADED RAW%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%trial 1
```

```

load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\UL\Rsk1_F_UL_rawrms_1.txt;
rms1=Rsk1_F_UL_rawrms_1(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_UL_raw_1.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_UL_raw_1.txt peakrms_1 -ASCII -TABS;

%trial 2
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\UL\Rsk1_F_UL_rawrms_2.txt;
rms1=Rsk1_F_UL_rawrms_2(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_UL_raw_2.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_UL_raw_2.txt peakrms_1 -ASCII -TABS;

%trial 3
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\UL\Rsk1_F_UL_rawrms_3.txt;
rms1=Rsk1_F_UL_rawrms_3(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_UL_raw_3.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_UL_raw_3.txt peakrms_1 -ASCII -TABS;

%trial 4
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\UL\Rsk1_F_UL_rawrms_4.txt;
rms1=Rsk1_F_UL_rawrms_4(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_UL_raw_4.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_UL_raw_4.txt peakrms_1 -ASCII -TABS;

%%%%%%%%%SKIDDER 1 SEAT LOADED RAW%%%%%%%%%

%trial 1
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\L\Rsk1_S_L_rawrms_1.txt;
rms1=Rsk1_S_L_rawrms_1(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_L_raw_1.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_L_raw_1.txt peakrms_1 -ASCII -TABS;

%trial 2
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\L\Rsk1_S_L_rawrms_2.txt;
rms1=Rsk1_S_L_rawrms_2(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_L_raw_2.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_L_raw_2.txt peakrms_1 -ASCII -TABS;

%trial 3
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\L\Rsk1_S_L_rawrms_3.txt;
rms1=Rsk1_S_L_rawrms_3(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_L_raw_3.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_L_raw_3.txt peakrms_1 -ASCII -TABS;

%trial 4
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\L\Rsk1_S_L_rawrms_4.txt;
rms1=Rsk1_S_L_rawrms_4(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_L_raw_4.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_L_raw_4.txt peakrms_1 -ASCII -TABS;

```

%%%%%%%%%%SKIDDER 1 FLOOR LOADED RAW%%%%%%%%%

```
%trial 1
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\L\Rsk1_F_L_rawrms_1.txt;
rms1=Rsk1_F_L_rawrms_1(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_L_raw_1.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_L_raw_1.txt peakrms_1 -ASCII -TABS;

%trial 2
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\L\Rsk1_F_L_rawrms_2.txt;
rms1=Rsk1_F_L_rawrms_2(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_L_raw_2.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_L_raw_2.txt peakrms_1 -ASCII -TABS;

%trial 3
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\L\Rsk1_F_L_rawrms_3.txt;
rms1=Rsk1_F_L_rawrms_3(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_L_raw_3.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_L_raw_3.txt peakrms_1 -ASCII -TABS;

%trial 4
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\L\Rsk1_F_L_rawrms_4.txt;
rms1=Rsk1_F_L_rawrms_4(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_L_raw_4.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_L_raw_4.txt peakrms_1 -ASCII -TABS;
```

%%%%%%%%%%

%%%%%%%%%%SKIDDER 1 SEAT UNLOADED W%%%%%%%%%

```
%trial 1
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\UL\Rsk1_S_UL_wrms_1.txt;
rms1=Rsk1_S_UL_wrms_1(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_UL_w_1.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_UL_w_1.txt peakrms_1 -ASCII -TABS;

%trial 2
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\UL\Rsk1_S_UL_wrms_2.txt;
rms1=Rsk1_S_UL_wrms_2(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_UL_w_2.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_UL_w_2.txt peakrms_1 -ASCII -TABS;

%trial 3
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\UL\Rsk1_S_UL_wrms_3.txt;
rms1=Rsk1_S_UL_wrms_3(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_UL_w_3.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_UL_w_3.txt peakrms_1 -ASCII -TABS;

%trial 4
```



```

load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\UL\Rsk1_S_UL_wrms_4.txt;
rms1=Rsk1_S_UL_wrms_4(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_UL_w_4.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_UL_w_4.txt peakrms_1 -ASCII -TABS;

```

%%%%%%%%%%%%SKIDDER 1 FLOOR UNLOADED W%%%%%%%%%

```

%trial 1
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\UL\Rsk1_F_UL_wrms_1.txt;
rms1=Rsk1_F_UL_wrms_1(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_UL_w_1.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_UL_w_1.txt peakrms_1 -ASCII -TABS;

%trial 2
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\UL\Rsk1_F_UL_wrms_2.txt;
rms1=Rsk1_F_UL_wrms_2(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_UL_w_2.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_UL_w_2.txt peakrms_1 -ASCII -TABS;

%trial 3
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\UL\Rsk1_F_UL_wrms_3.txt;
rms1=Rsk1_F_UL_wrms_3(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_UL_w_3.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_UL_w_3.txt peakrms_1 -ASCII -TABS;

%trial 4
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\UL\Rsk1_F_UL_wrms_4.txt;
rms1=Rsk1_F_UL_wrms_4(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_UL_w_4.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_UL_w_4.txt peakrms_1 -ASCII -TABS;

```

%%%%%%%%%%%%SKIDDER 1 SEAT LOADED W%%%%%%%%%

```

%trial 1
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\L\Rsk1_S_L_wrms_1.txt;
rms1=Rsk1_S_L_wrms_1(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_L_w_1.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_L_w_1.txt peakrms_1 -ASCII -TABS;

%trial 2
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\L\Rsk1_S_L_wrms_2.txt;
rms1=Rsk1_S_L_wrms_2(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_L_w_2.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_L_w_2.txt peakrms_1 -ASCII -TABS;

%trial 3
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\L\Rsk1_S_L_wrms_3.txt;

```

```

rms1=Rsk1_S_L_wrms_3(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_L_w_3.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_L_w_3.txt peakrms_1 -ASCII -TABS;

%trial 4
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\seat\L\Rsk1_S_L_wrms_4.txt;
rms1=Rsk1_S_L_wrms_4(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_S_L_w_4.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_S_L_w_4.txt peakrms_1 -ASCII -TABS;

%%%%%%%%%%%%%SKIDDER 1 FLOOR LOADED W%%%%%%%%%%%%%

%trial 1
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid1\floor\L\Rsk1_F_L_wrms_1.txt;
rms1=Rsk1_F_L_rawrms_1(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_L_w_1.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_L_w_1.txt peakrms_1 -ASCII -TABS;

%trial 2
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid2\floor\L\Rsk1_F_L_wrms_2.txt;
rms1=Rsk2_F_L_rawrms_2(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_L_w_2.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_L_w_2.txt peakrms_1 -ASCII -TABS;

%trial 3
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid2\floor\L\Rsk1_F_L_wrms_3.txt;
rms1=Rsk2_F_L_rawrms_3(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_L_w_3.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_L_w_3.txt peakrms_1 -ASCII -TABS;

%trial 4
load C:\FILES\schoolfiles\MY_THESIS\skidprocessed\Rskid2\floor\L\Rsk1_F_L_wrms_4.txt;
rms1=Rsk2_F_L_rawrms_4(:,2:7);
a_rms1=mean(rms1)
save overallrms_sk1_F_L_w_4.txt a_rms1 -ASCII -TABS;
peakrms_1=max(rms1)
save peakrms_sk1_F_L_w_4.txt peakrms_1 -ASCII -TABS;

```

Calculates the Running RMS Acceleration of Signal

%%%

% Written By: Natasha Lee-Shee & Sarah Cation 2007

% Name: runningrms.m

%Description: This function calculates the running RMS of a signal

%%%

```
function runner=runningrms(data,wtime,otime,fs)
%-----function written by Natasha Lee-Shee 2007-----
%This function calculates the running RMS of a signal.
%
%runner=runningrms(data,wtime,otime,fs)
%
%runner: column vector of output running rms signal
%data: column vector of input signal
%wtime: size of running window in seconds
%otime: size of overlap for slide motion in seconds
%fs: sampling frequency of input signal in Hertz
%
%-----
%
win=wtime*fs; %full window
window=round(win/2); %preparing window to span data point equally
overlap=round(otime*fs);
[rsize,col]=size(data);
clear col;

%runner=zeros(rsize,1); %initialise matrix
i=window+1; %initialise data counter to ensure window starts in data-set
while (i+window)<=rsize
    runner(i-window:i-window+overlap,1)=(mean(data(i-window:i+window,1).*data(i-window:i+window,1)))^0.5;
    i=i+overlap;
end
%if i<rsize %RMS for last values
% runner(i:rsize,1)=mean(data(i:rsize,1).*data(i:rsize,1))^0.5;
%end
%figure
%plot(runner)
%figure
%plot(data)
%clear
```

Appendix B -- CONSENT TO PARTICIPATE IN RESEARCH

The consent to participate in research was submitted under Robert J Jack, PhD candidate and Michele Oliver, Associate Professor, at the University of Guelph.

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. dissertation 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.

PROCEDURES

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 heel 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 with

out nay 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 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 "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

Field Study Questionnaire

A modified Laurentian University "Evaluation of Whole-body-vibration, Seat Design & Performance, and Sitting Posture in Large Mobile Equipment" survey questionnaire was used.

Modifications were made by Robert J. Jack
Questionnaire was administered by Robert J. Jack

Skidder Test Sheet

Date: _____ Time: _____

Vehicle Type: _____

Vehicle Size: _____

Vehicle ID Number: _____

Maintenance: _____

Tire Pressure: _____

Seat Height: _____

Operator ID Number: _____

Other Comments: _____

Pictures:

Description

Whole vehicle

File Name/Location: _____

Seat

File Name/Location: _____

Route/Track

File Name/Location: _____

Operator ID# _____

Vibration Data Trials

[illegible]

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

**Musculoskeletal Disorder and
Operator Cab Design Questionnaire**

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 principal 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

or

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
 11. How would you rate your physical fitness level?
☐ poor ☐ average ☐ above average ☐ excellent
 12. 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
 13. On average, how many minutes are your activity sessions?
☐ 0-14 min ☐ 15-29 min ☐ 30-44 min ☐ over 45mins
 14. What types of activities do you perform?

 15. Shank length? _____
 16. Thigh length? _____
- Operator ID# _____

Part B: Musculoskeletal Disorders

The body has been divided into seven different areas.

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.
 5. 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)

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

Operator ID# _____

Shoulder

20. 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)

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

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

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

24. Have you ever had to change duties or jobs or miss work because of your neck trouble?

☐ Yes

☐ No

Operator ID# _____

Upper Back

25. 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)

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

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

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

29. Have you ever had to change duties or jobs or miss work because of your neck trouble?

☐ Yes

☐ No

Operator ID# _____

Elbows

30. 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)

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 neck?

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

34. Have you ever had to change duties or jobs or miss work because of your neck trouble?

☐ Yes

☐ No

Operator ID# _____

Low Back

35. 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)

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

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

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

39. Have you ever had to change duties or jobs or miss work because of your neck trouble?

☐ Yes

☐ No

Operator ID# _____

Wrist/Hands

40. 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)

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

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

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

44. Have you ever had to change duties or jobs or miss work because of your neck trouble?

☐ Yes

☐ No

Operator ID# _____

Hips/Thighs/Buttocks

45. 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)

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

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

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

49. Have you ever had to change duties or jobs or miss work because of your neck trouble?

- ☐ Yes ☐ No

Operator ID# _____

Knees

50. 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)

51. 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

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

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

54. Have you ever had to change duties or jobs or miss work because of your neck trouble?

☐ Yes

☐ No

Operator ID# _____

Ankles/Feet

55. 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)

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

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

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

59. Have you ever had to change duties or jobs or miss work because of your neck trouble?

☐ Yes

☐ No

Operator ID# _____

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.

Task Description	How often does this occur?	How was visibility impaired? What couldn't be seen?	What aspect of the cab design impaired your visibility?	How did your impaired visibility affect you posture? Describe the posture of the neck, shoulders, truck, hips, and legs.

62. When operating a skidder, are there any times where you have to adjust your posture in order manipulate the machine's controls?

☐ Yes

☐ No

Operator ID# _____

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

Task Description	How often does this occur?	Describe why you have to change your posture to manipulate the machine's controls during the task	Describe the adopted posture of the neck, shoulders, truck, hips, and legs.

Operator ID# _____

***THANK YOU FOR YOUR
PARTICIPATION***