FOOT-TRANSMITTED VIBRATION: EXPOSURE CHARACTERISTICS AND THE BIODYNAMIC RESPONSE OF THE FOOT

by

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Abstract

Research shows miners can be exposed to foot-transmitted vibration (FTV) when operating various pieces of underground mining equipment, and case reports suggest workers are experiencing symptoms similar to those of hand-arm vibration syndrome in their feet. A field study was conducted to measure and document FTV exposure associated with operating underground mining equipment, and probable health risks were determined based on both ISO 2631-1 (1997) for WBV and ISO 5349-1 (2004) for HAV. Seventeen participating operator's also reported musculoskeletal discomfort. Seventeen male participants ranging between 24-61 years of age, with an average height and mass of 175.0cm and 88.2kg volunteered for the study. Seventeen pieces of equipment were tested; 1 locomotive, 1 crusher, 9 bolter drills (4 scissor platforms, 2 Maclean, 2 Boart/basket, and 1 RDH), and 6 jumbo drills.

Including all seventeen pieces of underground mining equipment, the vibration acceleration ranged from 0.13-1.35m/s^2 with dominant frequencies between 1.25-250Hz according to ISO 2631-1. According to ISO 5349-1 vibration acceleration ranged from 0.14-3.61m/s^2 with dominant frequencies between 6.3-250Hz. Furthermore, the magnitude of FTV measured on the jumbo drills with grated platforms (#5 and #6) was less than FTV measured from the jumbo drills with, solid metal surfaces. Additionally, twelve of the seventeen equipment operators indicated a complaint of discomfort in their lower body (specifically at the level of the knee or lower). The health risk analysis based on ISO 2631-1 indicated that one operator (bolter drill #9) was exposed to vibration above the criterion value, while the health risk analysis based on ISO 5349-1 indicated

that two operators (jumbo drill #1 and bolter drill #1) were exposed to vibration above the criterion value. Operators reported very severe or severe discomfort; however, the same operators were not the operators of the equipment with FTV exposure levels above the ISO standards, leaving evidence to suggest that the standards are not properly assessing injury risk to vibration exposure via the feet. Future research is needed to develop a standard specific for FTV and to determine the link between early musculoskeletal injury reporting and the onset of vibration white foot. To do so, a better understanding of the biodynamic response of the foot to FTV is needed.

A laboratory study was conducted to 1) measure and document transmissibility of FTV from (a) floor-to-ankle (lateral malleolus), and (b) floor-to-metatarsal, during exposure to six levels of vibration (25Hz, 30Hz, 35Hz, 40Hz, 45Hz, and 50Hz) while standing, and 2) to determine whether independent variables (vibration exposure frequency, mass, arch type) influence transmissibility (dependent variable) through the foot. A two-way repeated measures analysis of variance (ANOVA) was conducted. There was a significant interaction between transmissibility location and exposure frequency ($\lambda = 0.246$, $F(5,25) = 15.365$, $p = 0.0001$). There were significant differences in mean transmissibility between the ankle and metatarsal at 40Hz [$t(29) = 4.116$, $p = 0.00029$], 45Hz [$t(29) = 6.599$, $p = 0.00000031$], and 50Hz [$t(29) = 8.828$, $p = 0.000000001$]. The greatest transmissibility at the metatarsal occurred at 50Hz and at the ankle (lateral malleolus) transmissibility was highest from 25-30Hz, indicating the formation of a local resonance at each location.

Future research should focus on identifying resonance frequencies at different locations on the feet. This information is needed to develop an exposure guideline to help protect workers from exposure to FTV, and to develop personal protective equipment capable of attenuating harmful FTV exposure frequencies.

Acknowledgements

During my undergraduate degree I was fortunate enough to attend a talk given by Venus Williams at a Women of Influence conference. She told a story about how her father brought home the movie Cinderella and let all of the girls (5 daughters) watch it. After the movie he proceeded to ask each of them what the most important part of the movie was? One-daughter answers, “If you work hard, you will eventually get everything you want in life.” A second daughter replied, “If you’re really nice to people, you will have lots of friends who will help you.” The father says, “No. The most important part of the movie is when Cinderella thanks the Fairy God Mother for everything she was given.”

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Co-Authorship

Chapters 2 and 3 have been presented as manuscripts ready for submission and publication in peer-reviewed journals. The following is a list of proposed papers with contributing authors:

Chapter 2: K., Goggins, T., Eger, and A. Godwin
INVESTIGATION OF VIBRATION CHARACTERISTICS ACCORDING TO ISO 2631-1 AND ISO 5349-1, AND SELF REPORTED MUSCULOSKELETAL DISCOMFORT FOR MINERS EXPOSED TO VIBRATION VIA THE FEET

Chapter 3: Goggins, K., Eger, T., Godwin, A., Jack, R.J., and Boudreau-Larivière, C.
EXAMINATION OF VIBRATION TRANSMISSIBILITY FROM FLOOR TO METATARSAL AND FLOOR TO ANKLE BETWEEN 25 AND 50 HZ

Author Contributions

All phases of data collection and analysis were led by K. Goggins in consultation with Dr. Eger. Dr. Godwin assisted K. Goggins with the statistical analysis and Dr. Jack assisted with the data processing and analysis for the laboratory study in Chapter 3. Dr. Boudreau-Lariviere provided additional methodological guidance associated with the laboratory study and expertise regarding the physiological response of the body to vibration.

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GLOSSARY

Abbreviation	Long Form
A(8)	8-hour energy equivalent vibration total value
ANOVA	analysis of variance
ANCOVA	analysis of covariance
a_{hv}	vibration total value of frequency-weighted r.m.s. acceleration (sometimes known as the vector sum or the frequency-weighted acceleration sum); it is the root-sum-of-squares of the a_{hw} for the three measured axes of vibration (ISO 5349-1)
a_{wx}	frequency-weighted r.m.s. acceleration in the x-axis (ISO 2631-1)
a_{wy}	frequency-weighted r.m.s. acceleration in the y-axis (ISO 2631-1)
a_{wz}	frequency-weighted r.m.s. acceleration in the z-axis (ISO 2631-1)
COP	centre of pressure
DF	dominant frequency
FTV	foot-transmitted vibration
HAV	hand-arm vibration
HAVS	hand-arm vibration syndrome
HGCZ	health guidance caution zone
ISO	International Organization for Standardization
MATlab	matrix laboratory
r.m.s.	root-mean-square
SD	standard deviation
SPSS	statistical package for the social sciences
VATS	vibration analysis toolkit
VDV	vibration dose value
VWFt	vibration white foot
WBV	whole-body vibration
W_d	weighting factor, applied to the x & y axes, as described in IS0 2631-1
W_h	frequency-weighting characteristics for hand-transmitted vibration, as described in ISO 5349-1
W_k	weighting factor, applied to the z-axis, as described in IS0 2631-1

VIBRATION: TERMINOLOGY AND DEFINITIONS

Most of the vibration vocabulary relevant to the thesis document has been listed and defined. However, for a complete listing of common terminology and definitions used throughout this thesis the reader should refer to ISO 2631-1 (1997): Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration and ISO 5349-1 (2004): Mechanical vibration – Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration.

***A*(8)** – A convenient alternative term for the daily vibration exposure $a_{hv(eq,8h)}$, expressed in meters per second squared (m/s^2), including all whole-body vibration exposures during the day.

Amplification: An increase in amplitude and intensity of a signal.

Attenuation: A reduction in amplitude and intensity of a signal.

Biodynamic/biomechanical response: The science of the physical, biological and mechanical properties and responses of the human body (tissues, organs, parts and systems) to an external force (vibration) or in relation to the internal forces, produced by an interplay of external forces and the body's mechanical activity.

Datalogger: A fully portable, subject worn, programmable data acquisition unit.

Dominant frequency: A frequency at which a maximum value occurs in a spectral density curve.

Frequency-weighted: A term indicating that a wave-form has been modified according to some defined frequency-weighting.

Frequency-weighting: A transfer function used to modify a signal according to a required dependence on vibration frequency.

FTV: Foot-transmitted vibration is vibration that is transmitted to the feet and legs of operators from vibrating tools or vibrating machinery.

HTV: Hand-transmitted vibration is vibration that is transmitted to the hands and arms of operators from vibrating tools or vibrating machinery.

ISO 2631-1: The International Standard for Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration.

ISO 5349-1: The International Standard for Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration.

MATLab: A high-level language and interactive environment for numerical computation, visualization, and programming. Allows for data analysis, algorithm development, and model and application creation.

Multiple resolution cross-correlation (MRXcorr): a procedure used to align data time histories from two separate dataloggers.

Resonance Frequency: Simply put, the frequency at which resonance occurs. At the resonant frequency of a system, maximal oscillation will occur. Resonant frequency is the point at which maximum displacement between organs and skeletal structures occurs, thereby placing strain on the body tissue involved.

Root-mean-square (r.m.s.): For a set of numbers, the square root of the average of their squared values.

Transmissibility: Transmissibility is defined as the ratio of the vibration measured between two points.

VATS: The vibration analysis toolkit. A software application used to derive the various measures required by the ISO 2631-1 standard for assessing the health effects of whole-body vibration exposure and the ISO 5349-1 for assessing the health effects of hand-transmitted vibration.

Vibration: An oscillatory motion about a fixed reference point.

WBV: Whole body vibration is vibration that is transmitted into the human body through the buttocks, back and/or feet of a seated person, the feet of a standing person, or the supporting area of a recumbent person.

CHAPTER ONE

REVIEW OF LITERATURE

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REVIEW OF LITERATURE

1.1 Introduction

A number of environmental factors can place a worker's health at risk, including workplace temperature, noise, and exposure to various types of vibration (Bovenzi, 1998; ISO 2631-1, 1997; Griffin, 1990). Certain industries, notably mining, construction, and forestry involve high levels of vibration, including complex 6 degree of freedom (6-df) vibration (Dickey et al., 2006). Workers can be exposed to whole body vibration (WBV), which occurs when the human body is supported on a surface, which is vibrating, or hand transmitted vibration (HTV) that occurs when vibration enters through the hands of workers using vibrating tools (Bovenzi, 2005). It has been well documented that prolonged exposure to WBV places workers at increased risk for health problems, including spine and neck disorders, vascular disorders, hearing loss, gastrointestinal disorders, as well as motion sickness (Pope et al., 2002; Bovenzi et al., 2006; Bovenzi, 2008). Prolonged exposure to HTV places workers at risk for hand-arm-vibration syndrome, a complex of osteoarticular, neurological and vascular disorders including vibration induced white finger (Bovenzi, 2005; Griffin, 2008; Hagberg et al., 2008). The broad spectrum of equipment and diverse postures of workers operating the equipment exposes miners to different types of vibration, sometimes simultaneously (Eger et al., 2008). Miners can be exposed to foot transmitted vibration (FTV) when operating locomotives, bolters, jumbo drills, and or drills attached to platforms workers stand on (Thompson et al., 2010). More specifically, miners who work with bolters face unique circumstances whereby they are exposed at two contact points because they are standing on a vibrating platform (FTV) while handling a vibrating tool (HTV). Case reports suggest miners are experiencing pain, discomfort, and blanching in the toes more often than co-workers not exposed to vibration via the feet (Thompson et al., 2010; Leduc et al., 2011).

Researchers studying the effects of HAV syndrome have found a correlation between the neurological and vascular symptoms observed in the upper extremities and symptoms observed in the feet of workers affected by HAV syndrome (Sakakibara, 1998; Hedlund, 1989; Hashiguchi et al., 1994). A recent case study also reported a miner was diagnosed with vibration induced white foot without a corresponding diagnosis of HAV syndrome (Thompson et al., 2010). Given the anatomical and physiological similarities of the hands and the feet, and recent reports of vibration induced white foot associated with HAV syndrome (Leduc et al., 2011), it is not unreasonable to question the health risks associated with FTV. The majority of research on FTV focuses on the transmissibility of vibration in the standing position versus sitting position as opposed to the actual effects of vibration on the foot itself (Fritz, 2000; Matsumoto & Griffin, 2000). There are two common International Standards for occupational safety that address WBV exposure ISO 2631-1 (1997) and HAV exposure ISO 5349-1(2004); neither are designed to evaluate FTV. A review of available literature on FTV indicates the need for further investigation specific to vibration exposure at the feet in order to gain a better understanding of risk factors.

The purpose of the present research on FTV is two-fold. The initial study will document the characteristics of FTV experienced by underground mine workers, while the second study will examine the biodynamic response of the foot when exposed to different frequencies of FTV. In order to gain a better understanding of the role of FTV, the focus of this review will incorporate: an understanding of vibration and its transmissibility; the epidemiological effects of WBV, HTV, FTV and standing vibration; the mechanics of the foot and documented injuries; as well as a review of previous field studies on FTV.

1.2 Vibration Overview

1.2.1Vibration Basics

Vibration is often complex, contains many frequencies, occurs in several directions and changes over time (ISO 2631-1, 1997). Vibration is an oscillatory motion, which can be created in different forms: sinusoidal, random, stationary and transient. Sinusoidal motion is a periodic motion that repeats itself over a certain time interval. The frequency of this motion is expressed as cycles of motion per second. The standard international (S.I.) unit currently utilized to define the frequency of vibration is Hertz (Hz) (Cardinal & Pope, 2003). Linear vibration can be measured in the x, y, z, axis and rotational vibration can be measured about the same axis resulting in a 6 degree of freedom (6-df) signal, (vertical, fore and aft, lateral, roll, pitch and yaw). Recently, researchers have started to evaluate comfort and health effects associated with exposure to 6-df vibration (Oliver et al., 2010; Dickey et al., 2008; Dickey et al., 2010). Human response to vibration is dependent on the magnitude, frequency and direction of the vibration signal (Griffin, 1990). Vibration magnitude is quantified by its displacement (m), its velocity (m/s) or its acceleration (m/s^2) (Bovenzi, 2005). Biodynamic investigations, which show the relationship between human physiology and environmental stimuli, have shown that vibration frequency is the dependent factor in how the human body responds to vibration (Griffin, 1990).

1.2.2 Biodynamic Response

Many factors influence the human response to vibration both intrinsic and extrinsic. Intrinsic variables can include population type (age, sex, size, and health), experience and body posture, motivation, financial involvement, expectations and types of activities (ISO 2631-1, 1997). More specifically, population type (age, sex, size, and health) relate to the biodynamic response due to their potential effects on vasoconstriction of vasculature affecting blood flow to the periphery. Experience and body posture, motivation, financial involvement, expectations and types of activities need to be considered as many workers are willing to disregard their short-term symptoms or discomfort without regard for cumulative effects. Whereas extrinsic variables can include vibration magnitude, vibration frequency, vibration axis, vibration input position, vibration duration, seating, restraints, and other environmental influences such as noise, heat, acceleration, and light (Bovenzi, 1998; ISO 2631-1, 1997; Griffin, 1990).

Other factors believed to influence the injurious effects of vibration, include the duration of exposure which can be measured as daily, yearly, or lifetime cumulative exposure, the pattern of exposure either continuous, intermittent, or with rest periods (Bovenzi, 2005). Dependent variables, which can be measured to determine the biodynamic response of the human body to vibration include: mechanical impedance, vibration transmissibility and absorbed energy. Independent variables, which can be manipulated or controlled to determine if they lead to changes in the biodynamic response as measured by dependent variables include individual user characteristics such as how the tool is held, the driving style, skill level of the individual, and the use of personal protective equipment (Bovenzi, 2005).

1.2.3 Transmissibility

Transmissibility is a measure of the ability of the body to either amplify or suppress input vibration. A variety of biodynamic responses, particularly those between the point at which the vibration enters the body and the point at which it is measured are reflected in the transmissibility of the human body. The process of averaging the individual data to obtain a mean or median transmissibility curve loses the individual response and the large range of inter-subject variability (Padden & Griffin, 1998). Some of the variables which affect transmissibility are the type and magnitude of vibration, body posture and muscle tension.

Transmissibility is defined as the ratio of the vibration measured between two points (Mansfield, 2005). When the majority of the vibration is transmitted through an object or body the transmissibility value obtained is high (around 1.0). Conversely, if most of the vibration is attenuated, or not transmitted through the object or body, the transmissibility value will be low (around 0.0). A transmissibility value greater than 1.0 indicates that the object is amplifying the vibration. Transmissibility values can be obtained using the following formula:

$$Transmissibility\ of\ vibration = \frac{Vibration\ output(in\ m/s^2)}{Vibration\ input(in\ m/s^2)}$$

1.3 Resonant Frequency

Resonant frequency is the point at which maximum displacement between organs and skeletal structures occurs, thereby placing strain on the body tissue involved. To stimulate the natural frequency of an isolated organ without exciting the whole-body resonances is almost impossible (Randall et al., 1997). The principle resonance of the human body in most literature is reported as 4-6 Hz. Experimental studies have found that resonance frequencies of most of the organs or other parts of the body lie between 1 and 10Hz, which are in the range of frequencies found in occupational machines (Noorloos et al., 2008). Unfortunately, the majority of studies tend to examine the seated driver and focus on the effects of WBV transmitted through the seat pan to the seat of the operator and not exposure to vibration via the feet in the standing individual. However, Randall and colleagues (1997) examined the resonant frequencies of standing humans and found the overall range to be 9-16 Hz independent of mass, height, and mass to height ratio. The frequency at which the hand-arm system is believed to be at greatest risk of injury is in the 20-40 Hz range while the fingers are at greater risk above 100 Hz (Griffin, 1990; Dong et al, 2004). There is little literature available on resonant frequency specific to the feet, though Forta et al., (2011) found the absolute threshold for the feet for vertical vibration (expressed in terms of acceleration) independent of frequency to be from 8-25 Hz. There are no reported resonant frequency values specific to the feet, however given the anatomical and physiological similarities between the hands and feet it is not unreasonable to speculate the frequencies would be in the same range.

1.4 Epidemiological Evidence

It has been estimated that 4-7% of all employees in the United States, Canada, and some European countries are exposed to potentially harmful WBV (Bovenzi et al., 2002). Exposure to WBV has been associated with an increased risk of spine and neck disorders, vascular disorders, hearing loss, gastrointestinal disorders, changes in joint stability, as well as motion sickness (Pope et al., 2002; Bovenzi et al., 2006; Bovenzi, 2008).

Although WBV has been indicated as a risk factor, other factors may also help contribute to the development of injuries, especially in the drivers of heavy equipment vehicles. Prolonged sitting, awkward postures, stress and fatigue as well as individual factors such as pre-existing health problems, age and body mass can also contribute to an increase prevalence of injury.

In addition to the strong evidence of harmful effects and risk factors associated with WBV, a number of researchers have focused on the effects and risk factors related specifically with HAV from the use of vibrating tools and equipment (Bovenzi, 2005; Griffin, 2008; Hagberg et al., 2008; Murata et al., 1991). Hand-arm-vibration syndrome includes a complex of osteoarticular, neurological and vascular disorders. Raynaud's phenomenon or vibration-induced white finger constitutes the vascular component of HAV syndrome, peripheral neuropathy with sensory impairment comprises the neurologic component, and degenerative changes of the bones and joints of the upper extremities, particularly the wrists and elbows characterize the osteoarticular element (Bovenzi, 2005).

Occupations at risk for HAV syndrome include forestry workers, miners, construction workers, and metal workers. Approximately 1.7- 5.8% of workers in the United States, Canada, and European Countries are exposed to HTV (Bovenzi, 2005). Epidemiologically the prevalence of vibration white finger (VWF) ranges from 0-5% in geological areas with warm climates, to 80-100% of exposed workers in northern climates (Bovenzi, 2005).

Researchers studying the effects of HAV syndrome have found a correlation between the neurological and vascular symptoms observed in the upper extremities and symptoms observed in the feet of workers affected by HAV syndrome. However, there has been one reported case of a worker with vibration induced white foot without a corresponding diagnosis of HAVS (Thompson et al., 2010).

1.5 Hand-Arm Vibration

Little is known about the effects of FTV. With the anatomical and physiological similarities between the feet and the hands it is prudent to review comparable literature regarding the hand arm system in order to gain a better understanding of the potential risk factors associated with FTV. HTV occurs when vibration enters the body through the hands. Vibration frequencies in the 6.3-1250 Hz range can precipitate disorders in the hand-arm system (Bovenzi, 2005; ISO 5349-1, 2004). Prolonged exposure to HTV from powered processes or tools has been associated with vascular, neurological and osteoarticular changes in the upper limbs. The occurrence of digital tingling and numbness, decreased tactile perception and loss of manipulative dexterity in workers using vibrating tools is greater than those not exposed to HTV. Studies have revealed an increase in sensorineural disorders with an increase of daily vibration exposure, duration of exposure, or lifetime cumulative vibration dose (Bovenzi, 2005).

Palmer et al. (2001) and Musson et al. (1989), both conducted postal surveys to assess the extent to which workers are exposed to HTV. Musson's study obtained 169 respondents from the Netherlands which included workers using a variety of impact power tools; riveting hammers (13), road breakers (36), chipping hammers (25), hammer drills (24), rammers (48) and other types of tools (23). Using 1900 working hours as the equivalent of a year in working time, it was calculated that workers were exposed to HTV for 23% of time worked. Results showed that 17% of respondents reported symptoms of white finger of which half reported the symptoms on both hands and all digits except the thumbs. This study concluded that the duration of HTV in conjunction with other risk factors contributed to symptom development of pain or stiffness of the back, neck and upper limbs as well as stomach. Palmer's survey investigated the prevalence of Raynaud's phenomenon among workers in Great Britain and estimated the number of cases attributable to HTV. The questionnaire focused on the history of vibration exposure both HTV and WBV as well as history of finger blanching. Of the 12907 respondents, 6913 were men and 5994 were women aged 16-64 years. Of these respondents 1835 (14.2%) reported finger blanching at some time, of these 1529 (11.8%) were cold induced and 597 (4.6%) had clearly demarcated blanching. Prevalence was higher in women than men and approximately 2% of respondents had consulted a physician regarding their symptoms. Higher risks were found in men who had sought medical advice for cold induced blanching, of these 37.6% of cases were attributable to HTV whereas only 5.3% of cases for females were attributable to HTV. Unfortunately the surveys focused solely on symptoms relative to the hand-arm system and did not inquire about similar symptoms in the lower extremities.

A number of researchers have examined the effects of HTV frequency and magnitude on the blood flow of the fingers and toes (Thompson & Griffin, 2009; Egan et al., 1996; Furuta et al, 1991). All three studies showed a significant reduction in blood flow to the fingers of both the exposed and non-exposed hands, and a study by Egan (1996) showed a reduction in toe blood flow and an increase in heart rate. Egan and colleagues (1996) concluded that hand vibration produced a generalized increase in sympathetic tone in the heart and extremities, which may be a factor in the development of vasospastic disease with long term use of hand held vibrating tools.

Hashiguchi et al. (1994) studied the fingers and toes of 21 male patients with vibration syndrome and 13 male cadavers. They reported a thickening of the medial muscle layer of small arteries and arterioles as well as collagen fiber increases in connective tissues in perivascular regions of the fingers and toes of patients with vibration syndrome. It was concluded that these results in the toes could be attributed to not only direct vibration exposure of the foot itself but also to long term repeated circulatory disturbances and vasoconstriction caused by the sympathetic nervous system activation from HAV. This study also suggests the more severe the circulatory disturbance of the hand is the greater the likelihood of circulatory disturbance to the foot which correlates to findings that the more frequent the attacks of Raynaud's phenomenon in the fingers the greater the likelihood of complaints of coldness to the feet.

Vibration stimuli to the hand, is mediated by four classes of mechanoreceptive afferent nerve fibres in the glabrous skin of the hand. Each class of fibre is distributed differently over the skin surface and has a unique response to vibration stimuli. Fast adapting fibres (FA) include Meissner corpuscles (FA I) and Pacinian corpuscles (FA II). FA I fibres are most sensitive at frequencies between 5 and 50 Hz and FA II fibres at frequencies greater than about 40 Hz. Slow adapting (SA) fibres include Merkel discs (SA I) and Ruffini endings (SA II), which are most sensitive to vibration frequencies less than about 8 Hz (Morioka & Griffin, 2005). Absolute threshold is the lowest intensity at which vibration stimuli can be detected 50% of the time. Morioka and Griffin, (2005) examined mean vibration perception thresholds as a function of frequency at three locations on the hand; distal finger, distal palm, and proximal palm. Findings indicated that thresholds reduced systematically as the contact area increased from the fingertip to the whole hand, and the increased sensitivity with increased contact area (from finger to whole hand) may be caused by greater transmission of vibration from the hand than the finger and differences in contact pressures between hand and finger. The same mechanoreceptive afferent nerve fibres are present in the feet as well as the hands, therefore these reported differences between transmission at the fingers and the palm of the hand, combined with the anatomical similarities between the hands and feet suggest measurements on the foot should be taken at both the toes and the heel.

1.6 Standing Vibration

The majority of studies on standing vibration focus on transmissibility of vibration from the feet to the lumbar spine, cervical spine and head (Paddan, 1987; Griffin, 1990). Harazin and Grzesik (1998) investigated vertical WBV to six body segments while standing including the metatarsus, ankle, knee, hip shoulder and head. Results showed the magnitude of vibration being transmitted by the foot is amplified in the frequency range of 31.5-125Hz at the metatarsus and 25-63Hz at the ankle, which implies the formation of a local resonance.

The whole body resonant frequency is about 5Hz in a seated person, (Griffin, 1990). Randall et al. (1997) tested the vertical whole body resonant frequencies using a vibrating beam method, imposing a low acceleration magnitude at the feet of 113 fully clothed subjects. The reported overall resonant frequency range reported was 9-16 Hz (Randall et al., 1997).

Thuong and Griffin (2011) examined how the discomfort of standing people exposed to horizontal and vertical vibration depends on vibration frequency over the range 0.5-16 Hz. With horizontal vibration at frequencies less than 3.15 Hz, subjects experienced difficulty with stability and at higher frequencies discomfort was experienced in the legs and feet. With vertical vibration, discomfort was felt in the lower and upper body at all frequencies. As the horizontal vibration frequency increased discomfort in the legs and feet increased while difficulty with balance decreased.

1.7 Vibration and the Feet

Raynaud's phenomenon of the feet has been examined mostly in conjunction with hand-arm vibration syndrome, (Hashiguchi et al., 1994; Hedlund, 1989; Sakakibara et al., 1988; Sakakibara et al., 1991). Sakakibara et al. (1988) concluded the subjects with more frequent attacks of VWF had a higher prevalence of coldness in the fingers and legs, and that the prevalence of symptoms was higher in the fingers than legs. Also numbness was more common than coldness in the fingers but coldness more common than numbness in the legs. Hedlund (1989) examined 27 underground miners exposed to HAV or WBV, cold, and other environmental factors inducing vasoconstriction in some of the miners. Furthermore, the prevalence of Raynaud's phenomenon in both the fingers and toes was greater in the workers exposed to vibration than in the control group who had no vibration exposure (Hedlund, 1989).

Singh (2013) examined vibration transmissibility via the feet in standing individuals to determine whether or not gender played a role in transmissibility and subjective reports of discomfort. Results indicated that there was no significant difference in floor-to-ankle transmissibility by gender. Findings indicated that the z-axis vibration was lower at the ankle in all but one male subject suggesting that anatomical structures such as the heel fat pad may play a role in attenuating FTV from the floor through the foot to the ankle. This study also found the percent difference in z-axis vibration between the foot and ankle to be lower for females suggesting females attenuate FTV more effectively. This study in conjunction with the Harazin and Grzesik (1998) study both imply a local resonance within the foot in standing individuals subjected to vibration via the feet. FTV can either be attenuated or amplified and if attenuated the vibration energy is absorbed. Results of lowered transmissibility indicate that the vibration energy can be absorbed at some point between the metatarsus and the ankle (Harazin & Grzesik, 1998). Given the similar small bony and vascular structures of the hand and feet it is conceivable that the feet are potentially at risk for the same injuries associated with HTV.

The literature on vibration-white foot without corresponding hand-arm-vibration syndrome is limited to one case study, (Thompson et al., 2010). The subject in this study had a history of FTV, and presented with bilateral, symmetrical vasospastic disease in the feet only. This particular individual, a miner with a 35 year work history, was exposed to FTV through the use of underground bolters at least 4 hours per day, 3 days per week in the 4 years preceding the assessment. Doppler imaging showed no peripheral artery insufficiency in the arms or legs, and vascular, neurological and musculoskeletal examination of the lower extremities was unremarkable. Cold provocation plethysmography exhibited normal plethysmographic toe waveforms at room temperature with significant dampening of the waveforms post cold stress indicating a vasomotor disturbance associated with cold sensitivity in the toes but not the fingers.

A more recent study examining vibration characteristics and reported musculoskeletal discomfort levels of miners exposed to vibration via the feet (Leduc et al., 2011) indicated two of the seven workers in the study had a diagnosis of vibration white feet in conjunction with vibration induced white hand and all seven equipment operators reported discomfort in the lower limbs. This study focused on FTV from five different types of underground equipment classified as either primary or secondary source of vibration. If the measured vibration at the foot was generated by an engine required to move the vehicle, it was classified as primary source, and if the vibration measured at the foot was generated by a drill or other tool resting on or attached to the surface the worker stood on, it was classified as a secondary source. Results indicated a large difference in the dominant frequency produced by primary source machines and platforms that vibrate from secondary source equipment. Operator predicted health risks for the wooden raise platform and metal raise platform, both secondary sources of vibration transmission were above the health guidance caution zone (HGCZ) suggested in ISO 2631-1. The standards for measurement of WBV transmitted to the human body through the feet are dictated by ISO 2631-1, but given the results of these studies it is questionable whether or not ISO 5349-1, which dictates recommended exposure limits for hand transmitted vibration, is a more appropriate tool for measuring vibration at the feet.

1.8 Evaluating Health Effects

1.8.1 ISO 2631-1 (1997): Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration

ISO 2631-1 (1997) is the most commonly accepted standard when evaluating human exposure to WBV. This standard assists in quantifying WBV in accordance to human health and comfort, the probability of vibration perception, and incidence of motion sickness. This section of the ISO 2631-1 can be used on vibration transmitted to the human body in one of three ways: (1) the feet of a standing person, (2) the buttocks, back and feet of a seated person, or (3) the supporting area of a recumbent person, (ISO 2631-1, 1997). A transducer must be located between the person and the principal contact areas of the surface to measure vibration transmitted from a non-rigid material, such as a seat cushion.

Health, comfort and perception are dependent on the vibration frequency content. Thus, different frequency weightings are required for different directions; the two principal weightings utilized are W_k (Z axis of seat surface) and W_d (X, Y axes of seat surface). The W_k and W_d weighting factors are used to filter low range frequencies as compared to the W_h weighting factor used for HAV from ISO 5349-1 (2004) (Table 1.0). More specifically, for health the ISO 2631-1 also includes multiplying factors for vibration total value depending on the axis: $k_x = 1.4$, $k_y = 1.4$, and $k_z = 1.0$.

ISO 2631-1 has limits for the amount of daily vibration a person should be exposed to in order to minimize the risk of vibration induced injury. According to the standard, the frequency-weighted r.m.s. acceleration values for the lower and upper limits of the 8-h health guidance caution zone (HGCZ) are 0.45 and 0.90m/s^2. In addition, the VDVs (vibration dose values) of the lower and upper limit of the 8-h HGCZ are 8.5 and 17m/s$^{1.75}$. Although vibration accelerations are measured in three directions (x, y, and z), only the axis associated with the dominant frequency is compared to the HGCZ.

1.8.2 ISO 5349 (2004): Mechanical vibration – Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration

This standard specifies general methods for measuring and reporting hand-transmitted vibration for periodic and random vibration exposure in three orthogonal axes (x, y, and z) for one-third octave bands, having centre frequencies from 6.3 to 1250Hz. In order to accurately measure hand-transmitted vibration, the transducers must be capable of measuring with a frequency range of at least 5 to 1500Hz, which is sufficient to cover the octave bands with centre frequencies from 8 to 1000Hz. The transducer must be located on the principal contact surface to measure vibration transmitted from a non-rigid material, similar to ISO 2631-1 (1997).

For research and development purposes and to improve knowledge of the dose-response relationship, it is strongly recommended that one-third octave band data be obtained for each acceleration component. There is also a weighting filter (W_h), which represents the relative health risk of certain vibration frequencies for the hand-arm system. The W_h weighting curve allows for a higher range of frequencies to be recorded without adding a weighting factor to them.

Table 1. Comparison of ISO 2631-1(1997) and ISO 5349-1(2004).

	ISO 2631-1(1997)	**ISO 5349-1(2004)**
Measures	Whole Body Vibration (WBV)	Hand-Arm Vibration (HAV)
Sampling Frequency	500Hz	1000Hz
Frequency Range	0.5-80Hz	6.3-1250Hz
Health Weighting Factor (Filter)	W_k (Z axis of seat surface) W_d (X,Y axes of seat surface)	W_h (health risk of certain vibration frequency for the hand-arm system)
HGCZ [A(8)]	0.45-0.90m/s^2	< 2.0m/s^2

1.9 Thesis Objectives

The purpose of this research is to better understand the characteristics of FTV in order to identify potential injury risks and to determine the most appropriate method of assessing injury risk. These objectives will be accomplished through both field and laboratory studies.

The objectives of the field study include: (1) to measure and document the characteristics and dominant frequencies of vibration entering the body via the feet on various underground mining equipment; (2) to determine and compare predicted health risks based on both ISO 2631-1 (1997) and ISO 5349-1 (2004); and (3) to examine differences in operator reported musculoskeletal discomfort.

The specific objectives of the laboratory investigation component will be to: (1) measure and document the transmission of FTV from (a) floor-to-ankle, and (b) floor-to-metatarsal with exposure to different levels of vibration while standing; (2) to determine if independent variables (vibration exposure frequency, mass, arch type) influence dependant variable transmissibility through the foot.

1.10 Thesis Outline

In order to accomplish the objectives of this study and to gain a better understanding of the complexities of evaluating FTV this paper will include the following lines of investigation.

1. Chapter 1 – Literature Review: This chapter has been designed to provide background knowledge on relevant vibration concepts, terms, and documented health problems. Previous research, which has been conducted within the field has been summarized and critiqued in order to provide a justification for the current research project.

2. Chapter 2 – Manuscript 1: The objectives of the field study include: (1) measurement and documentation of the characteristics and dominant frequencies of vibration entering the body via the feet on various underground mining equipment; (2) determination and comparison of predicted health risks based on both ISO 2631-1 (1997) and ISO 5349-1 (2004); and (3) examination of differences in operator reported musculoskeletal discomfort.

3. Chapter 3 – Manuscript 2: The objectives of the laboratory testing component include: (1) measurement and documentation of the transmission of FTV from (a) floor-to-ankle, and (b) floor-to-metatarsal, during exposure to varying levels of vibration while standing; (2) determination of whether vibration exposure frequency, mass, arch type (independent variables) influence transmissibility (dependant variable) through the foot.

4. Chapter 4 – General Discussion: Within this chapter the findings from both the field (Chapter 2) and laboratory (Chapter 3) studies are reviewed as well as potential links between the two studies identified. The relevance to miners and the mining industry in general is discussed.

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CHAPTER TWO

INVESTIGATION OF VIBRATION CHARACTERISTICS ACCORDING TO ISO 2631-1 AND ISO 5349-1, AND SELF REPORTED MUSCULOSKELETAL DISCOMFORT FOR MINERS EXPOSED TO VIBRATION VIA THE FEET

CHAPTER TWO:
INVESTIGATION OF VIBRATION CHARACTERISTICS ACCORDING TO ISO 2631-1 AND ISO 5349-1, AND SELF REPORTED MUSCULOSKELETAL DISCOMFORT FOR MINERS EXPOSED TO VIBRATION VIA THE FEET

ABSTRACT

Miners can be exposed to foot-transmitted vibration (FTV) when operating locomotives, bolters, jumbo drills and/or drills attached to platforms workers stand on. Case reports suggest miners are experiencing pain, discomfort, and blanching in the toes more often than their co-workers who are not exposed to vibration via the feet. However, very few studies have reported the characteristics of FTV or reported probable health risks based on common international exposure standards. Thus the objectives of the present study were (1) to measure and document the characteristics of FTV associated with operation of common underground mining equipment; (2) to determine and compare health risks based on both ISO 2631-1 (1997) and ISO 5349-1 (2004); and (3) to examine differences in operator reported musculoskeletal discomfort.

Seventeen male participants ranging in age between 24-61 years with an average height and mass of 175.0cm and 88.2kg, respectively volunteered for the study. Seventeen pieces of equipment were tested; 1 locomotive, 1 crusher, 9 bolter drills (4 scissor platforms, 2 Maclean, 2 Boart/basket, and 1 RDH), and 6 jumbo drills. Prior to all vibration measurements, participants were asked to complete a musculoskeletal disorder questionnaire. Two tri-axial accelerometers were used to simultaneously measure exposure to FTV. The accelerometer(s) were secured to the vibration platform with either a magnet, or tie-wraps, which were used to mount a rubber pad housing the accelerometer directly against the vibrating surface.

Health risks associated with FTV were determined in accordance with ISO 2631-1 and ISO 5349-1 standards. According to ISO 2631-1 8-hour exposure to frequency-weighted r.m.s. acceleration (a_w) in the dominant axis below 0.45m/s^2, between 0.45m/s^2-0.9m/s^2 and above 0.9m/s^2 is associated with a low, moderate, and high probability of health risks to the whole-body respectively. Guidance provided by ISO 5349-1, indicates exposure to a vibration total value (a_{hv}) greater than 2 m/s^2 is associated with increased health risks to the hand-arm system.

Incorporating all seventeen pieces of underground mining equipment, the vibration acceleration ranged from 0.13-1.35m/s^2 with dominant frequencies between 1.25-250Hz according to ISO 2631-1 and according to ISO 5349-1 vibration acceleration ranged from 0.14-3.61m/s^2 with dominant frequencies between 6.3-250Hz. Focusing more specifically on bolter drills, using ISO 2631-1 the average dominant frequency was 3.54(±2.60) Hz and the average frequency-weighted RMS acceleration was 0.32(±0.36) m/s^2 in the z-axis. With ISO 5349-1 the average dominant frequency for bolter drills was 14.17(±14.66) Hz and the average frequency-weighted RMS acceleration was 0.74(±1.08) m/s^2 for all axes. Operating bolter drill (RDH #9) and jumbo drill (#1) exposed workers to vibration above the ISO 2631-1 HGCZ, while operating jumbo drill (#1) and bolter drill (#1) exposed workers to vibration above the ISO 5349-1 recommended value. The musculoskeletal disorder (MSD) questionnaire indicated six of the 17 participants had been diagnosed with hand-arm-vibration syndrome and one of the six also indicated they had been diagnosed with vibration induced white-feet.

Preliminary findings appear to suggest there are differences in probable health risk depending on the ISO standard used to evaluate FTV. Current guidelines suggest ISO

2631-1 be used to comment on health risks to the whole-body when exposed to FTV. However, ISO 5349-1, typically used to evaluate exposure to hand-arm vibration, might be better suited to evaluate health risks (specifically to the feet and toes) associated with exposure to FTV with dominant frequency values above 20 Hz. It is also possible that neither standard is suited for evaluating FTV exposure and a new standard specific to the feet should be developed.

Key words: standing vibration, mining, health risk, white-feet, foot-transmitted vibration

2.1 Introduction

Vibration is often complex, contains many frequencies, occurs in several directions and changes over time (ISO 2631-1, 1997). Gaining insight into the effects of vibration exposure and the various modes of transmissibility is equally complex. Certain industries notably mining, construction, and forestry involve exposure to high levels of vibration including complex 6 degree of freedom (6-df) vibration (Dickey et al., 2006). Workers can be exposed to whole body vibration (WBV), which occurs when the human body is supported on a surface, which is vibrating, or hand transmitted vibration (HTV), which occurs when vibration enters through the hands of workers using vibrating tools (Bovenzi, 2005). A worker can also be exposed to foot-transmitted vibration (FTV) if they stand on a vibrating platform. More specifically, miners can be exposed to FTV when operating locomotives, bolters, jumbo drills, and or drills attached to the platforms workers stand on (Thompson et al., 2010). In some industries a worker may be simultaneously exposed to WBV, HTV and/or FTV.

It has been well documented that prolonged exposure to WBV places workers at increased risk for health problems, including spine and neck disorders, vascular disorders, hearing loss, gastrointestinal disorders, changes in joint stability, as well as motion sickness (Pope et al., 2002; Bovenzi et al., 2006; Bovenzi, 2008). Additionally, prolonged exposure to HTV has been shown to place workers at risk for hand-arm-vibration syndrome (HAVS), a complex of osteoarticular, neurological and vascular disorders including vibration white finger (Bovenzi, 2005; Griffin, 2008; Hagberg et al., 2008). Researchers studying the effects of HAVS have found a correlation between the neurological and vascular symptoms observed in the upper extremities and symptoms observed in the feet of workers affected by HAVS (Sakakibara, 1988; Hedlund, 1989; Hashiguchi et al., 1994). A study by Hedlund (1989) found 6 of 27 miners displayed Raynaud's phenomenon of the feet after having stood on platforms with attached drills, and one case study on a miner reported the occurrence of vibration induced white foot without a corresponding diagnosis of HAVS (Thompson et al., 2010). Given the anatomical and physiological similarities of the hands and feet, and recent reports of vibration induced white feet associated with HAVS (Leduc et al., 2011) it is not unreasonable to question the health risks associated with FTV.

Currently, the ISO standard to address WBV is ISO 2631-1 and the ISO standard to address HAV is ISO 5349-1. ISO 2631-1 (1997) assists in quantifying human exposure to WBV in accordance to human health and comfort, the probability of vibration perception, and incidence of motion sickness. ISO 5349-1 (2004) specifies general methods for measuring and reporting HTV for periodic and random vibration exposure in three orthogonal axes (x, y, and z) for one-third octave bands, having centre frequencies from 6.3 to 1250Hz. The standards apply weighting filters, which represent the relative health risk of certain vibration frequencies for the human body and hand-arm system, to the raw vibration frequencies. Vibration exposure at resonance is linked with increased risk of injury. Resonant frequency is the point at which maximum displacement between organs and skeletal structures occur, thereby placing strain on the body tissue involved (Randall et al., 1997). Due to differences in structure, each region of the body has a varied resonant frequency (Table I). Both international standards have limits for the amount of vibration a person can safely be exposed to, based on the probability of injury risk resulting from exposure to WBV and HTV (Table 1).

Presently there are no International Standards specific to the measurement of FTV (Table 1) and it remains unclear which standard, ISO 2631-1 for WBV or ISO 5349-1 for HAV, would be more applicable for measuring and evaluating FTV exposure. The literature suggests the finger-hand-arm system is most susceptible to vibration at higher frequencies of 40-100 Hz for the hand-arm system, and >100 Hz for the fingers (Dong et. al., 2004). It has also been reported that there is a prevalence of vascular-induced disorders associated with HTV which tends to be greater in workers using tools that have higher dominant frequencies, for example greater than 63Hz (Bovenzi, 2010). Structurally the hand (27 bones) and foot (26 bones) are somewhat similar, each containing a proximal part (carpus or tarsus), a middle segment (metacarpus or metatarsus), and a distal portion (phalanges). However, functionally the hand and foot are very different. The hand functions as a tactile and grasping organ and the foot is for support and locomotion. Consequently, the foot is more sturdily constructed with less moveable parts than those of the hand. Given the structural similarities between the anatomy of the hands and feet it is not unreasonable to speculate that the resonant frequencies would be within a similar range and therefore the feet would be more susceptible to vibration at these higher frequencies. The weightings curves for ISO 2361-1 and ISO 5349-1 differ. In the standards for WBV, ISO 2631-1, frequencies above 8 Hz are negatively weighted because exposure above 8 Hz is believed to be less harmful to the whole body. The standards for HAV, ISO 5349-1, also contain negative weightings factors for all acceleration frequencies excluding 8-16 Hz because these frequencies are considered to be less injurious to the hands. When considering the anatomical similarities in the hands and feet and the knowledge that the hands are susceptible to vibration exposure at higher frequencies, in drawing a parallel it would appear that ISO 5349-1 for HAV might be better suited to measure FTV.

Table 1: Comparison of human response to vibration and international standards for evaluation of WBV, HAV and FTV exposures.

	WBV	**HAV**	**FTV**
Resonance Frequencies	Pelvis/Spine 3-5Hz 8-12Hz	Hand/Arm 30-40Hz Fingers 125-300Hz	Feet/Toes ?
International Standard for health evaluation	ISO 2631-1	ISO 5349-1	No set standard
Exposure Limit	A(8) 0.45-0.9m/s^2	A_{hv} 2.0m/s^2	?
ISO frequency Range	ISO 2631-1 0.50-80Hz	ISO 5349-1 6.3-1250Hz	?

The need for further research in the area of FTV has been heightened by recent findings. Leduc and colleagues (2011) published the first paper on FTV exposure in mining. Using ISO 2631-1 the authors reported a large difference in the dominant frequency produced by equipment that has a motor to cause locomotion (primary source) and platforms that vibrate from drills/bolters (secondary source). However, findings were limited due to a small sample size (7 pieces of equipment), and limited multiples of the same pieces of equipment for comparison. Also, this study only used ISO 2631-1 (1997), and as previously identified this standard actually may not be the most appropriate for evaluating FTV exposure. Leduc et al., (2011) suggested ISO 5349-1 should also be used in future field studies.

With all of the unknown factors regarding FTV exposure, in particular the resonant frequency of the foot itself, how vibration affects the different structures of the foot, how vibration is transmitted through the foot, it is evident there is a need to document FTV exposure characteristics and to compare to similar body structures such as the hands. Furthermore, the probability of health risks to the feet resulting from exposure to FTV should be determined based on guidance in ISO 2631-1 and ISO 5349-1. Specific objectives for this study include: (1) to measure and document the characteristics and dominant frequencies of vibration entering the body via the feet on various underground mining equipment; (2) to determine and compare probable health risks based on both ISO 2631-1 (1997) and ISO 5349-1 (2004); and (3) to examine differences in operator reported musculoskeletal discomfort. It is hypothesized that FTV characteristics (frequency and acceleration), will be similar to results found in the underground field study by Leduc and colleagues (2011), where workers bolting from platforms and jumbo drills experienced vibration at higher dominant frequencies (31.5-40 Hz) than locomotive operators (3.15-6 Hz). It has been documented that the hands are susceptible to vibration exposure at higher frequencies (Dong et. al., 2004; Bovenzi, 2010). Based on differences in the International Standards and taking into consideration the anatomical similarities between the hands and the feet it is hypothesized that ISO 5349-1 for HAV will be a more appropriate standard for assessing probable health risks to FTV where higher dominant frequencies occur. Ultimately, differences in operator reported musculoskeletal discomfort are considered to be somewhat dependant on the type of equipment the worker works on. It is hypothesized that types of equipment known to expose workers to higher frequencies of vibration will result in greater discomfort complaints on the questionnaire.

2.2 Methodology

The procedures in this study were approved by the Laurentian University Research Ethics Board and all participants gave informed consent prior to the commencement of vibration measurement.

2.2.1 Participants

Seventeen male workers from five mines in northern Ontario were recruited from a sample of convenience. Upon arrival at the mine site, equipment operators were selected by the mine guide, depending on whether the equipment would be running and location within the mine. Participants ranged between 24-61 years with an average height and mass of 175.0 (±5.85) cm and 88.2 (±15.95) kg, respectively (Table 2). Equipment operators averaged 24 (±11.12) years of operation and estimated their daily vibration exposure to be between 2.5-9 hours for all equipment (Table 2).

2.2.2 Equipment

Foot-transmitted vibration exposure was measured from seventeen pieces of equipment including; 1 locomotive, 1 crusher, 9 bolter drills (4 scissor platforms, 2 Maclean, 2 Boart/basket, and 1 RDH), and 6 jumbo drills. All measurements occurred under typical operating conditions. The average vibration measurement duration was 41.5 (±16.2) minutes. Variance in measurement duration occurred due to differences in equipment operator set-up prior to bolting or drilling. Vibration exposure was processed during the active operation section of the measurement and a minimum 15-minute period of typical operation was required per piece of equipment.

2.2.3 Operator Musculoskeletal Disorder History

Operator reported musculoskeletal symptoms (pain/ache/discomfort) in the previous six months was determined using a body map (Appendix A) and 4-point scale (1=mild; 2=moderate; 3=severe; 4=very, very severe) (Leduc et al., 2011). Musculoskeletal symptoms for operators working on similar equipment were compared (Table 4 and Figure 3).

2.2.4 FTV Measurement

Two Series 2 10G tri-axial accelerometers (NexGen Ergonomics, Montreal, QC, CND) were used to measure vibration exposure. Depending on the material on the equipment floor surface the accelerometers were either magnet mounted to the platform (Figure 1(a)), or fastened using a rubber pad and tie wraps (Figure 1(b)). The details, notes and figures from all accelerometer set-ups for all seventeen pieces of equipment can be found in Appendix B. The accelerometers were configured to simultaneously collect measurements in accordance with ISO 2631-1 (1997) and ISO 5349-1 (2004) with a sampling rate of 500 Hz and 1000 Hz, respectively. Data recorded from the accelerometers were stored on a portable datalogger, DataLOG II P3X8 (Biometrics, Gwent, UK).

Table 2: Participant demographic information, work history, and vibration measurement duration.

Machine Operated	Age	Height (cm)	Mass (kg)	Equipment Regularly Operated	Years of Operation	Estimated Daily Exposure (hours)	Vibration Measurement Duration (minutes)
Locomotive	24	175.26	77.11	locomotive spare, jackleg - stoper, scoop	4	7	58
Crusher	61	185.42	99.79	rock breaker	24	9	93
(1) Bolter Drill - Scissor Platform	56	172.72	77.11	jumbo drill	31	7	42
(2) Bolter Drill - Scissor Platform	55	180.34	86.18	jackleg, stoper (off platform)	28	8 to 10	36
(3) Bolter Drill - Scissor Platform	27	177.8	83.91	stoper, jackleg (off lift)	4.5	3 to 4	40
(4) Bolter Drill - Scissor Platform	58	176.53	79.38	bolter	38	5	45
	32	170.18	70.31	bolter	7	5 to 6	
(5) Bolter Drill – Maclean	51	172.72	79.38	Maclean bolter	30	6	18
(6) Bolter Drill – Maclean	58	177.8	108.86	bolter	40	6	40
(7) Bolter Drill – Boart	48	175.26	81.65	Bolter-basket	15	7	39
(8) Bolter Drill – Boart	47	177.8	117.93	bolter	26	7	53
(9) Bolter Drill – RDH	55	177.8	86.18	N/A	33	6	20
(1) Jumbo Drill	56	172.72	77.11	jumbo drill	31	7	34
(2) Jumbo Drill	54	170.18	86.18	jumbo drill	33	3	40
(3) Jumbo Drill	39	158.75	72.57	jumbo drill	15	4 to 5	33
(4) Jumbo Drill	59	181.61	129.27	jumbo drill	38	6	36
(5) Jumbo Drill	51	180.34	95.25	jumbo drill	25	2 to 3	36
(6) Jumbo Drill	59	170.18	77.11	jumbo drill	20	3 to 6	43

2.2.5 Data Analysis

2.2.5.1 ISO 2631-1

The primary purpose of ISO 2631-1 is to define methods of quantifying WBV in relation to: human health and comfort; the probability of vibration perception; and the incidence of motion sickness. The frequency range considered for health, comfort and perception is 0.5 Hz to 80 Hz. Vibration analysis was conducted in accordance with ISO 2631-1 and carried out with the Vibration Analysis Tool-Set (VATS 3.4.3) software distributed by NexGen Ergonomics (Montreal, Quebec). The assessment of the effect of vibration on health is made independently along each axis. Frequency-weighted root-mean-square (r.m.s.) accelerations (a_{wx}; a_{wy}; a_{wz}) were calculated using Equation 1. And the appropriate weighting factors were also applied as described in ISO 2631-1 (x-axis = W_d; y-axis = W_d; z-axis = W_k). Scaling factors associated with the determination of health for seated exposure were also applied (x-axis, k=1.4; y-axis, k=1.4; z-axis, k=1.0). Frequency-weighted r.m.s. vector sum values (a_{xyz}), peak accelerations, crest factors (CF), and vibration dose values (VDV) for each axis were also calculated.

$$a_w = \left[\sum_i (W_i a_i)^2\right]^{\frac{1}{2}} \qquad (1)$$

Where a_w is the frequency-weighted acceleration, W_i is the weighting factor for the i th one-third octave band, and a_i is the r.m.s. acceleration for the I th one-third octave band.

The axis with the highest frequency-weighted r.m.s. acceleration value and VDV was selected for comparison to the ISO-2631-1 health guidance caution zone (HGCZ) limits associated with eight hours of daily exposure. Operating time per shift was asked within the musculoskeletal disorder questionnaire (Leduc et al., 2011) and for all participants averaged 5.79 (±1.79) hours within the course of an eight-hour shift. Predicted health risks were then assessed and compared to ISO 2631-1 (1997) health guidance caution zone (HGCZ) limits for daily vibration exposure. According to the HGCZ, the health effects of frequency-weighted r.m.s. acceleration values below 0.45m/s^2 have not been clearly documented and/or objectively observed. Frequency-weighted r.m.s. acceleration values within 0.45-0.9m/s^2 advise caution with respect to potential health risk is, and frequency-weighted r.m.s. acceleration values above 0.9m/s^2 results in increased probability of adverse health effects from WBV exposure.

2.2.5.2 ISO 5349-1

ISO 5349-1 specifies general requirements for measuring and reporting hand-transmitted vibration exposure in three orthogonal axes. The values obtained can be used to predict adverse effects of hand-transmitted vibration over the frequency range covered by the octave bands from 8 Hz to 1000 Hz. Vibration analysis was conducted in accordance with ISO 5349-1and carried out with the Vibration Analysis Tool-Set (VATS 3.4.3) software distributed by NexGen Ergonomics (Montreal, Quebec). For ISO 5349-1 it is assumed that vibration in each of the three directions is equally detrimental. The frequency weighting W_h reflects the assumed importance of different frequencies in causing injury to the hand. Thus, the evaluation of vibration exposure is based on a quantity that combines all three axis, deemed the vibration total value a_{hv}, and is defined as the root-sum-of squares of the three component values (Equation 2).

$$a_{hv} = \sqrt{\left(a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2\right)} \qquad (2)$$

Where a_{hv} is the vibration total value, a_{hwx} is the vibration acceleration in the x-axis, a_{hwy} is the vibration acceleration in the y-axis, and a_{hwz} is the vibration acceleration in the z-axis.

The daily vibration exposure is then derived from the magnitude of the vibration (vibration total value) and the daily exposure duration. The daily vibration exposure is expressed in terms of the 8-h energy-equivalent frequency-weighted vibration total value, or A(8) (Equation 3).

$$A(8) = a_{hv}\sqrt{\frac{T}{T_0}} \qquad (3)$$

Where *A(8)* is the 8-h energy-equivalent frequency-weighted vibration total value, *T* is the total daily duration of exposure to the vibration a_{hv}, and T_O is the reference duration of 8 h (28800s).

According to ISO 5349-1, a vibration total value of frequency-weighted r.m.s. acceleration (a_{hv}), sometimes known as the vector sum or the frequency-weighted acceleration sum, greater than 2.0 m/s^2 is problematic and could result in an increased risk of vascular, neurological, or musculoskeletal disorders. According to ISO 5349-1 (2004) symptoms of HAVs are rare in persons exposed with an 8-h energy-equivalent vibration total value, A(8) of less than 2 m/s^2 and unreported for A(8) values of less than 1 m/s^2.

2.2.5.3 Probability of Health Risk Comparison

Health risk probability, associated with FTV, according to ISO 2631-1 and ISO 5349-1 were compared with reported MSD ache/pain/discomfort (Table 4). Musculoskeletal ache/pain/discomfort of three (severe ache, pain, numbness or discomfort) or four (very, very severe ache, pain, numbness or discomfort) were combined with indication of diagnosed white hand or white feet, and equipment that exposed operators to vibration above either ISO standard, to determine whether there was a connection between the equipment exposing operators to vibration above the International Standards limits and the ache/pain/discomfort complaints from the questionnaire (Figure 3).

Figure 1(a): Magnet mounted accelerometer set-up for metal surface platforms. One tri-axial accelerometer is screwed directly into the red magnet and the second tri-axial accelerometer is taped to two magnets and mounted directly on the metal ridge of a bolting platform.

Figure 1(b): Seat-pad accelerometer set-up for grated metal platforms and non-metal surface platforms. The tri-axial accelerometers are contained in a channel in the rubber pads and sit flat and tight against the vibrating surface of a jumbo drill.

2.3 Results

2.3.1 Standing Vibration Characteristics

The dominant frequency (Hz) of the standing surface and frequency-weighted r.m.s. acceleration (m/s^2) for all axis (a_{wx}, a_{wy}, a_{wz}) and total sum of the axis (a_{hv}) are reported in Table 3 for seventeen pieces of underground mining equipment. For all ISO 2631-1 (1997) WBV measurements the z-axis was the dominant axis associated with the highest levels of acceleration for all equipment. However, for ISO 5349-1 (2004) HAV the z-axis was the dominant axis for all equipment, except for bolter drill #4 – scissor platform (x-axis) and jumbo drill #1 (x and y-axis) (Table 3).

There were a total of nine bolter drills, including four types: scissor platform, Maclean®, Boart, and RDH®. Using ISO 2631-1 the average dominant frequency for bolter drills was 3.54(±2.60) Hz and the average frequency-weighted RMS acceleration was 0.32(±0.36) m/s^2 in the z-axis. With ISO 5349-1 the average dominant frequency for bolter drills was 14.17(±14.66) Hz and the average frequency-weighted RMS acceleration was 0.74(±1.08) m/s^2 for all axes.

A total of six jumbo drills were involved in the study. Utilizing ISO 2631-1 the average dominant frequency for jumbo drills was 53.21(±97.48) Hz and the average frequency-weighted RMS acceleration was 0.33(±0.15) m/s^2 in the z-axis. Using ISO 5349-1 the average dominant frequency for jumbo drills was 107.35(±115.70) Hz and the average frequency-weighted RMS acceleration was 1.02(±1.18) m/s^2 for all axes. Exceptions were Jumbo drill #3 and #4, which were reported to expose workers to dominant frequencies of 250Hz. However, measurements for jumbo drill #3, were conducted during an irregular round of drilling. The operator was completing a drilling round with one boom on a "blind corner", which meant using a spotter to give instructions on where to place the drill on the rock face. Jumbo drill #4 also had one boom operating and during this particular measurement the operator also had to change a drill bit. Under typical operation, a jumbo drill is aligned straight at the drilling wall and drill bits do not have to be changed while the operator is drilling a round (or an entire rock face with approximately 16 holes). Jumbo drills #5 and #6 exposed the operators to much lower dominant frequencies, between 1.25 – 6.3 Hz. The measurements for these two jumbo drills (5 and 6) were the only measurements taken on grated platforms.

2.3.2 Probable Health Risk

According to the ISO 2631-1, using the frequency-weighted r.m.s. acceleration 8hr HGCZ, only one worker was exposed to FTV above the criterion value (bolter drill – RDH #9) and one worker was exposed to FTV within the HCGZ (jumbo drill #1) (Figure 2(a)). In addition, according to ISO 5349-1 operators of jumbo drill #1 and bolter drill #1 were exposed to vibration above the vibration total value of frequency-weighted r.m.s. acceleration (a_{hv}) daily exposure value of 2.0m/s^2 (Figure 2(b)).

2.3.3 Musculoskeletal Discomfort and Injuries

Of the seventeen operators included in this study, all but two operators reported some degree of musculoskeletal ache/pain/discomfort or injury complaint. Operator of bolter #3 (scissor platform) and operator of jumbo drill #2 (Table 4) had no complaints to report. Five of the seventeen (29.4%) operators reported a three (severe ache, pain, numbness or discomfort) or four (very, very severe ache, pain, numbness or discomfort) prior to the vibration testing (Figure 3). Eight operators (47.1%) specifically complained of an ache/pain/discomfort in their right and left feet; these operators included the locomotive operator, three bolter drill operators and four jumbo drill operators. Five operators (29.4%) complained of right or left knee pain, and four of these five operators had no concurrent foot pain or discomfort. Therefore, a total of twelve (70.6%) equipment operators had a complaint of discomfort in their lower body, specifically at the level of the knee or lower.

Although it was not specifically asked in the questionnaire, six of the seventeen participants (35.3%) self-reported they had been diagnosed with vibration white-hand and one of the six also indicated he had been diagnosed with vibration white-foot. Only two of the operators who indicated a diagnosis of vibration white-hand also reported severe ache/pain/discomfort. Consequently, there is evidence to suggest that the workers experiencing vibration levels above the ISO standard references considered with workers who indicated a diagnosis of vibration white-hand or white-feet, does not necessarily correlate with the workers who are currently experiencing and reporting symptoms (Figure 3).

Table 3: Summary of FTV characteristics associated with mining equipment operation measured in accordance with ISO 2631-1 and ISO 5349-1 standards.

	FTV Exposure Characteristics									
	ISO 2631-1 (1997)					ISO 5349-1 (2004)				
	Dominant Frequency (Hz)	Frequency-weighted RMS acceleration (m/s^2)				Dominant Frequency (Hz)	Frequency-weighted RMS acceleration (m/s^2)			
Equipment Type	**DF_{xyz}**	**a_{wx}**	**a_{wy}**	**a_{wz}**	**sum**	**DF_{xyz}**	**a_{wx}**	**a_{wy}**	**a_{wz}**	**sum (a_{hv})**
Locomotive	2.5	0.15	0.26	0.41	0.59	8	0.19	0.30	0.29	0.46
Crusher	4	0.18	0.29	0.40	0.62	6.3	0.20	0.21	0.31	0.42
(1) Bolter Drill - Scissor Platform	2.5	0.15	0.09	0.28	0.37	6.3	1.84	1.57	2.21	3.28
(2) Bolter Drill - Scissor Platform	2.5	0.06	0.07	0.15	0.19	8	0.10	0.04	0.10	0.15
(3) Bolter Drill - Scissor Platform	2.5	0.04	0.05	0.13	0.16	6.3	0.05	0.09	0.09	0.14
(4) Bolter Drill - Scissor Platform	8	0.08	0.08	0.25	0.30	40(x)	0.14	0.12	0.28	0.33
(5) Bolter Drill - Maclean	6.3	0.07	0.10	0.18	0.25	8	0.13	0.19	0.17	0.28
(6) Bolter Drill - Maclean	1.25	0.09	0.10	0.13	0.23	6.3	0.11	0.11	0.10	0.19
(7) Bolter Drill - Boart	1.25	0.18	0.16	0.21	0.39	6.3	0.08	0.12	0.22	0.27
(8) Bolter Drill - Boart	6.3	0.19	0.19	0.27	0.47	6.3	0.17	0.12	0.20	0.29
(9) Bolter Drill - RDH	1.25	0.23	0.29	1.25	1.35	40	0.48	1.00	1.38	1.77
(1) Jumbo Drill	31.5	0.19	0.12	0.56	0.64	100 (x,y)	0.39	0.36	3.57	3.61
(2) Jumbo Drill	31.5	0.15	0.12	0.42	0.50	31.5	0.46	0.48	0.51	0.84
(3) Jumbo Drill	2.5	0.41	0.76	0.39	1.28	250	0.28	0.23	1.00	1.06
(4) Jumbo Drill	250	0.06	0.09	0.16	0.23	250	0.11	0.15	0.21	0.28
(5) Jumbo Drill	2.5	0.08	0.06	0.20	0.24	6.3	0.14	0.09	0.20	0.26
(6) Jumbo Drill	1.25	0.18	0.21	0.38	0.54	6.3	0.29	0.25	0.39	0.55

*All of the dominant frequencies (DFs) are in the z-axis unless otherwise stated.

Table 4: Operator reported musculoskeletal discomfort questionnaire results.

Equipment Type	**ISO 2631-1**		**ISO 5349-1**		**Musculoskeletal Discomfort Report***
	DF (Hz)	**a_{wz} (m/s^2)**	**DF (Hz)**	**a_{hv} (m/s^2)**	**(ache; pain; discomfort:1=mild; 4=very severe)**
Locomotive	2.5	0.41	8	0.46	N=2; LB=3; RH=2; LH=2; RF=2; LF=2
Crusher	4	0.40	6.3	0.42	RK=2; LK=2
(1) Bolter Drill – Scissor Platform	2.5	0.28	6.3	3.28	RS=3-4; LS=3-4; UB=3-4; HT=1; RF=2; LF=2
(2) Bolter Drill – Scissor Platform	2.5	0.15	8	0.15	N=2; LB=2; RH=2; LH=2
(3) Bolter Drill – Scissor Platform	2.5	0.13	6.3	0.14	
(4) Bolter Drill – Scissor Platform	8 6.3	0.25	40(x) 8	0.34	LB=3; RF=1; LF=1 HT=1
(5) Bolter Drill – Maclean	1.25	0.18	6.3	0.28	N=1; RH=2; LH=2
(6) Bolter Drill – Maclean	1.25	0.13	6.3	0.19	RH=1; LH=1; RF=1; LF=1
(7) Bolter Drill – Boart	6.3	0.21	6.3	0.27	LB=2; RK=2; LK=2
(8) Bolter Drill – Boart	1.25	0.27	40	0.29	RK=1
(9) Bolter Drill – RDH	31.5	1.25	100 (x,y)	1.77	RK=2
(1) Jumbo Drill	31.5	0.56	31.5	3.61	RS=3-4; LS=3-4; UB=3-4; HT=1; RF=2; LF=2
(2) Jumbo Drill	2.5	0.42	250	0.84	
(3) Jumbo Drill	250	0.39	250	1.06	RH=2; LH=2; HT=2
(4) Jumbo Drill	2.5	0.16	6.3	0.28	N=2.5; RE=3.5; LE=3.5; LB=1.5; RH=3-4; LH=3-4; RF=1; LF=1
(5) Jumbo Drill	1.25	0.20	6.3	0.26	N=2-3; RS=2; LS=2; LB=2; HT=2; RK=2; LK=2; RF=3; LF=3
(6) Jumbo Drill	2.5	0.38	8	0.55	RF=2; LF=2

* N=neck; RS=right should; LS=left shoulder; UB=upper back; RE=right elbow; LE=left elbow; LB=lower back; RH=right wrist/hand; LH=left wrist/hand; HT= hips & thighs; RK=right knee; LK=left knee; RF=right foot/ankle; LF=left foot/ankle

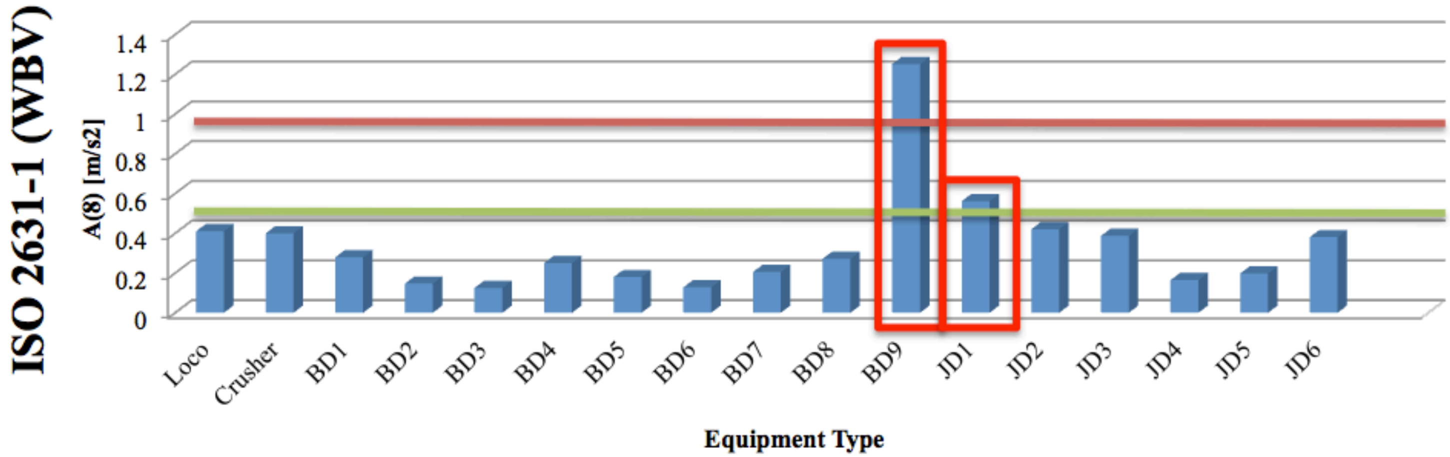

Figure 2(a): A(8) values according to ISO 2631-1 with the HCGZ (horizontal lines), lower limit 0.45m/s^2 in green and upper limit 0.90m/s^2 in red. The values outlined with a red box indicate the equipment that exceeded the limits of the ISO 2631-1 standard.

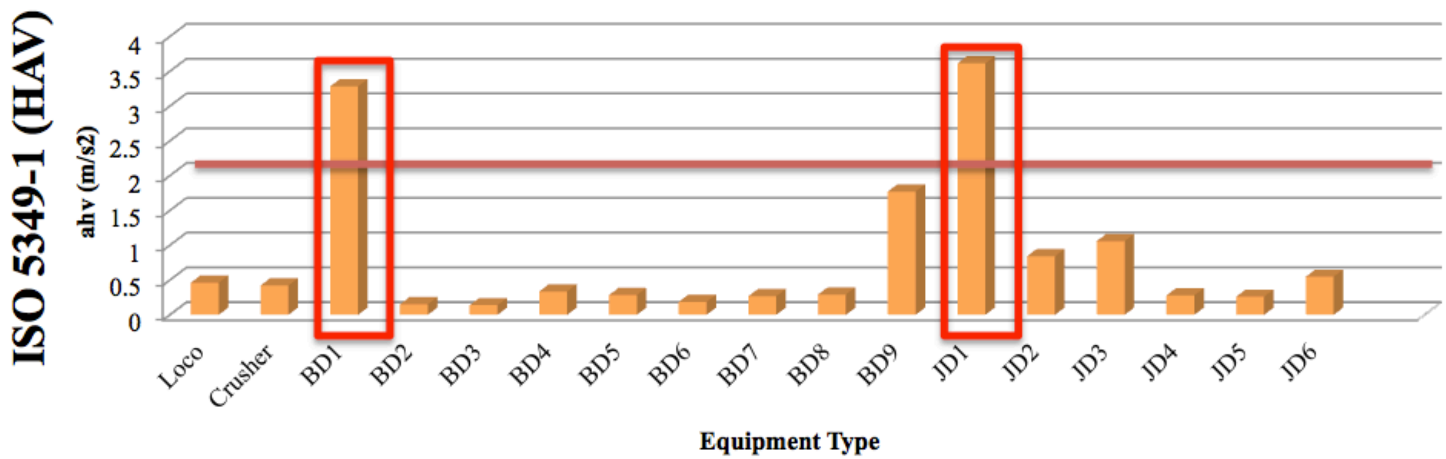

Figure 2(b): a_{hv} values according to ISO 5349-1 with the exposure limit value (red horizontal line) at 2.0m/s^2. The values outlined with a red box indicate the equipment that exceeded the limits of the ISO 5349-1 standard.

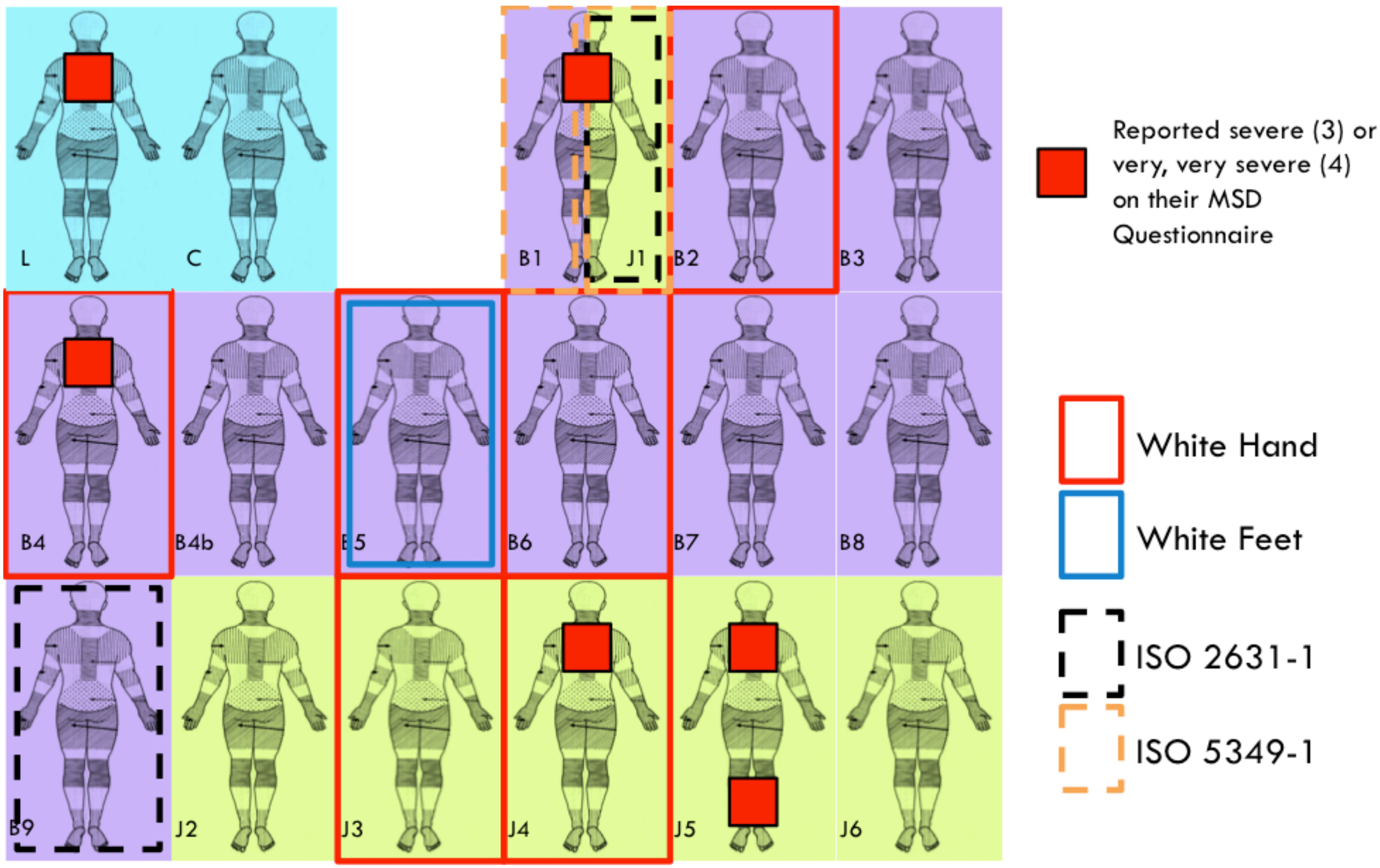

Figure 3: Summary of musculoskeletal discomfort questionnaire combined with indication of diagnosed white hand or white feet, and equipment that exposed operators to vibration above the ISO standard referenced. Small red squares indicate operator reports of severe (3) or very, very severe (4) musculoskeletal disorder questionnaire in either the upper body (above the waist) or lower body (below the waist). Operators outlined in red boxes indicated they had white hand and operators outlined in blue boxes indicated they had white feet. Operators outlined in black dotted boxes were exposed to vibration levels above the ISO 2631-1 standard and operators outlined in orange dotted boxes were exposed to vibration levels above the ISO 5349-1 standard. (L= Locomotive, C= Crusher, B= Bolter Drill, J = Jumbo Drill)

2.4 Discussion

The primary objective of this study was to measure and document the characteristics and dominant frequencies of vibration entering the body via the feet on various underground mining equipment using both ISO 2631-1 and ISO 5349-1. The locomotive in this study had a dominant frequency (DF) of 2.5 Hz and vibration magnitude of $0.41 m/s^2$ according to ISO 2631-1 and a DF of 8 Hz and vibration magnitude of $0.46 m/s^2$ according to ISO 5349-1, which is comparable to the recent field study by Leduc and colleagues (2011) where locomotive operation produced a z-axis dominant frequency below 6.3Hz with a vibration magnitude less than $0.43 m/s^2$ according to ISO 2631-1. The locomotive operator in this study also reported neck and severe lower back pain, analogous to the locomotive operator in Leduc's study who had a unique reporting of pain or discomfort in the neck (Leduc et al., 2011). The dominant frequency of the locomotive, ranging from 2.5-8 Hz is within the 4-8 Hz range, which is the known resonant frequency of the lumbar region and causes an increased susceptibility to injury (Griffin, 1990; Mansfield and Griffin, 2002).

Applying both, ISO 2631-1 and ISO 5349-1, the average dominant frequencies (Hz) and average frequency-weighted RMS accelerations (m/s^2) for all bolter and jumbo drills is listed in Table 5. A field study completed by Leduc and colleagues (2011) was limited to only one bolter drill and one jumbo drill where vibration was measured using only ISO 2631-1 for comparison to the current study (Table 5). The values from the present study are separately averaged for each type of equipment (bolter drills and jumbo drills),making comparison to the results of the Leduc et al. (2011) study difficult due to its limited sample. Additional comparison to the individual results from the current study also did not uncover perfectly matched results with either the bolter or jumbo drill from the Leduc et al. (2011) study. This is not surprising given the number of extrinsic variables that can influence vibration including: vibration magnitude, vibration frequency, vibration axis, vibration input position, vibration duration, and other environmental influences such as noise, heat, acceleration, and light (Bovenzi, 1998; ISO 2631-1, 1997; Griffin, 1990).

Table 5: Summary of ISO 2631-1 (WBV) and ISO 5349-1 (HAV) results for 9 bolter drills and 6 jumbo drills. Additional results for 4 jumbo drills, discounting the 2 jumbo drills with exceedingly high dominant frequencies (250Hz).

		ISO 2631-1 (WBV)	**ISO 5349-1 (HAV)**
9 Bolter Drills	Average dominant frequency (Hz)	3.54(±2.60)	14.17(±14.66)
	Average frequency-weighted RMS acceleration (m/s^2)	0.32(±0.36)	0.74(±1.08)
Bolter Drill (Leduc et al., 2011)	*Average dominant frequency (Hz)*	*5*	
	Average frequency-weighted RMS acceleration (m/s^2)	*0.11*	
6 Jumbo Drills	Average dominant frequency (Hz)	53.21(±97.48)	0.33(±0.15)
	Average frequency-weighted RMS acceleration (m/s^2)	107.35(±115.70)	1.02(±1.18)
4 Jumbo Drills (without outliers)	Average dominant frequency (Hz)	18.81(±19.87)	18.90(±14.54)
	Average frequency-weighted RMS acceleration (m/s^2)	0.39(±0.15)	1.32(±1.55)
Jumbo Drill (Leduc et al., 2011)	*Average dominant frequency (Hz)*	*31.5*	
	Average frequency-weighted RMS acceleration (m/s^2)	*0.16*	

Two of the jumbo drill measurements, jumbo drill 5 and 6, were the only measurements taken on grated platforms. These jumbo drills were found to expose the operators to lower dominant frequencies, between 1.25 – 6.3 Hz. Due to the porous nature of the grated platform compared to a solid metal platform it is possible that the grated platforms are better at distributing and attenuating vibration.

The second objective of this study was to determine and compare probable health risks based on both ISO 2631-1 and ISO 5349-1. Operating bolter drill – RDH 9 exposed the operator to vibration above the ISO 2631-1 Health Guidance Caution Zone (HGCZ) with an A(8) value above 0.9m/s^2 (Figure 2(a)). According to the same standard jumbo drill 1 exposed the operator to vibration levels within the HGCZ of 0.45-0.9m/s^2 (Figure 3(a)), while operating jumbo drill 1 and bolter drill 1, exposed operators to vibration above the ISO 5349-1 recommended value of 2.0m/s^2 (Figure 2(b)). One of the principle reasons for the differences in predicted health risk is the distinction between the International Standards. Since exposure at resonance is linked to an increased risk of injury, the standards use frequency-weighting curves, which are adjusted depending on the assumed resonant frequency of the area of the body in question. For ISO 2631-1 for WBV, the W_k frequency-weighting curve for the z-axis alters all frequencies, but those between 4-8Hz (Figure 4(a)). The resonant frequency of the pelvis/spine has been found to be between 3-5Hz (Mansfield & Griffin, 2002; Griffin, 1990), hence ISO 2631-1 is more geared towards protecting the lower back and spine from injury resulting from WBV exposure. ISO 5349-1 for HAV uses a frequency-weighting curve (W_h), which assumes that vibration in each of the three directions is equally detrimental. The frequency weighting W_h reflects the assumed importance of different frequencies in causing injury to the hand. Upon examining the frequency-weighting curve for ISO 5349-1, acceleration frequencies between 8-16Hz are not altered (Figure 4(b)). The resonant frequency of the hand-arm system is in the frequency range of 20-40 Hz (Griffin, 1990; Dong et al., 2004), thus ISO 5349-1 is adjusted to protect the hands from injury resulting from HAV vibration.

It has been documented (Leduc et al., 2011) and results from this study indicate that jumbo and bolter drill operators have higher reports of MSDs. However, upon examining the frequency-weighting curves for both ISO 2631-1 (Figure 4(a)) and ISO 5349-1 (Figure 4(b)), and looking specifically at the 30-40Hz range, it becomes apparent that the magnitude of the frequency-weighted acceleration is altered as compared to an un-weighted signal, which could result in under predicting the injury risk at these higher frequencies (30-40Hz). ISO 5349-1 might be more appropriate for evaluating FTV, but it is also possible that neither standard is ideally suited for evaluating FTV exposure and a new standard may need to be created once the resonant frequency of the foot had been identified.

The third and final objective of the study was to examine differences in operator reported musculoskeletal discomfort. As far as self-reported musculoskeletal disorder questionnaire results, this study suggests six of the 17 (35%) participants self-reported having a diagnosis of vibration white-hand, which is comparable to a study completed by Hedlund (1989) where eleven of 27 (41%) showed typical symptoms of Raynaud's phenomenon, among them eight raise drifters. One of the participants also indicated he had been diagnosed with vibration white-foot. Six of the equipment operators also reported a musculoskeletal ache, pain or discomfort of 3 (severe) or 4 (very severe). Only two of the operators who had indicated a diagnosis of vibration white-hand were experiencing severe discomfort. Therefore there is evidence to suggest that the workers experiencing vibration levels above the ISO standard references and whom had indicated a diagnosis of vibration white-hand or white-feet do not necessarily correlate with the workers who are currently experiencing symptoms (Figure 3). The reports of diagnosed vibration white-hand may be greater than those of white-foot because patients with HAVS may have simultaneous, although usually less severe, vascular symptoms in the feet, and symptoms in the feet usually occur after hand symptoms are already present (Schweigert, 2002; Thompson 2010), as vibration exposure of the hand stimulates

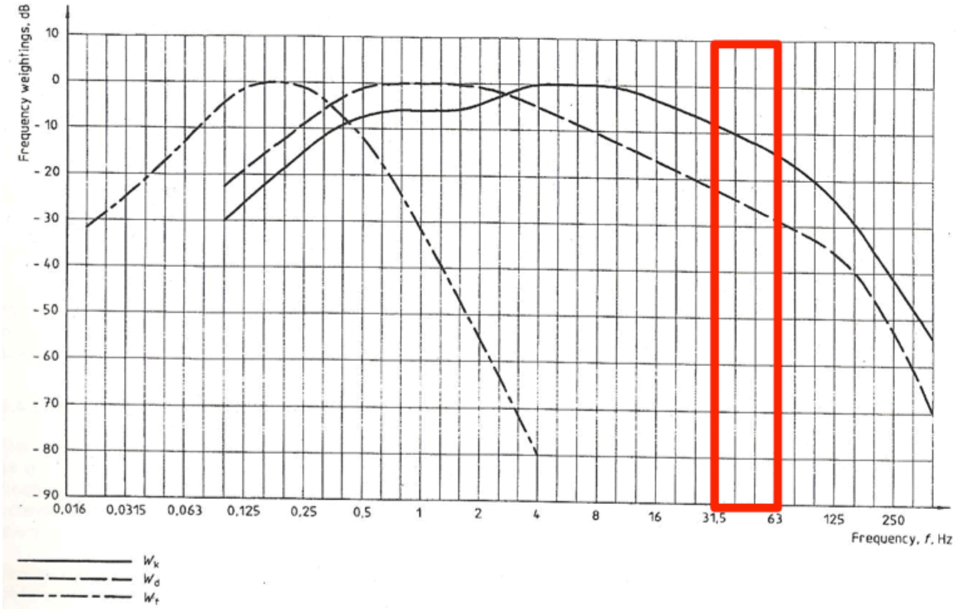

Figure 4(a): ISO 2631-1 frequency-weighting curves W_k, W_d, and W_f for seated whole-body vibration, band limiting included. Red box highlights dominant frequencies found in both this study and a study by Leduc and Colleagues in 2011.

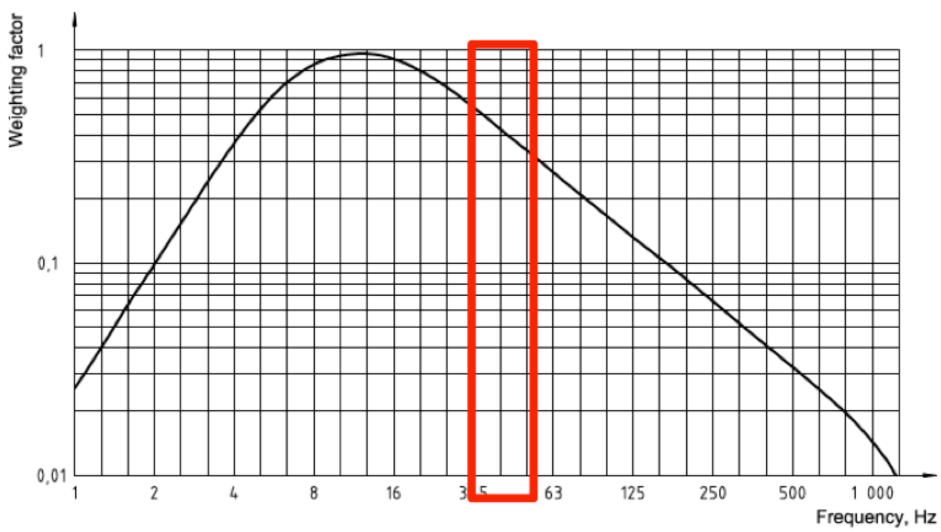

Figure 4(b): ISO 5349-1 frequency-weighting curve W_h for hand-transmitted vibration, band limiting included. Red box highlights dominant frequencies found in both this study and a study by Leduc and Colleagues in 2011.

sympathetic activity in the sympathetic nerves innervating the skin of the foot, eventually inducing constriction of the toe vessels (Sakakibara et al., 1990). Another explanation for the variance in reported diagnosis of vibration white-hand and workers currently experiencing symptoms could be the years of vibration exposure. When comparing the participants who had reported a diagnosis of vibration white-hand compared to those who did not, the average years of vibration exposure was 31.5±8.6 years compared to 21.1±11.0 years respectively. Workers who have been exposed to vibration longer can also become accustomed to the exposure and in essence may not be aware of early symptoms until they become problematic. The most common diagnostic tool for diagnosing VWF is the 1986 Stockholm classification, however a criticism of this tool is that early asymptomatic vascular injuries such as digital organic microangiopathy are not reported on the scale (Noel, 2000). A postal survey conducted by Palmer & Griffin (2000) on the prevalence of Raynauds phenomenon in Great Britain indicated that only one fifth of respondents (2%) had consulted a doctor about their symptoms.

As with most field studies, there are limits to how much of the environment can be controlled during testing especially underground, but all measurements were conducted while equipment operators performed their normal work requirements. Testing was conducted at five mine sites in Ontario, therefore differences in road maintenance, terrain, and operating strategies were likely. Differences in equipment set-ups including different drill bits or rotation frequencies, different models of drills, different number of drills operating at each test location, and different placement of the accelerometers can also result in inconsistency in measurements. A second limitation to this study involves the musculoskeletal disorder questionnaire; the questionnaire did not specifically ask the participants whether they had been diagnosed with white hand or white foot. Therefore, conclusions regarding the number of participants with these diagnoses cannot be confirmed, the results can only be reported as is. In the future a more in depth questionnaire should be utilized to get a more complete medical history of each participant.

Future research regarding FTV is needed to identify the resonant frequency of the foot, which in turn will help to determine the appropriateness of the current standards and establish whether a new standard needs to be created for FTV. More specifically, controlled laboratory studies should be completed to examine whether body mass and foot arch types affect vibration transmissibility in the foot and how vibration frequency influences transmissibility of vibration through the foot. Information derived from future research should also be used to design personal protective equipment to help protect workers from FTV. For example, if the resonant frequency of the foot is 60 Hz, a standard needs to be designed to ensure 60 Hz exposures are not filtered out, for instance ISO 2631-1 would not be appropriate. Then engineering solutions could be implemented to reduce exposure to 60Hz vibration and personal protective equipment such as insoles, boots, or mats could be constructed to attenuate vibration at 60 Hz. Since it remains unknown which standard is more appropriate for evaluating FTV, when measuring FTV in the interim both ISO 2631-1 and ISO 5349-1 should be used to evaluate predicted health risk. If measurements using both standards are not possible, it could be suggested that if the dominant frequency is below 20 Hz use ISO 2631-1 because the W_k weighting curve does not use a negative weighting in the 4-12Hz range (Figure 4(a)), making it better designed to predict injury risk for lower frequency exposure. Additionally, if the dominant frequency is above 20 Hz use ISO 5349-1 because the W_h weighting curve does not negatively weight exposure frequencies between 8-20Hz (Figure 4(b)), meaning it is better designed to predict injury risk for higher frequency exposure than ISO 2631-1.

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CHAPTER THREE:

EXAMINATION OF VIBRATION TRANSMISSIBLITY FROM FLOOR TO METATARSAL AND FLOOR TO ANKLE BETWEEN 25 AND 50HZ

CHAPTER THREE:
EXAMINATION OF VIBRATION TRANSMISSIBILITY FROM FLOOR TO METATARSAL AND FLOOR TO ANKLE BETWEEN 25 AND 50HZ

ABSTRACT

Vibration exposure at resonance has been directly linked to increased risk of injury: however, the biodynamic response of the foot at resonance has not been quantified to date, and the resonant frequency of the foot still needs to be identified. The frequency at which the hand-arm system is believed to be at greatest risk of injury is in the 20-40 Hz range, while the fingers are at greater risk above 100 Hz, as exposure at these frequencies leads to vibration amplification. Given the similarities between the anatomy of the hands and feet it is not unreasonable to speculate that the resonant frequencies for the foot might be in the same range.

Thirty male participants with an average age, height, and mass of 28(±9) years, 180.6(± 8.7) cm, and 85.65(±12.37) kg respectively, volunteered for the study. Prior to the vibration exposure protocol each participant's foot arch type was classified using a foot imprint technique. Four ADXL326, 19g tri-axial accelerometers were utilized to measure vibration (1) on the vibration platform medial to the distal head of the first metatarsal, (2) on the skin at the distal head of the first metatarsal, (3) on the vibration platform paralleling the medial malleolus, and (4) on the skin at the lateral malleolus. Participants stood in a comfortable posture on a vibration platform with their heels aligned over two marked positions while randomly exposed for 45 seconds to six vibration frequencies (25Hz, 30Hz, 35Hz, 40Hz, 45Hz, and 50Hz), while vibration transmissibility was measured from the floor-to-metatarsal and from the floor-to-ankle.

Two separate two-way repeated measures ANCOVAs revealed that neither the three-way interaction of location*frequency*AI [$\lambda = 0.816$, $F(5,24) = 1.080$, $p = 0.396$] or location*frequency*mass [$\lambda = 0.959$, $F(5,24) = 0.203$, $p = 0.958$] were significant ($p<0.05$). Using a two-way repeated measures ANOVA the location x frequency interaction was significant $\lambda = 0.246$, $F(5,25) = 15.365$, $p = 0.0001$. More specifically, differences in mean transmissibility between the ankle and metatarsal were significant at 40 Hz ($p < 0.001$), 45 Hz ($p < 0.001$), and 50 Hz ($p < 0.001$). The greatest transmissibility for the metatarsal occurred at 50Hz and for the ankle (lateral malleolus) from 25-30Hz indicating the formation of a local resonance at each location.

Key words: foot-transmitted vibration, standing vibration, biodynamic response of the foot, health risk, white-feet

3.1 Introduction

Multiple occupations expose workers to foot-transmitted vibration (FTV). Exposure occurs when vibration enters the body at the feet and is transmitted through the feet and legs from vibrating tools, vibrating machinery, or standing on vibrating platforms or surfaces (Eger et al., 2008; Thompson et al., 2010; Leduc et al., 2011). Workers can also be exposed to whole-body vibration (WBV) when the supporting surface they work on vibrates, or hand-transmitted vibration (HTV) when vibration enters through the hands of workers using vibrating tools (Bovenzi, 2005). Exposure to FTV has been reported in mining, farming, forestry and construction (Dickey et al., 2006; Laeger, 1994; Thompson et al., 2010; Toibana et al., 1994). Miners can be exposed to FTV when operating locomotives, bolters, jumbo drills, and or drills attached to platforms workers stand on (Thompson et al., 2010). More specifically, miners who work with bolters face unique circumstances whereby they are exposed at two contact points because they are standing on a vibrating platform (FTV) while handling a vibrating tool (HTV). A case study involving a 46 year old mink farmer who operated a small wagon, reported he had a confirmed diagnosis of vibration-induced white toes from having to place his left foot on a vibrating platform for two to three hours a day during his 12 years in the occupation (Laeger, 1994). Other research suggests miners are experiencing pain, discomfort, and blanching in the toes more often than co-workers not exposed to vibration via the feet (Thompson et al., 2010; Leduc et al., 2011; Hedlund, 1989).

Researchers studying the effects of hand-arm-vibration syndrome (HAVS) have found a correlation between the neurological and vascular symptoms observed in the upper extremities and symptoms observed in the feet of workers affected by HAVS. Raynaud’s phenomenon of the feet has been examined mostly in conjunction with HAVS, a complex of osteoarticular, neurological and vascular disorders including vibration induced white finger (VWF) (Bovenzi, 2005; Griffin, 2008; Hagberg et al., 2008; Hashiguchi et al., 1994; Hedlund, 1989; Sakakibara et al., 1988; Sakakibara et al., 1991). Sakakibara et al. (1988) concluded the subjects with more frequent attacks of vibration-white foot (VWFt) had a higher prevalence of coldness in the fingers and legs, and that prevalence of symptoms was higher in the fingers than legs, also numbness was more common than coldness in the fingers but coldness more common than numbness in the legs. Hedlund (1989) examined 27 underground miners who were exposed to HAV or WBV, and cold or other environmental factors inducing vasoconstriction. It was found that the prevalence of Raynaud's phenomenon in both the fingers and toes was greater than in the control group who had no vibration exposure. The literature on VWFt without corresponding hand-arm-vibration syndrome is limited to one case study, (Thompson et al., 2010). The subject in this study had a history of FTV, and presented with bilateral, symmetrical vasospastic disease in the feet only. This particular individual, a miner with a 35 year work history, was exposed to FTV through the use of underground bolters at least 4 hours per day, 3 days per week in the 4 years preceding the assessment. A more recent study examining vibration characteristics and reported musculoskeletal discomfort levels of miners exposed to FTV indicated two of the seven workers had a diagnosis of VWFt in conjunction with vibration induced white hand and all seven equipment operators reported discomfort in the lower limbs (Leduc et al., 2011). Furthermore, Goggins and colleagues (Chapter 2) reported six of the seventeen participants (35.3%) self-reported they had been diagnosed with vibration white-hand and one of the six also indicated he had been diagnosed with VWFt.

Determining potential health risks associated with FTV is problematic as there are presently no standards specific to evaluating human exposure to FTV. Common standards currently utilized to assess human exposure to vibration are ISO 2631-1 (1997): The International Standard for Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration, and ISO 5349-1 (2004): The International Standard for Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration. Both international standards have guidelines for the amount of vibration a person can safely be exposed to, based on the probability of injury risk resulting from exposure to WBV and HTV (Table 1).

The international standards differ in the way the frequency-weightings adjust the raw vibration signal. Focusing specifically on the W_k frequency-weighting for the z-axis the only frequencies that are not altered with a negative weighting are between 4-8Hz (ISO 2631-1, 1997). Therefore for the WBV standard, frequencies above 8 Hz are negatively weighted and thus exposures above 8 Hz actually appear less damaging. The standard for HAV, ISO 5349-1, also contains negative weightings factors, although exposure frequencies between 8-16Hz are not negatively weighted, and this curve does not affect the higher frequencies as severely as ISO 2631-1. Typically the weighting curves were developed to leave frequencies believed to be associated with injury (resonant frequencies) unaltered. Given the similarities between the anatomy of the hands and feet it is not unreasonable to speculate that the resonant frequencies would be in the same range. The literature suggests the finger-hand-arm system is most susceptible to vibration at higher frequencies (40-100 Hz for the hand-arm system, >100 Hz for the fingers (Dong et. al., 2004)). Furthermore, the prevalence of vascular-induced disorders associated with

HTV tends to be greater in workers using tools that have dominant frequencies greater than 63Hz (Bovenzi, 2010). A recent study examining FTV in miners suggests ISO 5349-1 may be the more appropriate standard for assessing FTV (Leduc et al. 2011). Results indicated operator predicted health risks for the wooden raise platform and metal raise platform, both secondary sources of vibration transmission were above the health guidance caution zone (HGCZ) suggested in ISO 2631-1. In order to determine the most appropriate standard to use in assessing health risks associated with FTV further information regarding the biodynamic response and resonant frequency of the foot is required.

Biodynamic response is the relationship between human physiology and environmental stimuli. A number of factors influence the human response to vibration both intrinsic and extrinsic. Intrinsic variables can include population type (age, sex, size, and health), experience, body posture, and types of activities (ISO 2631-1, 1997). Conversely extrinsic variables can include vibration magnitude, vibration frequency, vibration axis, vibration input position, vibration duration, and other influences such as noise, heat, acceleration, and light (Bovenzi, 1998; ISO 2631-1, 1997: Griffin, 1990). When evaluating the biodynamic response of the human body to vibration, an understanding of the resonant frequency and transmissibility is required. The resonant frequency is the frequency of maximum transmissibility, occurring when the forcing frequency (frequency of exposure to the human body) and the natural frequency (frequency of the body structure) coincide. Thus, the resonant frequency is the point at which maximum displacement between organs and skeletal structures occurs, thereby placing strain on the body tissue involved (Randall et al., 1997), causing vibration exposure at resonance to be directly linked with increased injury risk.

Maximal transmissibility occurs at a structure's resonant frequency. Transmissibility is a measure of the ability of the body to either amplify or suppress input vibration. A variety of biodynamic responses, particularly those between the point at which vibration enters the body and the point at which it is measured are reflected in the transmissibility of the human body (Padden & Griffin, 1998). Transmissibility is defined as the ratio of the vibration measured between two points (Mansfield, 2005). When the majority of the vibration is transmitted through an object or body the transmissibility value obtained is high (around 1.0). Conversely, if most of the vibration is attenuated, or not transmitted through the object or body, the transmissibility value will be low (around 0.0). A transmissibility value greater than 1.0, indicates that the object or body has amplified the vibration. Due to differences in structure, each region of the body has a different resonant frequency. The frequency at which the hand-arm system is believed to be at greatest risk of injury is in the 20-40 Hz range, while the fingers are at greater risk above 100 Hz (Griffin, 1990; Dong et al., 2004), because exposure at these frequencies leads to vibration amplification. A study completed by Forta and colleagues (2011) investigated the difference thresholds for vibration of the foot while subjects were seated and had their feet on foot pedals. Only the right foot was exposed to vibration. Two sessions were completed involving either 16 or 125 Hz vibration exposure and entailing two measures of the absolute threshold and six measures of the differences threshold (at 'reference magnitudes' 6, 9, 12, 18, 24 and 30 dB above the subjects' absolute threshold). Forta et al., (2011) found the absolute threshold for the feet for vertical vibration (expressed in terms of acceleration) independent of frequency to be from 8-25 Hz. Also at 125 Hz, regardless of the vibration magnitude, all subjects had indicated they felt the vibration most at the sole of the feet. This study focused on the absolute thresholds of the feet for a seated person and not vibration transmissibility of the feet for a standing person, which is required to further improve understanding of resonance at the foot.

Singh (2013) examined vibration transmissibility via the feet in standing individuals and reported the z-axis vibration was lower at the ankle in all but one male subject, suggesting that anatomical structures such as the heel fat pad may play a role in attenuating FTV from the floor through the foot to the ankle. Gender was found to have no significant difference in floor-to-ankle transmissibility. The specific resonant frequency values of the foot or its structures have not been specifically identified, however Harazin and Grzesik (1998) examined the transmission of vertical WBV in ten standing subjects for ten postures at six body segments and found the magnitude of vibration being transmitted by the foot to be amplified in the frequency range of 31.5-125 Hz at the metatarsus and at 25-63 Hz at the ankle (malleolus medialis), implying the formation of a local resonance within the foot. However, this study was limited to ten subjects and did not take into account any anthropometric measurements of the foot.

A number of variables can potentially affect the biodynamic response of foot-transmitted vibration, including mass and arch type. The area of foot contact can vary depending on arch type; individuals with a higher arch will have less area in direct contact with a vibrating surface than those with a low arch. Absolute threshold is the lowest intensity at which vibration stimuli can be detected 50% of the time. Morioka and Griffin, (2005) examined mean vibration perception thresholds as a function of frequency at three locations on the hand; distal finger, distal palm, and proximal palm. Findings indicated that thresholds reduced systematically as the contact area increased from the fingertip to the whole hand, and the increased sensitivity with increased contact area (from finger to whole hand) may be caused by greater transmission of vibration from the hand than the finger and differences in contact pressures between hand and finger. The same mechanoreceptive afferent nerve fibres are present in the feet as well as the hands, therefore these reported differences between transmission at the fingers and the palm of the hand, combined with the anatomical similarities between the hands and feet suggest measurements on the foot should be taken at both the toes and the heel.

As the vibration energy is obviously absorbed at some point between the metatarsus and the ankle, and given the similar small bony and vascular structures of the hand and feet it is conceivable that the feet are potentially at risk for the same injuries associated with hand-transmitted vibration. Vibration stimuli to the hand, is mediated by four classes of mechanoreceptive afferent nerve fibres in the glabrous skin of the hand. Each class of fibre is distributed differently over the skin surface and has a unique response to vibration stimuli. Fast adapting fibres (FA) include Meissner corpuscles (FA I) and Pacinian corpuscles (FA II). FA I fibres are most sensitive at frequencies between 5 and 50 Hz and FA II fibres at frequencies greater than about 40 Hz. Slow adapting (SA) fibres include Merkel discs (SA I) and Ruffini endings (SA II), which are most sensitive to vibration frequencies less than about 8 Hz (Morioka & Griffin, 2005).

In order to gain a better understanding of the biodynamic response of the foot to vibration, this study will measure and document the transmission of FTV from (a) floor-to-ankle, and (b) floor-to-metatarsal, during exposure to varying levels of vibration while standing; and determine whether vibration exposure frequency, mass, arch type (independent variables) influence transmissibility (dependent variable) through the foot. It is hypothesized that transmissibility will be greater at the metatarsal than at the ankle because there is more mass distributed through the ankle and the metatarsal is free to move around more easily. Furthermore, we hypothesize that higher arches will be associated with greater transmissibility compared to lower arches given that less foot surface area touching the platform (high arch index) results in a greater mass concentration at the heal, rearfoot (ankle), and the forefoot (metatarsal). In comparison, an individual with a lower arch index would have more foot surface area touching the platform, leading to a broader distribution of mass through the foot, which could result in a decrease in transmissibility. Finally, transmissibility is hypothesized to be greater at higher frequencies because the higher frequencies are believed to be closer to the resonant frequency of the foot, (based on the reported resonance of the palm (Griffin, 1990; Dong et al., 2004)).

3.2 Methodology

The test procedures in the present study were approved by Laurentian University's Research Ethics Board. All participants gave informed consent prior to the commencement of vibration measurement.

3.2.1 Participants

Thirty male participants were recruited from a sample of convenience at Laurentian University with an average age of 28(±9) years, and height, and mass of 180.6(± 8.7) cm, and 85.65(±12.37) kg respectively (Table 2). Participants had no previous history of musculoskeletal injury, vasculopathy, neuropathy, motion sickness, diabetes, or history of head injury in the 6-months prior to testing. Participants were required to complete a short questionnaire prior to the commencement of the experimental protocol in order to ascertain their age, mass, height, and verify previous MSD history, and vibration exposure history (Table 2) (Leduc et al., 2011). All participants completed the procedure in its entirety.

3.2.2 Arch Type Assessment

Prior to the vibration exposure protocol each participant's foot arch type was classified using the foot imprint technique developed by Cavanagh and Rogers (1987). According to Cavanagh and Rogers (1987) arch index (AI) is defined as the ratio of the area of the middle third of the toeless footprint (truncated foot) to the total footprint area. An AI of less than 0.21 indicates a high arch while an AI of greater than 0.26 indicates a low arch. To calculate the AI participants were required to immerse the bottom portion of their right foot into a box containing edible colorant and then step onto graph paper consisting of 0.36cm^2 grids with their full body weight, leaving their functional foot impression on the paper. Once the graph paper dried the AI was calculated according to Equation 1 using the surface area divisions from Figure 1 (Cavanagh and Rogers, 1987).

$$Arch\ Index(AI) = \frac{B}{(A+B+C)} \qquad (1)$$

Where A is the surface area of the forefoot, B is the surface area of the midfoot, and C is the surface area of the hind foot (Cavanagh and Rogers, 1987).

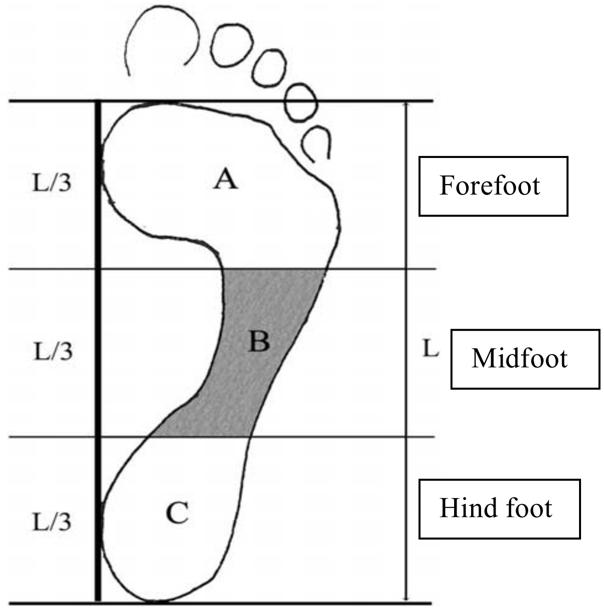

Figure 1: Division of foot print for the measurement of the Arch Index (AI). (Cavanagh and Rogers, 1987).

3.2.3 Vibration Exposure

An exercise vibration platform (Power Plate North American, Inc., Irvine, CA) was utilized to generate six different frequencies of vibration, including: 25Hz, 30Hz, 35Hz, 40Hz, 45Hz and 50Hz. The corresponding running RMS un-weighted average acceleration values and coherence at each frequency are reported in Table 1. These particular frequencies were selected to simulate the range of vibration frequencies experienced by miners exposed to FTV when drilling off platforms and raises used in underground mining (Leduc et al., 2011; Goggins, Chapter 2). Participants were randomly exposed to each vibration frequency for 20 seconds (with one repeat) to become accustomed to the exposure. Participants were then randomly exposed to each of the six frequencies of vibration for 45 seconds. During this 45 seconds exposure vibration transmissibility was measured from the floor to the toe and the floor to the ankle. A minimum 10-second rest interval between vibration exposures was selected based on previous research by Dickey and colleagues (2006).

Table 1: Calibration information for the Power Plate (North American, Inc., Irvine, CA) including: the dominant frequency (Hz), resultant running RMS un-weighted average acceleration (m/s^2) and coherence.

Frequency Indicated on PowerPlate (Hz)	Recorded Dominant Frequency (Hz)	Accelerometer Number and Location	Running RMS Un-weighted Average Acceleration (m/s^2)	Coherence
25	26	1 (platform at metatarsal)	8.88	1.00
		3 (platform at ankle)	7.20	1.00
30	31	1 (platform at metatarsal)	10.90	1.00
		3 (platform at ankle)	9.07	1.00
35	36	1 (platform at metatarsal)	12.80	1.00
		3 (platform at ankle)	10.84	1.00
40	41	1 (platform at metatarsal)	13.70	1.00
		3 (platform at ankle)	11.64	1.00
45	46	1 (platform at metatarsal)	14.43	1.00
		3 (platform at ankle)	12.71	1.00
50	50	1 (platform at metatarsal)	14.15	1.00
		3 (platform at ankle)	12.97	1.00

3.2.4 Vibration Measurement Equipment and Data Collection

Four ADXL326, 19g tri-axial accelerometers (custom design University of Windsor, ON) were utilized to measure vibration, the four specific measurement locations include:

(1) Directly on the vibration platform medial to the distal head of the first metatarsal;

(2) Directly on the skin at the distal head of the first metatarsal;

(3) Directly on the vibration platform paralleling the medial malleolous; and

(4) Directly on the skin at the lateral malleolus (Figure 2).

Data were collected at a sampling frequency of 1000 Hz and stored on two portable dataloggers, DataLOG II P3X8 (Biometrics, Gwent, UK). All ADXL326, otherwise referred to as “teardrop”, accelerometers were calibrated prior to any vibration testing, a description of the calibration procedure is provided in Appendix D.

Participants were instructed to stand on the vibration platform in a comfortable neutral posture and align their heels over two marked positions. Participants were then instructed to stand with a slight bend in the knees and to relax their shoulders and place their hands comfortably to their sides. Finally, participants were reminded not to hold onto the handles above the platform unless they needed to regain their balance.

Figure 2: Anterior (top left), posterior (top right), and lateral (bottom) views of ADXL326 accelerometer attachment.

Table 2: Participant demographic information and arch index (AI), including surface area (SA) of rearfoot, midfoot, forefoot, and total surface area (mm^2).

Participant #	Age	Height (cm)	Mass (kg)	Arch Index	Rearfoot SA (mm^2)	Midfoot SA (mm^2)	Forefoot SA (mm^2)	Total SA (mm^2)
1	20	178	81.4	0.220	88.5	63.5	136	288
2	21	185.5	90.7	0.256	99.5	84	144.5	328
3	22	189	90.7	0.258	156.5	92.5	156.5	358
4	33	167	87.0	0.253	79	66	115	260
5	24	181	88.4	0.339	101.5	129.5	150	381
6	21	193	104.3	0.282	122.5	114.5	169	406
7	38	194	93.4	0.195	109	61	142.5	312.5
8	21	189	97.2	0.268	119	99	150.5	368.5
9	26	188	97.0	0.221	109	72	144.5	325.5
10	56	179	82.5	0.305	106.5	110	143.5	360
11	30	167	85.2	0.323	94.5	114	143.5	352
12	28	185	85.2	0.251	101	80	136.5	317.5
13	22	175	57.6	0.255	83.5	78	144	305.5
14	28	160.5	83.6	0.259	98	80.5	131.5	310
15	43	200	121.5	0.301	117	131	187	435
16	19	177	63.2	0.195	95	55.5	133.5	284
17	21	180	77.1	0.257	96	86	152.5	334.5
18	20	180	75.2	0.258	108.5	90	150	348.5
19	46	184	85.2	0.184	96.5	52	133.5	282
20	28	173	93.4	0.302	98	94.5	119.5	312
21	34	178	90.7	0.258	101.5	88.5	152	342
22	21	174	74.8	0.197	88.5	51.5	121	261
23	32	181	80.7	0.121	95.5	28.5	111	235
24	23	170	72.1	0.258	91	75	124	290
25	25	190	90.0	0.247	111	91.5	167	369.5
26	20	181	69.4	0.270	89.5	84	136.5	310
27	45	183	97.7	0.223	109.5	74.5	149.5	333.5
28	19	173	89.3	0.291	98.5	97.5	138	334
29	20	185	77.5	0.221	90.5	67	144.5	302
30	23	178	86.1	0.280	97	91	137	325
Mean	*27.63*	*180.6*	*85.65*	*0.252*	*101.72*	*83.42*	*142.13*	*325.68*
S.D.	*9.49*	*8.69*	*12.37*	*0.045*	*14.55*	*23.08*	*16.01*	*43.18*

3.2.5 Data Analysis

All vibration data were processed using the Vibratools custom MATlab program (The Mathworks Inc., MA, USA v 7.1.) (Appendix E). All data remained un-weighted throughout the data analysis. A multiple resolution cross-correlation (MRXcorr) procedure was used to align both 6-signal data time histories, a process previously validated by Jack et al., in 2008. The time histories were then band-pass filtered with the high-pass and low-pass cutoff frequencies set to 0.5Hz and 100Hz respectively in accordance with ISO 2631-1 (1997). For each vibration exposure the un-weighted peak accelerations, root-mean-squared (RMS) average accelerations, running RMS accelerations, the dominant 1/3-octave band exposure frequencies, the Discrete Fourier Time Series (DFT) power spectra, and the coherence were computed.

The un-weighted peak accelerations were determined by full wave, rectifying the data and selecting the largest recorded acceleration value. The RMS average accelerations were determined using Equation 2 (ISO 2631-1, 1997) and crest factors (CFs) were determined by taking the ratio of the peak acceleration to the RMS average acceleration for each individual exposure measurement.

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

Where *a* is the un-weighted RMS average acceleration, *a(t)* is the un-weighted acceleration as a function of time (*t*) and *T* is the measurement duration.

The running RMS average accelerations were calculated using 1-second sliding window averaging with a 90% overlap (Equation 3), and determined for all three basicentric translational axis and exposure frequencies (ISO 2631-1, 1997).

$$a(t_0) = \left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0}\left[\left(a(t)\right)\right]^2 dt\right]^{\frac{1}{2}} \qquad (3)$$

Where $a(t_0)$ is the un-weighted running RMS average acceleration, $a(t)$ is the instantaneous un-weighted acceleration as a function of time (t), τ is the integration time for the running average, and t_0 is the time of observation.

The transfer functions were also calculated using the cross-spectral density (CSD) method (Equation 4 – Griffin, 1990; Smith, 1999) across the frequency ranges previously mentioned for all accelerometers. From these transfer functions the dominant transmission frequency (frequency with the greatest transfer function modulus magnitude) was determined for all three basicentric translational axis at the metatarsal and ankle.

$$T_{io}(f) = \frac{CSD_{io}(f)}{PSD_{ii}(f)} \qquad (4)$$

Where T_{io} is the complex transfer function between the platform metatarsal or ankle input *(ii)* accelerations and the metatarsal and ankle output *(oo)* accelerations at frequency f. CSD_{io} indicates a cross-spectral density function between the platform input accelerations and accelerations for the output of the metatarsal and ankle. PSD_{ii} represents the power-spectral density of the platform input.

Transmissibility is defined as the ratio of the running RMS acceleration output to input. Transmissibility was calculated at the metatarsal (Equation 5) and the ankle (Equation 6) in the z-axis for comparison.

$$T_{metatarsal} = \frac{a_z(TD02)}{a_z(TD01)} \qquad (5)$$

Where $T_{metatarsal}$ is the transmissibility at the metatarsal, $a_z(TD02)$ is the un-weighted running RMS average acceleration on top of the metatarsal, and $a_z(TD01)$ is the un-weighted running RMS average acceleration on the platform at the metatarsal.

$$T_{ankle} = \frac{a_z(TD04)}{a_z(TD03)} \qquad (6)$$

Where T_{ankle} is the transmissibility at the ankle, $a_z(TD04)$ is the un-weighted running RMS average acceleration on the lateral ankle, and $a_z(TD03)$ is the un-weighted running RMS average acceleration on the platform at the ankle.

In addition to 1/3-octave bandwidth running RMS average acceleration spectra (ISO 2631-1, 1997) and Discrete Fourier Time Series (DFT) power spectra were also determined using a 1-second Hanning window with the same 90% overlap as the 1/3-octave band running RMS average acceleration analysis.

The degree of the correlation between the input and output was expressed in terms of the coherence (Equation 7). Coherence being a value between 0 and 1, the greater the coherence the greater the correlation between the two signals being analyzed (Mansfield, 2005).

$$coherence(f)^2 = \frac{|CSD_{input-output}(f)|^2}{PSD_{input}(f) x\, PSD_{output}(f)} \qquad (7)$$

Where CSD is the cross-spectral density and PSD is the power spectral density.

For the purpose of this paper the root-mean-squared (RMS) average accelerations, the dominant 1/3-octave band exposure frequencies, floor-to-ankle transmissibility, floor-to-metatarsal transmissibility, and the coherence were evaluated.

3.2.6 Statistical Analysis

Prior to any statistical analysis, the data were transformed using a logarithmic transformation (Equation 8), as suggested by Tabachnick and Fidell (2007) and Howell (2007), to ensure the assumption of normality was met.

$$NEWX = LG10(X + C) \qquad (8)$$

Where *X* is the original variable and *C* is a constant added to each score so that the smallest score is 1.

3.2.6.1 Effects of Arch Index on Transmissibility

A two-way repeated measures analysis of covariance (ANCOVA) was conducted to examine the effects of arch type (covariate), frequency (independent variable) and location (independent variable) on vibration transmissibility magnitude (dependent variable) at the metatarsal (toe) and ankle. Significance was achieved when $p<0.05$.

3.2.6.2 Effects of Mass on Transmissibility

A two-way repeated measures analysis of covariance (ANCOVA) was conducted to examine the effects of mass (covariate), frequency (independent variable) and location (independent variable) on vibration transmissibility magnitude (dependent variable) at the metatarsal (toe) and ankle. Significance was achieved when $p<0.05$.

3.2.6.3 Effects of Location and Frequency on Transmissibility

A two-way repeated measures analysis of variance (ANOVA) was conducted to examine the effects of location and frequency (independent variables) on vibration transmissibility magnitude (dependent variable). The goal of repeated-measures designs is to determine whether participants changed significantly across conditions (frequencies). Significance was achieved when $p<0.05$.

3.3 Results

The average floor to ankle (FTA) and floor to metatarsal (FTM) transmissibility results for thirty participants are displayed in Figure 3. Floor to ankle transmissibility was greater at the lower frequencies and floor to metatarsal transmissibility was greater at higher frequencies (Figure 4a & 4b). Participants 2, 17, and 26 experienced peak floor to ankle transmissibility at 25-30 Hz, ranging between 1.4 and 1.8, implying vibration at the ankle was amplified at 25 and 30 Hz for these three participants. For five other participants (8,9, 15, 18, and 27) FTM transmissibility was always higher than FTA transmissibility. Lastly, participants 5, 11, 13, and 17 had two intersections between their FTA and FTM transmissibilities (Figure 4a&4b).

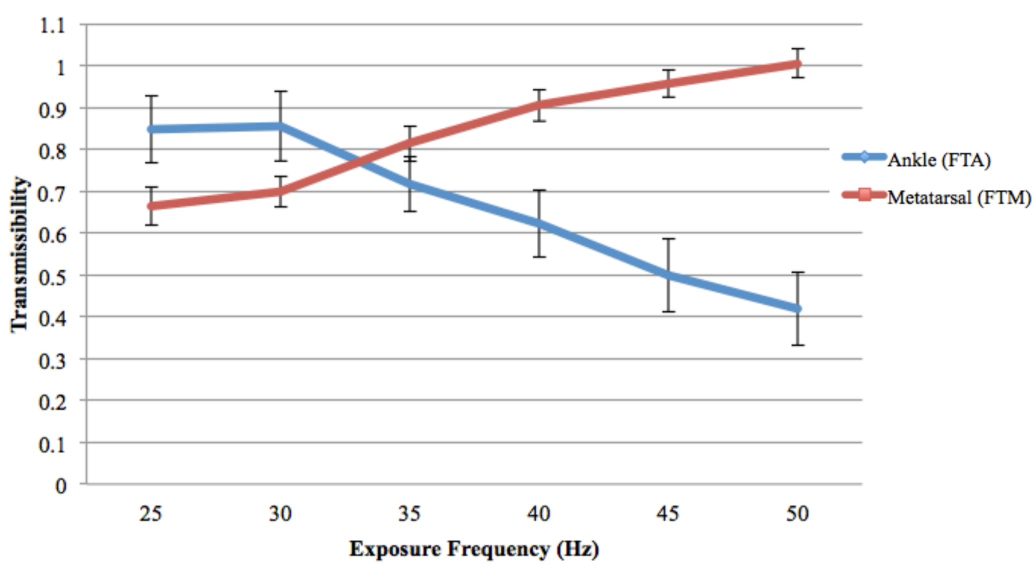

Figure 3: Average transmissibilities of 30 male subjects from floor to ankle (blue) and floor to metatarsal (red) at six frequencies (25, 30, 35, 40, 45 and 50Hz).

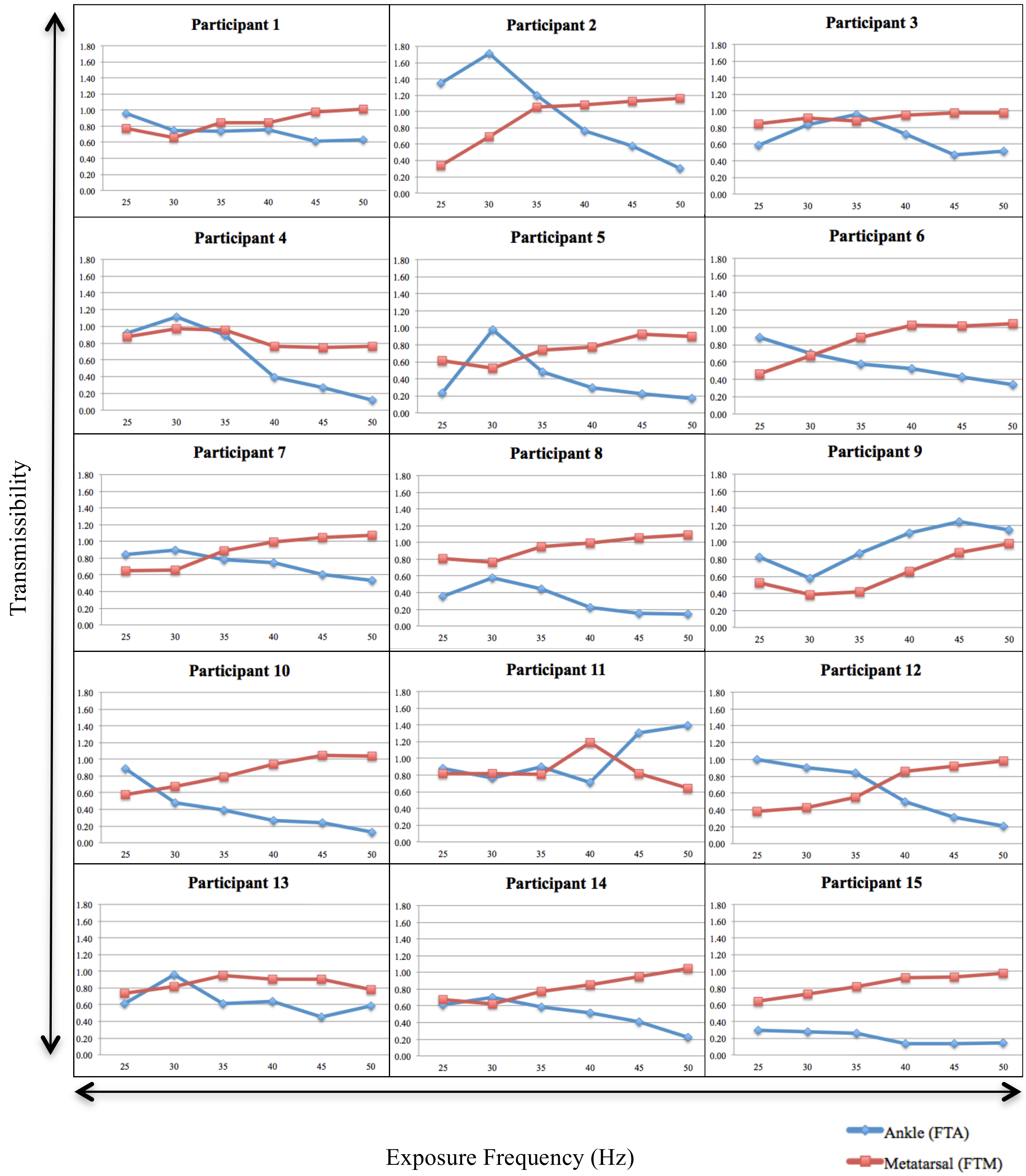

Figure 4(a): Floor to ankle (blue) and floor to metatarsal (red) transmissibility at six frequencies (25, 30, 35, 40, 45 and 50Hz) for participants 1-15.

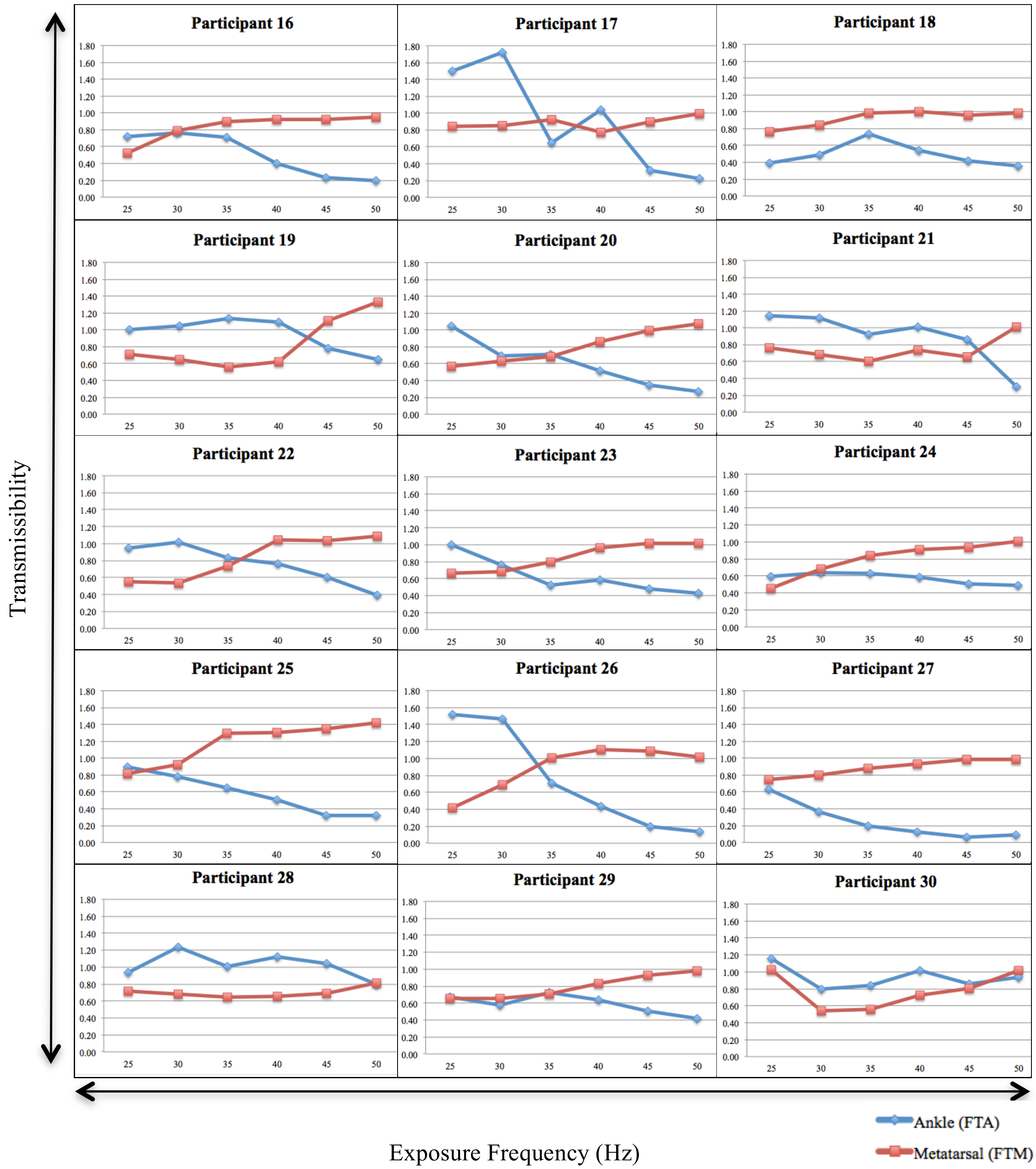

Figure 4(b): Floor to ankle (blue) and floor to metatarsal (red) transmissibility at six frequencies (25, 30, 35, 40, 45 and 50Hz) for participants 16-30.

For all statistical analysis the dependent variable was transmissibility, measured as a ratio between the running RMS acceleration input to output. The independent variables were location with two levels (toe and ankle) and frequency with six levels (25Hz, 30Hz, 35Hz, 40Hz, 45Hz, 50Hz).

3.3.1 Effects of Arch Index (AI) on Transmissibility

The two-way repeated measures ANCOVA revealed that neither the three-way interaction of location*frequency*AI [$\lambda = 0.816$, $F(5,24) = 1.080$, $p = 0.396$] or the two-way interaction with location*AI [$\lambda = 0.989$, $F(1,28) = 0.323$, $p = 0.575$] and frequency*AI [$\lambda = 0.932$, $F(5,24) = 0.349$, $p = 0.877$] were significant ($p<0.05$) (Appendix F).

3.3.2 Effects of Mass on Transmissibility

The two-way repeated measures ANCOVA revealed that neither the three-way interaction of location*frequency*mass [$\lambda = 0.959$, $F(5,24) = 0.203$, $p = 0.958$] or the two-way interaction with location*mass [$\lambda = 0.967$, $F(1,28) = 0.959$, $p = 0.336$] and frequency*mass [$\lambda = 0.884$, $F(5,24) = 0.627$, $p = 0.680$] were significant ($p<0.05$) (Appendix G).

3.3.3 Effects of Location and Frequency on Transmissibility

A two-way repeated measures analysis of variance was conducted to evaluate the effect of location and frequency on vibration transmissibility (Appendix H). The location and frequency main effects and location x frequency interaction effect were tested using the multivariate criterion of Wilks' lambda (λ). The location x frequency interaction was significant $\lambda = 0.246$, $F(5,25) = 15.365$, $p = 0.0001$, the location main effect was significant, $\lambda = 0.644$, $F(1,29) = 16.032$, $p = 0.0001$, and the frequency main effect was significant $\lambda = 0.513$, $F(5,25) = 4.754$, $p = 0.003$.

Table 3: Summary of SPSS significance results for an ANOVA, ANCOVA using arch index covariate, and an ANCOVA using mass covariate.

	ANOVA	**ANCOVA (AI)**	**ANCOVA (Mass)**
Main Effect: Location	λ=0.644 F=16.032(1,29) p=0.0001 eta^2=0.356	λ=0.017(1,28) p=0.897 eta^2=0.001	λ=0.165(1,28) p=0.687 eta^2=0.006
Main Effect: Frequency	λ=0.513 F=4.754(5,25) p=0.003 eta^2=0.487	λ=0.573(5,24) p=0.720 eta^2=0.107	λ=1.134(5,24) p=0.370 eta^2=0.191
Interaction: Location*Frequency	λ=0.246 F=15.365(5,25) p=0.0001 eta^2=0.754	λ=1.777(5,24) p=0.156 eta^2=0.270	λ=0.727(5,24) p=0.610 eta^2=0.131

Six paired-samples t-tests were conducted to follow up the significant location main effect (Appendix I). Familywise error rate was controlled for across the tests using Holm's sequential Bonferroni approach. Differences in mean transmissibility between the two locations were significant between the toe at 40 Hz and the ankle at 40 Hz $t(29) = 4.116$, $p < 0.001$, between the toe at 45 Hz and the ankle at 45 Hz $t(29) = 6.599$, $p < 0.001$, and between the toe at 50 Hz and the ankle at 50 Hz $t(29) = 8.828$, $p < 0.001$ (Table 4).

Table 4: Summary of SPSS results for paired-samples t-tests to examine location main effect.

Pair	t	Df	p
t25 – a25	-2.127	29	0.042087219
t30 – a30	-1.962	29	0.059386732
t35 – a35	1.725	29	0.095140618
t40 – a40	4.116	29	0.000291778*
t45 – a45	6.599	29	0.000000312*
t50 – a50	8.828	29	0.000000001*

*Significance was determined using Holm's sequential Bonferroni approach with p=0.05.

Thirty paired-samples t-tests were computed to assess the significant frequency main effect. Differences between the six frequencies were evaluated at both locations separately (Appendix H), controlling for familywise error rate using Holm's sequential Bonferroni approach. At the ankle twelve of the fifteen paired-samples were significant, the three pairs which were not significantly different were those at the lower frequencies a25 – a30 ($t(29) = -0.114$, $p = 0.910$), a25 – a35 ($t(29) = 2.094$, $p = 0.045$), and a30 – a35 ($t(29) = 2.402$, $p = 0.022$) (Table 5).

Table 5: Summary of SPSS results for paired-samples t-tests to examine frequency main effect.

Ankle	t	df	P	Metatarsal	t	df	p
a25 – a30	-0.114	29	0.910254829	t25 – t30	-0.918	29	0.366100282
a25 – a35	2.094	29	0.045159362	t25 – t35	-3.344	29	0.002288238*
a25 – a40	3.822	29	0.000647165*	t25 – t40	-5.211	29	0.000014124*
a25 – a45	4.910	29	0.000032540*	t25 – t45	-6.369	29	0.000000581*
a25 – a50	5.940	29	0.000001877*	t25 – t50	-7.325	29	0.000000046*
a30 – a35	2.402	29	0.022916628	t30 – t35	-5.552	29	0.000005483*
a30 – a40	3.662	29	0.000993822*	t30 – t40	-7.300	29	0.000000049*
a30 – a45	4.605	29	0.000075999*	t30 – t45	-7.581	29	0.000000023*
a30 – a50	5.470	29	0.000006881*	t30 – t50	-7.529	29	0.000000027*
a35 – a40	2.771	29	0.009649413*	t35 – t40	-4.324	29	0.000164825*
a35 – a45	5.135	29	0.000017443*	t35 – t45	-4.665	29	0.000064297*
a35 – a50	6.381	29	0.000000564*	t35 – t50	-4.553	29	0.000087815*
a40 – a45	4.085	29	0.000317690*	t40 – t45	-2.137	29	0.041199389
a40 – a50	5.629	29	0.000004432*	t40 – t50	-2.483	29	0.019061900
a45 – a50	3.898	29	0.000527046*	t45 – t50	-1.746	29	0.091367048

*Significance was determined using Holm's sequential Bonferroni approach with p=0.05.

Finally, fifteen paired-samples t-tests were completed using tetrad comparisons, involving four means to evaluate whether the mean differences between the two locations are the same between any two frequencies (Appendix H), again controlling for familywise error rate using Holm's sequential Bonferroni approach. All pairs were significantly different, except for the differences between t25 – a25 and t30 – a30 (Table 6).

Table 6: Summary of SPSS results for paired-samples t-tests to examine location*frequency interaction effect.

Pair	t	df	p
t25 – a25 & t30 – a30	-0.425	29	0.674275419
t25 – a25 & t35 – a35	-3.444	29	0.001764169*
t25 – a25 & t40 – a40	-5.218	29	0.000013829*
t25 – a25 & t45 – a45	-6.641	29	0.000000279*
t25 – a25 & t50 – a50	-7.536	29	0.000000026*
t30 – a30 & t35 – a35	-3.917	29	0.000500492*
t30 – a30 & t40 – a40	-6.580	29	0.000000329*
t30 – a30 & t45 – a45	-7.490	29	0.000000030*
t30 – a30 & t50 – a50	-8.240	29	0.000000004*
t35 – a35 & t40 – a40	-4.866	29	0.000036805*
t35 – a35 & t45 – a45	-7.622	29	0.000000021*
t35 – a35 & t50 – a50	-8.091	29	0.000000006*
t40 – a40 & t45 – a45	-4.081	29	0.000321099*
t40 – a40 & t50 – a50	-4.951	29	0.000029071*
t45 – a45 & t50 – a50	-3.390	29	0.002033307*

*Significance was determined using Holm's sequential Bonferroni approach with p=0.05.

3.4 Discussion

In an effort to gain a better understanding of the biodynamic response of the foot to vibration exposure, transmissibility was measured at two locations, the ankle and the first metatarsal, while exposed to FTV at six frequencies: 25Hz, 30Hz, 35Hz, 40Hz, 45Hz, and 50Hz. The first objective of this study was to measure FTV transmissibility between the floor-to-ankle and floor-to-metatarsal. In general, floor-to-ankle transmissibility was highest (0.86) at 30Hz and floor-to-metatarsal transmissibility was highest (1.01) at 50Hz. The results of a two-way repeated measures ANOVA indicated the location x frequency interaction was significant $\lambda = 0.246$, $F(5,25) = 15.365$, $p = 0.0001$. More specifically, differences in mean transmissibility between the ankle and metatarsal were significant at 40 Hz ($p = 0.00029$), 45 Hz ($p = 0.00000031$), and 50 Hz ($p = 0.000000001$) as seen in Figure 2. These results are in accordance with the hypothesis that transmissibility is greater at the metatarsal than at the ankle especially at the higher frequencies 40, 45, and 50Hz.

The interaction graphed in Figure 3 suggests the biodynamic response of the foot at both the ankle and toe is similar from 25 to 30 Hz. Between 30 and 35 Hz the relationship between the ankle and toe responses becomes inverted and intersects (at approximately 33Hz). From the point of intersection the ankle transmissibility continues to decrease until 50 Hz while the toe transmissibility continues to increase until 50 Hz. A study completed by Harazin and Grzesik (1998) used accelerometers to measure transmissibility of vibration from the floor to the metatarsus (ossa metatarsalia) and the ankle (malleolus medialis) with frequencies ranging from 4-250 Hz in one-third octave bands. Posture nine is identical to the posture in the current study. In the frequency range from 25-50 Hz the mean transmissibility values between the floor and metatarsus in posture nine ranged between 0.6-1.0 (Figure 5(b)) and the mean transmissibility values between the floor and malleolus medialis in posture nine appear to be above 1.0 (Figure 5(c)). The mean transmissibility values from the Harazin and Grzesik (1998) study at the ankle appear higher than the mean transmissibilities from the current study (Figure 2), where the values range between 0.42-0.86, but it should be noted that the measurements in the current study were taken on the malleolus lateralis, not the malleolus medialis. The transmissibility values from the two studies differ somewhat, but the overall trend is similar. Differences in methodology and measurement locations may account for the variation in transmissibility values. The medial malleolus is the medial head of the tibia, which articulates with the talus. The tibia is the second largest bone in the body and it bears much of the body's weight and is essential for movement. The medial malleolus is also an insertion point for the posterior tibotalar ligament, tibocalcaneal ligament, anterior tibotalar ligament, and the tibionavicular ligament. The medial arch is supported by the talus, navicular, the first, second and third cuneiforms, and the first, second and third phalanges. Alternatively, the lateral malleolus is the lateral head of the fibula, which articulates with the talus. The fibula is much smaller than the tibia, making it a much less weight baring bone, instead it acts as a stabilizing bone for the ankle. The lateral malleolus is also an insertion point for the anterior talofibular ligament, calcaneofibular ligament, and the posterior talofibular ligament. The lateral arch is supported by the talus, calcaneus, cuboid, and the fourth and fifth phalanges. As well the fat pad of the foot is located laterally which may account for increased attenuation. The magnitude of vibration being transmitted is lower at the ankle than the metatarsus in both studies; therefore it is apparent that vibration energy is attenuated at some point between the ankle and metatarsus.

Morioka and Griffin (2005) examined differences in absolute thresholds for the perception of vibration at the fingertip with thresholds for the whole hand over the frequency range 8-500Hz. Over the three conditions (palm, grip and fingertip), there were significant differences in absolute threshold at all frequencies (Friedman, $p < 0.005$), except at 31.5Hz (Friedman, $p = 0.21$). When consideration is given to the anatomical similarities between the hands and feet it is interesting to note the similarities between the present results and those of the Morioka and Griffin (2005) study. The fingers and palm can be compared to the metatarsal (toe) and ankle in this study. If this parallel is made and the corresponding line plots are examined, the interactions are very similar (Figure 4 & 5(a)). Although one plot uses transmissibility (Figure 4) and the other plot uses acceleration (m/s^2 r.m.s.) (Figure 5(a)), as previously noted transmissibility is actually a ratio of the RMS acceleration, thus the interactions can be considered, but the horizontal values cannot be directly compared. Initially the ankle and palm results are higher than the toe and fingertip, until the lines intersect between 30 and 35 Hz, thereafter the ankle and palm results continue to decrease as the toe and fingertip continue to increase.

The transmissibility results are not strictly limited to the interaction. The greatest transmissibility for the metatarsal occurred at 50Hz and for the ankle (lateral malleolus) from 25-30Hz (Figure 3), indicating the formation of a local resonance at each location. The findings are in line with (Harazin & Grzesik, 1998) who reported 1/3 octave band resonance frequency between 31.5-125Hz for the metatarsal and between 25-63Hz for the ankle. Similarly, Singh (2013) completed a study with sixteen participants (eight males and eight females) recording vibration on the floor and ankle with tri-axial accelerometers using ISO 2631-1 while standing on a low frequency (3.15-10Hz) and a high frequency (40Hz) vibration platform. This study reported greater transmissibility between the floor and ankle at lower FTV exposure frequencies (3.15-10Hz) than higher FTV exposure frequencies (40Hz). At the low frequency (3.15-10Hz) floor-to-ankle transmissibility averaged 1.06 with a standard deviation of ±0.09. These results are in line with the results of the Harazin & Grezesik (1998) study as floor-to-ankle transmissibility was also found to be greater than 1.0 between 3.15-10Hz (Figure 5(c)).

The secondary objective of this study was to determine whether arch index or mass influence vibration transmissibility through the foot. Results from two separate ANCOVAs indicate neither arch index nor mass have any significant effects ($p < 0.05$) on vibration transmissibility through the foot. A recent study by Singh (2013) examined floor to ankle transmissibility to determine whether gender, arch type and mass played a role in transmissibility at both low and high frequency FTV. Eight male and eight female participants with varying arch types and mass, were exposed to FTV with a dominant frequency below 10 Hz and a dominant frequency between 30-40Hz. Similarly, no difference in FTV by gender or arch type was confirmed (Singh, 2013).

There are several limitations in the study design that should be considered when interpreting the results from this study. First, vibration exposure magnitude and exposure frequency were not controlled independently. Unfortunately we were not able to maintain the same vibration exposure magnitude for all vibration exposure frequencies (Table). Therefore, changes in transmissibility reported in this study may not strictly be due to changes in frequency, since vibration exposure magnitude also increased with increases in exposure frequency. Furthermore, several researchers have reported transmissibility increases with increasing magnitude (Mansfield et al., 2006; Griffin, 2008; Dong et al., 2011).

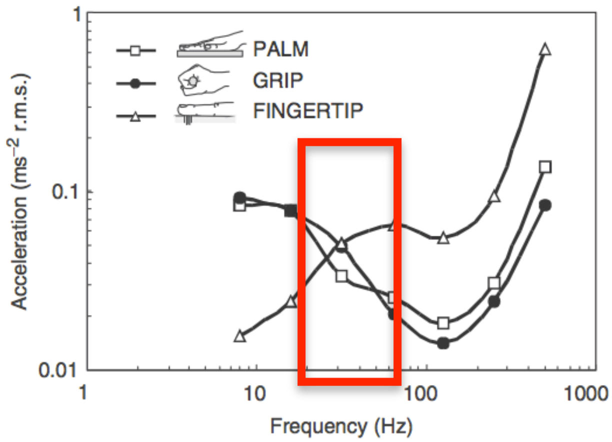

Figure 5(a): Comparison of median absolute thresholds between palm, grip and fingertip, expressed in acceleration (Morioka & Griffin, 2005).

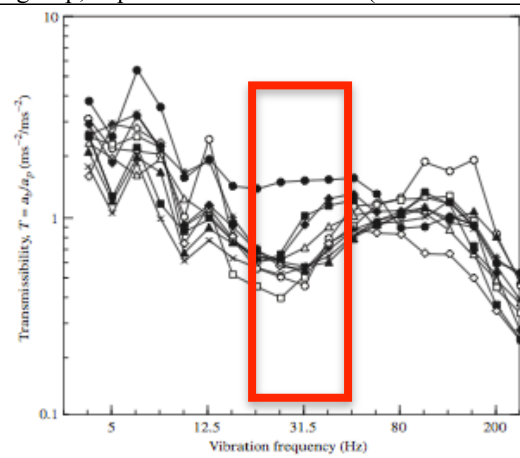

Figure 5(b): Mean transmissibilities between vertical floor acceleration and metatarsus acceleration for 10 subjects standing in ten postures (Harazin & Grezesik, 1998). Key posture for comparison is *.

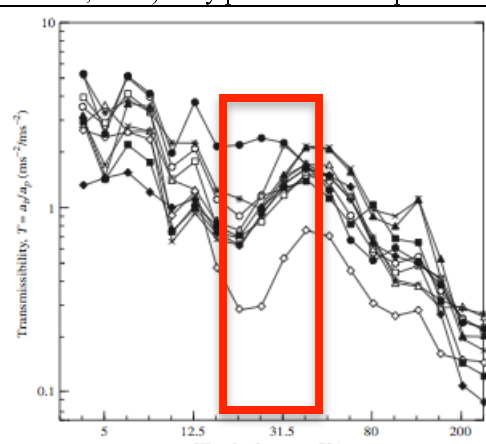

Figure 5(c): Mean transmissibilities between vertical floor acceleration and ankle acceleration for 10 subjects standing in ten postures (Harazin & Grezesik, 1998). Key posture for comparison is *.

Note: The red box indicates the area for comparison with this study.

Although participants' foot placement was controlled and all were given the same instruction with regards to how to stand it could not be confirmed that all participants' maintained the same posture throughout the 45-second FTV exposure period. Deviations in posture have been found to be a predominant variable influencing vibration transmissibility because it changes the surface contact of the human with the vibrating plane, influencing the position of the bony structures and the degree of tension in different muscle groups of the trunk and the extremities, in turn changing the resonant frequency of the body structure (Harazin & Grzesik, 1998; Paddan & Griffin, 1998; Mansfield et al., 2006; Zimmerman & Cook, 1997; Kitazaki & Griffin, 1998; Eger et al., 2008). Variations in the elbow joint angle have been reported to alter the impedance measured at the hand while operating a hand held device. Furthermore, it has been found that vibration transmissibility was greatest while working in a closed biomechanical chain with the extended elbow (Griffin, 1990; Adewusi et al., 2011). The ankle and knee joint angles were not thoroughly measured within this study, but it has been shown that significantly more vibration was transmitted to the head when standing (with straight legs) and bending the legs was found to greatly reduce the transmission of vibration to the head at frequencies above 4 Hz (Paddan & Griffin, 1998). Thus, variations in the ankle and knee angles could have greatly influenced the vibration transmissibility. Although not measured, we observed participants making small posture changes, which were more prevalent at higher exposure frequencies. Although we cannot confirm, anecdotal evidence from the participants suggests they were trying to maintain a posture that transmitted less vibration to their head. In the study by Harazin & Grzesik (1998), they found that above 25Hz, 50% of the variability in transmissibility was due to the postures for many reasons including relative positions of tissues, organs and their positions in relation the source of vibration and to the direction of propagation of vibration.

Changes in posture and segmental angles are accompanied by changes in contact force (weight distribution) and centre of mass (Paddan & Griffin, 1998). Information regarding the effects of contact force has been published with regards to hand-transmitted vibration in conjunction with absolute thresholds, but not transmissibility. It was noted in a study by Morioka and Griffin (2005) that increasing the contact force raised thresholds for vibration exposure. The current study hypothesized that an increase in mass would increase downward force onto the platform, which may decrease vibration transmissibility. Depending on centre of mass, there are differences in the amount of weight on the hindfoot (ankle) and the forefoot (metatarsal). If the majority of the mass is distributed to the hindfoot (ankle) it would be expected that transmissibility would be lower than at the forefoot (metatarsal), similar to results by (Eger et al., 2011) which revealed driving an LHD vehicle with an empty bucket exposed the LHD operator to significantly higher vibration levels than when driving with a full bucket. In future research, changes in posture and segmental angles could be determined and measured using a camera system with reflective markers on the joints of interest.

This study also had limitations with the arch index measurement because the centre of pressure location during foot-transmitted vibration exposure could not be confirmed. A final limitation to this study was that the postures were not precisely controlled throughout the experiment, where changes in posture have been identified as influential to vibration transmissibility (Harazin & Grzesik, 1998; Griffin 1990; Mansfield et al., 2006; Zimmerman & Cook, 1997; Kitazaki & Griffin, 1998; Eger et al., 2008).

Future research should include a larger range of FTV exposure frequencies starting at lower frequencies and also extending to higher frequencies above 100Hz because the resonant frequency of the ankle has been identified as being under 30Hz (Harazin & Grzesik, 1998; Singh, 2013) while the resonant frequency of the metatarsal has been recognized to be in the higher frequency range of 31.5-125Hz (Harazin & Grzesik, 1998). Future studies should also involve a foot map to more precisely measure foot length, surface area, and high-pressure areas with mass distribution. Confirming the resonant frequencies at different locations on the foot will help determine exposure frequencies that are most likely to lead to health risks (Furuta et al., 1991) in workers exposed to FTV. A greater understanding of the transmissibility properties of the foot is also needed to design personal protective equipment (PPE), such as mats, boots, and insoles, capable of attenuating FTV at the forefoot and rearfoot regions of the foot.

Knowing the resonant frequency of the foot will also assist in establishing the appropriateness of the current standard for measuring FTV. The international standards for measuring vibration exposure are not specific for the feet. ISO 2631-1 (1997) is designed to measure and evaluate WBV (although it does stipulate standing measurements should also be taken with this standard) and ISO 5349-1 (2004) is for measuring hand-transmitted vibration. These standards have weighting curves designed around the resonant frequencies of the body structures at risk of damage from vibration exposure, and in order to make a standard ideal for measuring FTV the resonant frequencies need to be known so weighting curves can be properly developed (Goggins, Chapter 2).

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CHAPTER FOUR:

GENERAL DISCUSSION

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4.1 Linking of Previous Chapters

There is evidence to suggest that miners are experiencing physiological and neurological damage to their feet from vibration exposure while operating underground mining equipment (Hedlund, 1989; Toibana, 1994; Thomspon, 2010; Leduc, 2011). The purpose of the field study was to measure and document the characteristics and dominant frequencies of vibration entering the body via the feet on various underground mining equipment; determine and compare predicted health risks based on both ISO 2631-1 (1997) and ISO 5349-1 (2004); and to examine differences in operator reported musculoskeletal discomfort. Differences in the values from both standards are evidence of how the two standards filter the incoming vibration signals differently. According to the ISO 2631-1 8hr HGCZ, only one worker was exposed to FTV above the criterion value (bolter drill – RDH 9) and one worker was exposed to FTV within the HCGZ (jumbo drill 1). Operators of jumbo drill 1 and bolter drill 1 were exposed to vibration above the ISO 5349-1 daily exposure value.

Results from the musculoskeletal discomfort questionnaire indicated of the seventeen operators included in this study, eight operators (47.1%) specifically complained of pain or discomfort in their right and left feet; these operators included the locomotive operator, three bolter drill operators and four jumbo drill operators. Twelve (70.6%) of the equipment operators had a complaint of discomfort in their lower body, specifically at the level of the knee or lower. Additionally, although it was not specifically asked in the questionnaire, six of the seventeen participants (35.3%) self-reported they had been diagnosed with vibration white-hand and one of these participants also indicated he had been diagnosed with vibration white-foot. Only two of the six operators who indicated a diagnosis of vibration white-hand also reported severe discomfort. Consequently, there is evidence to suggest that the workers experiencing vibration levels above criterion values in ISO 2631-1 or ISO 5349-1 do not necessarily correlate with the workers who are currently experiencing and reporting symptoms. This might suggest a latency period for the onset of vibration injury from exposure. Once physiological damage occurs pain may decrease, implying workers may become accustomed to the pain/discomfort and may not report it as high. The lack of correlation between discomfort reports and diagnosis of vibration white-hand or white-feet may imply workers already have neuropathies and may not be able to feel the pain/discomfort. Once neurological damage has occurred, the workers could be at an even higher risk of injury and sustained neurological damage because perception in their extremities (hands and feet) is diminished.

The field study indicated an alarming number of workers (70.6%) experiencing lower body discomfort while the vibration exposure measurements suggest only three are being exposed above the current ISO standards. These results imply that current standards are not appropriate for evaluating injury risk from FTV. In order to develop a standard specific to FTV, the resonant frequency of the foot must be identified to design appropriate weighting curves.

The findings with regards to vibration induced white-hand and vibration induced white-foot should be viewed with caution because a specific question regarding these diagnosis was not incorporated into the questionnaire. In fact, the percentage of workers with vibration white-hand or vibration white-foot could be higher than reported. All measurements were completed in mining communities in northern Ontario, where there is limited access to physicians and very limited access to medical expertise or specialists (Sibley & Weiner, 2011). Consequently, many workers may not be properly evaluated for vibration induced white-finger or vibration induced white-foot. In the future, questionnaires need to include questions regarding whether workers were diagnosed with vibration white-hand or vibration white-toe, and if yes, then how long have they had the diagnosis? Also are they taking any medications and do they have a history of smoking?

A laboratory study was completed to determine the biodynamic response of the foot by measuring the transmission of vibration from the floor to ankle, and the floor to metatarsal, when exposed to different levels of vibration while standing. Also determining if independent variables (vibration exposure frequency, mass, arch type) influence dependant variable transmissibility through the foot. The exposure frequencies were chosen to replicate those which miners are exposed to underground (Goggins, 2013; Leduc et al., 2011).

The interaction between location and frequency was significant (two-way repeated measures ANOVA $\lambda = 0.246$, $F(5,25) = 15.365$, $p = 0.0001$). Predominantly, differences in mean transmissibility between the ankle and metatarsal were significant at 40 Hz ($p < 0.001$), 45 Hz ($p < 0.001$), and 50 Hz ($p < 0.001$). However, the results using arch index and surface area as covariates did not significantly influence vibration transmissibility and washed out the significant frequency x location interaction. At the metatarsal the greatest transmissibility occurred at 50Hz, indicating the formation of a local resonance.

These results are comparable to those of another study indicating evidence of the three resonances at the central frequencies of 1/3 octave bands: 4-8Hz, 12.5Hz and 31.5-125Hz (Harazin & Grzesik, 1998). Floor to ankle transmissibility was greatest from 25-30Hz, again paralleling the Harazin & Grzesik (1998) study where the three resonances at the central frequencies of 1/3 octave bands were: 4-8Hz, 12.5Hz and 25-63Hz for the ankle. Floor-to-ankle transmissibility has also been identified as greatest when exposed to lower frequency vibration (3.15-10Hz) (Singh, 2013).

The laboratory study revealed a highly significant interaction, even after accounting for arch index (surface area). Consequently regardless of foot anatomy there are significant changes in transmissibility at different frequencies. However, after removing the effect of mass, the effect of frequency is eliminated, meaning that the mass of individual still plays a huge role in vibration transmission. Randall and colleagues (1997) examined the resonant frequencies of standing humans and found no significant relationship between the mass, height, or mass to height ratio and measured resonant frequency. As well a recent study by (Singh, 2013) found no significant difference in floor to ankle transmissibility based on body mass. Conversely a study on the influence of body mass on WBV on quad bikes indicated body mass was significant whereas as age height and driving experience were not. The response of the human body to vibration is frequency dependent (Griffin, 1990) therefore if the effect of mass eliminates the effect of frequency it can be assumed that mass plays some role. Even though mass cannot be directly correlated with increased risk due to vibration exposure, increased body mass can be correlated with increased health risks. Therefore, increased body mass inadvertently is a comorbid condition in increasing injury/health risk.

4.2 Relevance to the Mining Industry

Results from the field study (Chapter 2) identify the vibration exposure frequencies from the underground mining equipment and assist in documenting the properties of the vibration workers are being exposed to. There were variations in the dominant frequencies (Hz), average frequency-weighted RMS accelerations (m/s^2), and probable health risks according to both the ISO 2631-1 and ISO 5349-1 standards. It still remains unclear which standard is the best for measuring FTV, so future research in the field should utilize both ISO 2631-1 and ISO 5349-1. Standards for measuring vibration exposure and intervention should be based on the most conservative findings. Furthermore, field research with more specific medical histories needs to be completed in order to correlate FTV exposure with discomfort and the development of vibration white foot.

From the laboratory study it became apparent that location on the foot and frequency of exposure more significantly affect vibration transmissibility than arch index or mass (Chapter 3). Transmissibility at the ankle was greatest at 30Hz and transmissibility at the metatarsal was greatest at 50Hz. Therefore workers exposed to FTV at these frequencies could be at increased risk for vibration induced injury. Increasing research on the biodynamic response of the foot to document the resonant frequencies of different parts of the foot will hopefully lead to the development of proper insole and safety boot combinations to assist with exposures at the frequencies identified in the field (Chapter 2). It has been proven that shoe inserts of different shape and material combined with subject specific characteristics have been shown to influence comfort perception (Mundermann et al., 2001).

Immediate suggestions for minimizing injury risk include engineering solutions: (1) purchase equipment with decreased FTV magnitude and frequencies below 30-40Hz; (2) purchase anti-vibration drills (Leduc et al., 2010); and (3) purchase anti-vibration platforms (Leduc et al., 2010). From an administration standpoint, solutions are comprised of maintaining the equipment to ensure its performance is optimal, having shorter shift lengths to confirm vibration exposure durations of the workers, and keep the work environment warm and dry. Lastly, as previously addressed, further research needs to be completed on insoles and boots (Singh, 2013) and anti-vibration mats (Leduc et al., 2011) so workers can find the right combination to help attenuate vibration prior to vibration energy reaching their feet.

4.3 Relevance to the Medical Community

It is important for physicians to understand and recognize the symptoms of vibration white-foot early, so workers can try to limit vibration exposure known to cause injury. It is equally important for underground miners to see a physician annually so proper medical histories can be completed and recorded to better understand the pathology with regards to vibration exposure. Medical histories which are appropriate for determining symptoms of foot-transmitted vibration exposure and any resulting neurological damage can be extensive and time consuming but should include (not limited to): work history with which types of equipment, exposure length, number of shifts, and histories of connective tissue disease, diabetes mellitus, gout, arthritis, neurological problems, thyroid disease, frostbite to the fingers or toes, and smoking (Thompson, et al., 2010). As well as Doppler imaging (for peripheral artery insufficiency in the arms or legs), blood pressure, Adson's or Allen's testing (evidence of vessel occlusion), blood testing (for systemic causes of secondary Raynaud's phenomenon), and cold provocation plethysmography (Thompson, et al., 2010; Harada & Mahbub, 2008; Noel, 2000).

Physicians must also be aware that vibration exposure does not always directly affect the area of exposure. For instance, symptoms in the toe can result from not only direct exposure via the foot, but also long-term repeated vasoconstriction and circulatory disturbances in the foot through the activation of the sympathetic nerve system caused by hand-arm vibration (Hashiguchi et al., 1994). Furthermore, a more recent study by Thompson and Griffin (2009) showed that blood flow in the finger of the exposed side (right hand) showed a pattern of reduction immediately after vibration started, but the unexposed side (left hand) experienced a change in blood flow similar to that measured on the exposed side (right hand). Consequently, vibration exposure may not only damage the exposed limbs, but can also lead to damage in the contralateral limb or inferior/superior limbs.

The health care system is based around prevention, and one of the best strategies to handle vibration induced white-hand or vibration induced white-foot is to limit exposure. Epidemiological studies on workers using vibratory tools has suggested that the prevalence of vibration induced white finger changes from 0-5% in geographical areas with a warm climate, to 80-100% in northern Countries (Bovenzi, 2005; Griffin 1990). Since mining, forestry and construction are popular jobs in Northern Ontario, physicians need to become aware of the symptoms and occurrence of VWFt so that they can help their patients limit vibration exposure. There is the potential to create a medical monitoring program for any patients employed at a job where they are exposed to vibration (Bovenzi, 2005), not limiting the program strictly to FTV, but including WBV and HAV. Not only is the onus on the physicians to become more aware of the effect of vibration exposure, but workers need to be more proactive with their physicians and inform him/her if they are experiencing any symptoms. Symptoms include neurologic disorders: digital paresthesia and numbness, deterioration of finger or toe tactile perception, and loss of manipulative dexterity, as well as vascular disorders including: cold hypersensitivity in the hands or attacks of finger or toe blanching (Bovenzi, 1998).

4.4 Relevance to Manufacturers

Manufacturers need to work in combination with researchers to improve technology and develop appropriate interventions to protect workers. In the future, the main focus needs to be on designing and testing better equipment to reduce FTV. This equipment could include improved drills that would generate less vibration, enhanced platforms to isolate the worker from vibration and lead to attenuation, and advance PPE including combinations between insoles and boots to protect workers from vibration exposure via the feet.

4.5 Relevance to Researchers

Researchers must continue to measure and document FTV to verify the resonance frequencies of different regions of the foot. Field testing methodology must also be further optimized to improve results. The custom design teardrop accelerometers and code for analysis could be further developed to use for vibration measurements on the worker in the field. For instance the accelerometers could be placed directly on the foot within the safety boots to measure vibration exposure directly at the foot. Foot-transmitted vibration has yet to be measured directly on the foot in the field, it is typically measured on the platform (Leduc, 2011; Goggins, Chapter 2). A possible improvement to the current accelerometer design would be to design wireless accelerometers so the worker's movement is not restricted by the wires during testing. Finally, researchers can work to complete a longitudinal study to document vibration exposure and the onset of VWFt.

The results from this laboratory study are limited due to the need for proper foot mapping equipment to measure mass distribution and centre of pressure, as well as increasing the range of exposure frequencies to include higher frequencies above 100Hz since some of the underground mining equipment (2 jumbo drills) were found to have dominant frequencies of 250Hz (Goggins, Chapter 2).

4.6 Conclusions

Results from this study can be used by mining companies, health care providers, equipment manufacturers, and researchers to reduce vibration induced injury risk for workers exposed to FTV.

The field study (Chapter 2) documented the vibration characteristics of 17 pieces of underground mining equipment that expose workers to vibration via the feet. There were several key findings with an immediate application to industry. First, FTV was lower for jumbo drills with grated platforms (#5 and #6). Second, twelve of the seventeen equipment operators had a complaint of discomfort in their lower body; however, according to ISO 2631-1 only one operator (bolter drill #9) experienced vibration levels above the criterion value, and according to ISO 5349-1 only two operators (jumbo drill #1 and bolter drill #1) experienced vibration above the standard. These results suggest a latency period for the onset of vibration injury from exposure and the possibility that once physiological damage occurs, pain may decrease; implying workers may become accustomed to the pain/discomfort. This leaves evidence to suggest that the standards are not able to adequately equate FTV exposure levels with injury risk and/or the link between discomfort and onset of VWFt is not established. Therefore it is essential that workers are evaluated regularly by a physician for signs of vibration-induced injury.

The laboratory study (Chapter 3) was conducted to gain a better understanding of the biodynamic response of the foot to vibration exposure by measuring transmissibility from the floor-to-ankle and floor-to-metatarsal. There were significant differences in mean transmissibility between the ankle and metatarsal at 40Hz, 45Hz, and 50Hz. The greatest transmissibility for the metatarsal occurred at 50Hz and for the ankle (lateral malleolus) from 25-30Hz, indicating the formation of a local resonance at each location.

Future research, with regards to vibration exposure via the feet, should be focused on confirming the resonance frequencies at different locations on the feet. In order to confirm the resonant frequencies a lab study needs to be completed controlling both the magnitude and frequency of vibration, with a range of frequencies from 1-250Hz. In addition, weight distribution and centre of mass need to be measured while posture is controlled. To control posture one might contemplate using a camera system with reflective markers at each joint. Once this has been completed, it is possible that a new standard can be designed around these resonance frequencies specific to the feet to help reduce probable health risk to workers exposed to FTV, and appropriate PPE can be developed to isolate workers from vibration exposure via the feet.

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APPENDIX A

Recruitment Script,

Consent Form,

Questionnaires for Chapter 2

Recruitment Script

This announcement will be read by a member of the research team at a crew safety meeting in order to identify workers to participate in this study.

Hi, I am Professor Tammy Eger from Laurentian University and Katie Goggins and Courtney Harnish are research assistants with this project. We are interested in measuring the vibration you are exposed to when you stand on vibrating equipment. Exposure to vibration via the feet can result in general discomfort and in some cases “white-feet”. There are guidelines that suggest the level of vibration that is “safe” for you to be exposed to during a working shift. We are interested in knowing if you are exposed to vibration levels above the guidelines.

In order to measure whole-body vibration exposure a vibration measurement device will be secured to the floor of the equipment you stand on and if present the handle of the vibrating handtool you hold. If you stand on a mat vibration levels below the mat and at the mat surface will be measured. If you agree to participate we will collect vibration exposure measurements for a maximum of 1-hour. We will also ask you a few questions about your equipment operating history and musculoskeletal injury history.

There is no immediate benefit to you for participating in this study. However, if you are interested in your exposure levels we will prepare a report for you that will indicate if you are exposed to vibration levels below or above international guidelines for whole-body vibration exposure. Moreover, the vibration levels collected in this research project will be used in a future study to identify floor mats and shoe insoles that will help to “reduce” vibration levels associated with adverse health outcomes. In the future, better mats and shoe insoles will benefit all equipment operators.

If you are interested in participating in this study please read over the consent form which is being circulated.

Are there any questions?

If you are interested in participating please inform any member of the research team or your foreman.

Thanks for your attention.
Have a safe day.

Consent Form

Examination of vibration characteristics and benefits of "anti-vibration" mats and insoles for workers exposed to vibration via the feet

I, ____, am interested in participating in the study on the **Vibration characteristics and benefits of "anti-vibration" mats for workers exposed to vibration via the feet** conducted by Professor Tammy Eger, Ph.D., from Laurentian University (Funded by the Workplace Safety and Insurance Board of Ontario). The purpose of the study is to measure whole-body vibration exposure at the feet when I operate mining equipment. The study will also determine if operators of mining equipment are exposed to vibration levels above guidelines established by ISO 2631-1 and ISO 5349-1 for health. If the equipment I operate has an "anti-vibration" mat I also understand that the research team will measure vibration below and above the mat in order to determine the ability of the mat to reduce vibration associated with health risks.

If I agree to participate, I will be asked to stand over the floor area where the research team has secured an accelerometer (designed to measure vibration) while I operate mining equipment. I understand all measurements will be taken for a maximum of one hour under regular operating conditions – therefore I will not be exposed to vibration levels different from what I experience on a daily basis. I also understand that I will be asked to answer a few questions related to my equipment operating history and musculoskeletal injury history (The questionnaire will take ~ 10 minutes to complete).

I have been informed that only members of the research team will have access to the data collected. **My participation is strictly voluntary** and I am free to withdraw from the study at any moment or refuse to participate without any penalty. I have received assurance from the researcher that all data collected will remain strictly confidential. My individual results will not be reported. All collected data will be coded with a subject number and stored in a locked filing cabinet (in the Professor Eger's office) or a password secured laptop (only members of the research team will have access to the data). After a period of 7 years paper documents collected will be shredded. Vibration data will be kept in a database if I give permission for this – otherwise the electronic data files will be erased after 7 years.

I understand that I will receive no immediate benefit from my participation; however, results of the study will be used in a future laboratory study in order to identify better mats and shoe insoles (to reduce harmful vibration levels).

There are two copies of this consent form; one which the researcher keeps and one that I keep.

If I have any questions or concerns about the study or about being a participant, I may contact
the lead researcher, Professor Tammy Eger via email teger@laurentian.ca, or the Laurentian
University Research Office at 705-675-1151 ext. 3213. If I would like to receive a copy of the study results I can contact Professor Tammy Eger anytime after June 1, 2012.
I give permission to members of the research team to keep vibration data collected during this study in a vibration database for comparison with future vibration data collected.
□ No □ Yes

I agree to participate in this study.

Participant's Signature: ___________________________ Date: ____________________________

Researcher's Signature: ____________________________ Date: ____________________________

THANK YOU FOR YOUR PARTICIPATION.

Mining Equipment Operator
Musculoskeletal Disorder Questionnaire

BACKGROUND INFORMATION

This questionnaire is part of the “Vibration Research Project” being conducted by Laurentian University. The research team is interested in vibration exposure at the feet during the operation mining equipment. The research team is also interested in the level of muscle discomfort equipment operators might experience when operating mining equipment.

Researchers at Laurentian University will analyze the results of this questionnaire. No one from the company you work for will see your comments and individual results will not be reported.

This questionnaire will take approximately 10 minutes to complete. There are no correct answers to the questions. We hope you will take the time to share your views and ideas with us.

INSTRUCTIONS

- **Please answer ALL questions to the best of your ability.**

- **When you have completed the questionnaire please seal it in the envelope provided and return it to the Laurentian University representative or drop it into the WBV box located in the __________ office.**

THANK YOU FOR YOUR PARTICIPATION

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

Tammy Eger
Researcher
Laurentian University
705-675-1151 ext. 1005
teger@laurentian.ca

Part A: Background Information

1. What is your current age? _____________

2. What is your current weight? (lbs) _____________

3. What is your current height? (feet/inches) _____________

4. Gender: ____________

Part B: Equipment Operating History

5. What types of equipment do you operate on a regular basis (please list)?

____

____

____

6. How many years have you operated mobile equipment? ____________

7. At what age were you when you first began operating mobile equipment? _____________

8. What equipment type do you operate most often (please name)? ____________________________

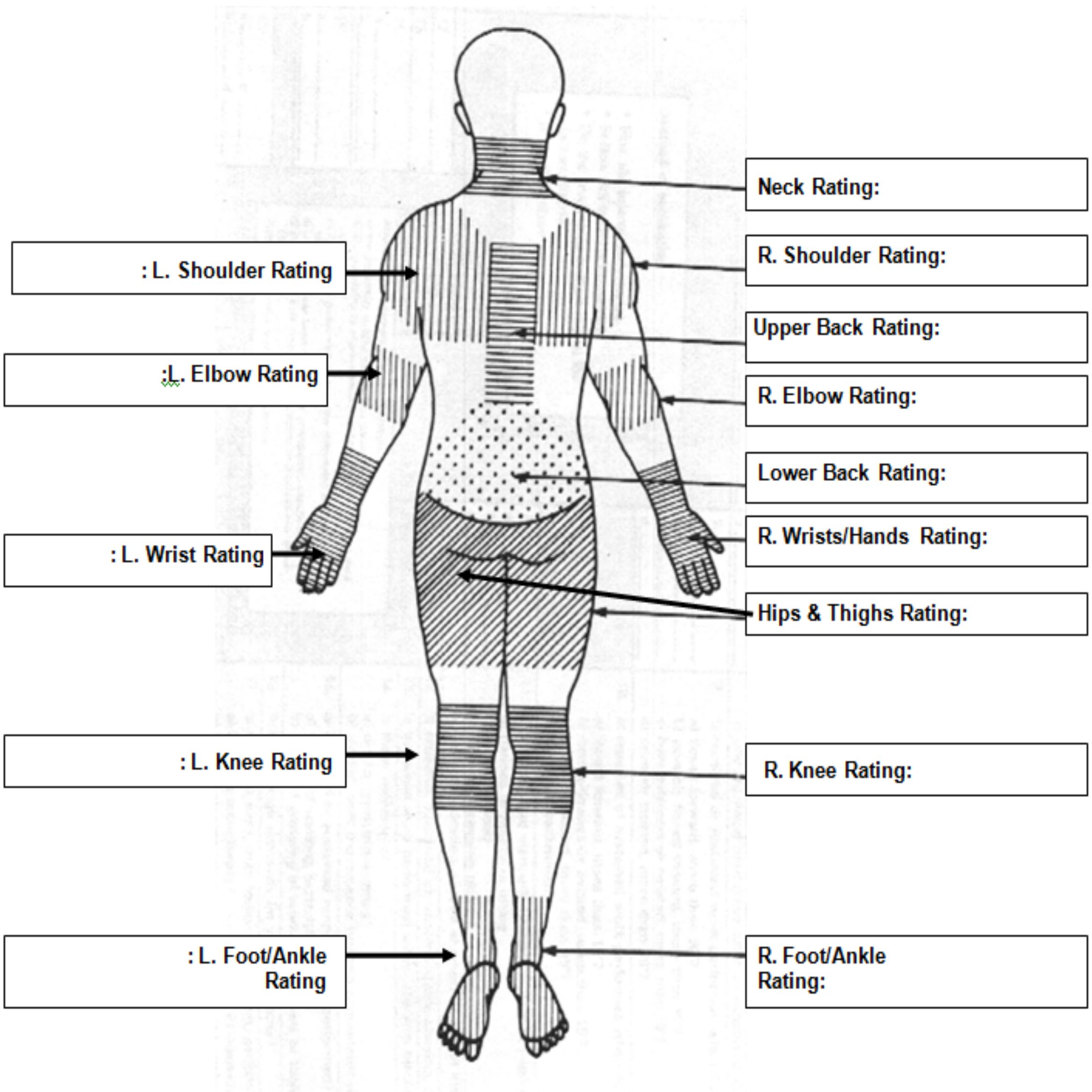
9. How many hours a day (on average) do you operate or work with equipment that exposes you to vibration? _____________

10. Have you always operated the same type of mobile equipment? YES/NO

    If NO what type of mobile equipment did you use to operate most often? _____________

Part C: Musculoskeletal Disorders
The body has been divided into fourteen different regions (right). For each body region please indicate if you have had any trouble (**ache, pain, numbness or discomfort**) in the region in the last 6 months. If you have had trouble in the area in the last 6 months rate the severity of the trouble, at the worst episode that you felt.

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



Thank-you for your time. Your participation in this project is greatly appreciated.

APPENDIX B

Table 5: Equipment measurement attachment and accelerometer set-up and additional notes about testing conditions.

Figures of accelerometer set-up from all mining equipment in Chapter 2

Table 5: Equipment measurement attachment and accelerometer set-up and additional notes about testing conditions.

Equipment	Measurement Location	Accelerometer Set-Up	Extra Notes
Locomotive	Middle of locomotive operator cab, to the left of the standing operator	Magnet mounted to the metal surface	- 3 trips per hour - transports people, equipment, rock, explosives, parts - operated remotely to load and dump (takes approximately 5 minute each)
Crusher	Directly on the surface where the operators stand	Magnet mounted to the metal surface	- easily accessible area on the floor
(1) Bolter Drill - Scissor Platform	On the metal edge of the platform, to the right of the operator	Magnet mounted to the smooth metal surface (grated surface)	- drilled the side wall and then moved to reposition the platform - drilled off platform at the back corner and moved the platform up and down to adjust rods
(2) Bolter Drill - Scissor Platform	On the metal edge at the rear edge of the platform	Magnet mounted to the smooth metal surface (perpendicular to platform)	- platform soaked and very cluttered - two drills operating simultaneously
(3) Bolter Drill - Scissor Platform	On the metal edge at the rear edge of the platform	Magnet mounted to the smooth metal surface	- older platform - in comparison to where the accelerometers were, operator moved around to operate at the far end of the platform and the far wall
(4) Bolter Drill - Scissor Platform	On the metal edge of the platform, to the right of where the operators are drilling	Magnet mounted to the smooth metal surface (perpendicular to platform)	- a wooden platform with metal sides - operating two jacklegs to drill off the platform
(5) Bolter Drill – Maclean	On the metal platform just underneath the operator's controls	Magnet mounted to the smooth metal surface	- there was a mat on the platform, measurement was taken underneath the mat

(6) Bolter Drill – Maclean	On the metal platform just underneath the operator's controls and just in front of the operator's feet	Magnet mounted to the smooth metal surface	- older model drill
(7) Bolter Drill – Boart	On the metal platform just behind the controls	Magnet mounted to the grated metal surface	- operator bolts from a bucket, moves the bucket up and into place – has one drill operating
(8) Bolter Drill – Boart	On the metal platform just below the seat, just behind the controls	Magnet mounted to the smooth metal surface	- operator bolts from a bucket - WBV accelerometer moved during testing, the HAV accelerometer was processed
(9) Bolter Drill – RDH	On the metal platform directly to the left of the controls	Magnet mounted to the smooth metal surface	- early part of signal is the drilling to set-up - combination of drilling and bolting
(1) Jumbo Drill	On the metal platform just underneath the operator's controls	Magnet mounted to the smooth metal surface	- using 1 boom - operator stands to place drill and sits while operating the drill - steps off the drill to make new markings - drilled approximately 6 holes
(2) Jumbo Drill	On the metal platform just underneath the operator's controls and directly in front of the feet	Magnet mounted to the metal surface (grated surface)	- operator stands while operating - drilled 1 hole - made adjustments to the drill bit - drilled 5 holes, machine was idling
(3) Jumbo Drill	On the metal platform in front of the operator's mat and just to the left on the control panel	Magnet mounted to the smooth metal surface	- using 1 boom - not a typical round – "blind corner" – operator needs to use a spotter and there is a lot of getting on and off the machine - operator will drill a total of 36 holes in this face - a rubber mat has been put in place over the grated platform

(4) Jumbo Drill	On the metal platform to the rear of the controls	Magnet mounted to the smooth metal surface	- using 1 boom - first section of measurement – the operator is trying to change a drill bit - had a rubber mat – the one with circles - operator takes seated breaks
(5) Jumbo Drill	On the grated platform, underneath and to the right of the controls	Seatpads and tie wraps used to mount accelerometers on grated platform	- operator stands on a mat - using 2 booms, both in action - drilling a "blind corner" to the left - this jumbo drill is only 1 year old
(6) Jumbo Drill	On the grated platform, underneath and to the left of the controls	Seatpads and tie wraps used to mount accelerometers on grated platform	- had two booms, only drilling with one at a time - operator said the drill is not spinning as fast

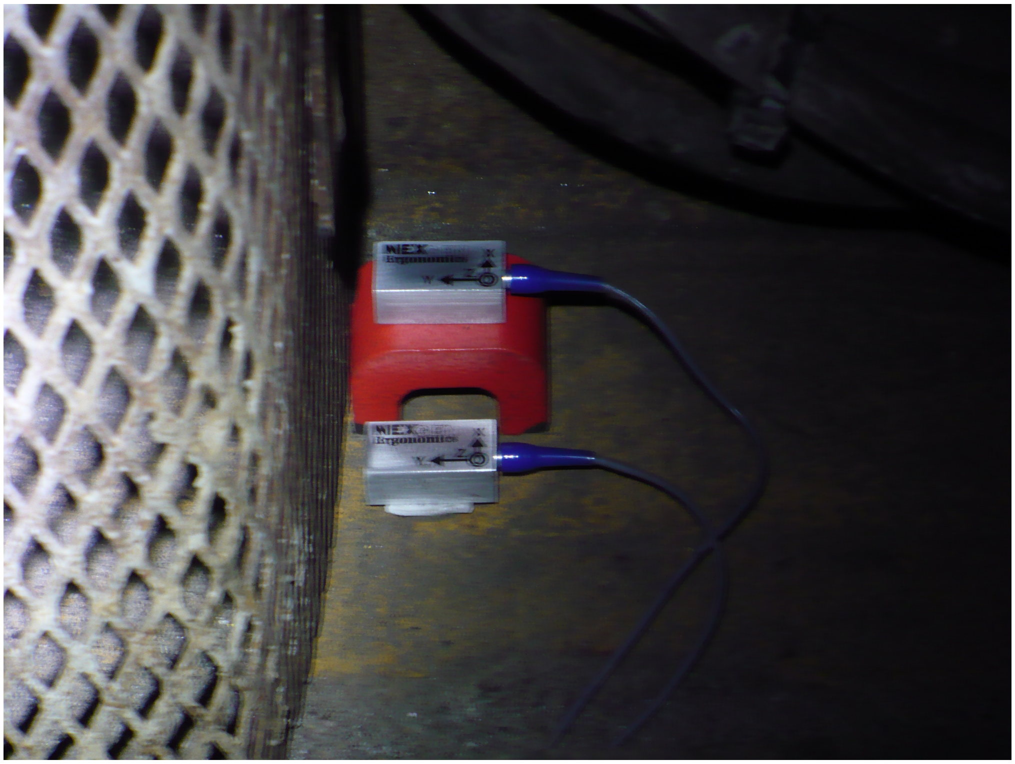


Figure 1: Accelerometer set-up for Locomotive 1.

Figure 2: Accelerometer set-up for Crusher 1.

Figure 3: Accelerometer set-up for Bolter Drill 1 – Scissor Platform.

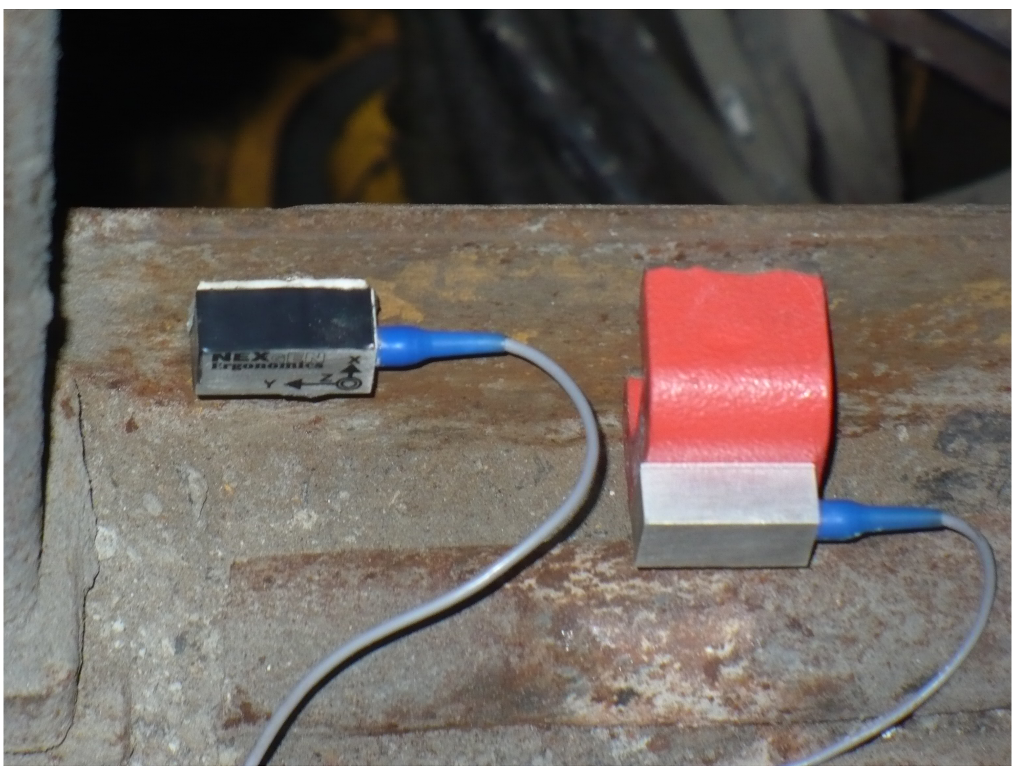


Figure 4: Accelerometer set-up for Bolter Drill 2 – Scissor Platform.

Figure 5: Accelerometer set-up for Bolter Drill 3 – Scissor Platform.

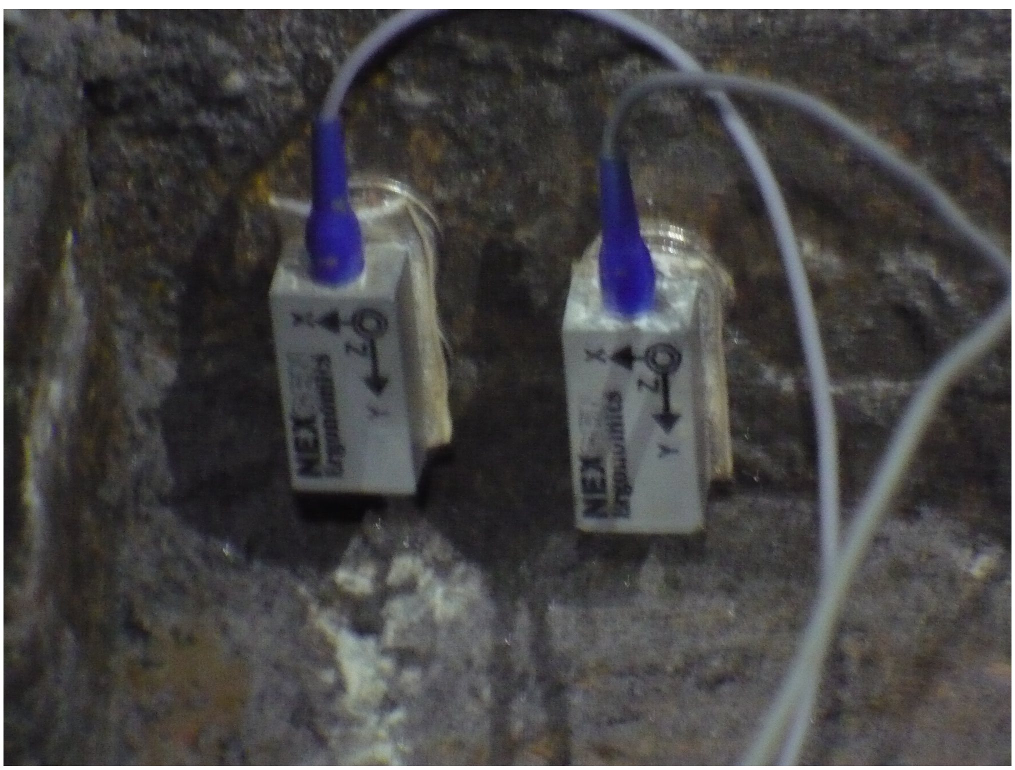


Figure 6: Accelerometer set-up for Bolter Drill 4 – Scissor Platform.

Figure 7: Accelerometer set-up for Bolter Drill 5 – Maclean.

Figure 8: Accelerometer set-up for Bolter Drill 6 – Maclean.

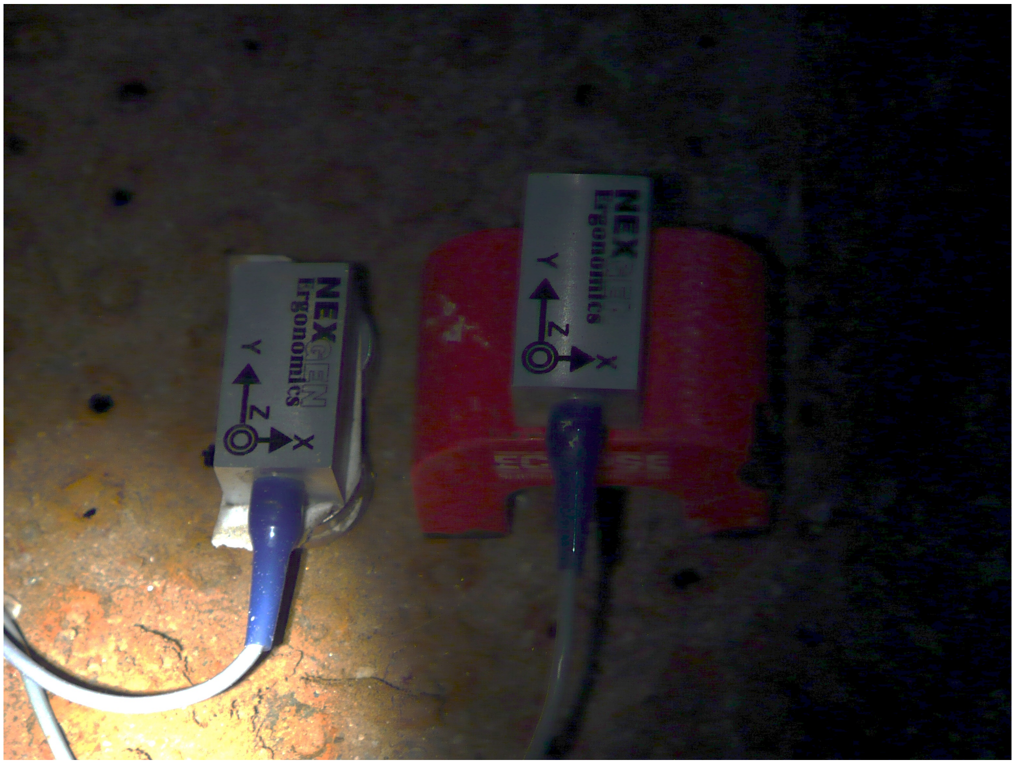


Figure 9: Accelerometer set-up for Bolter Drill 7 – Boart.

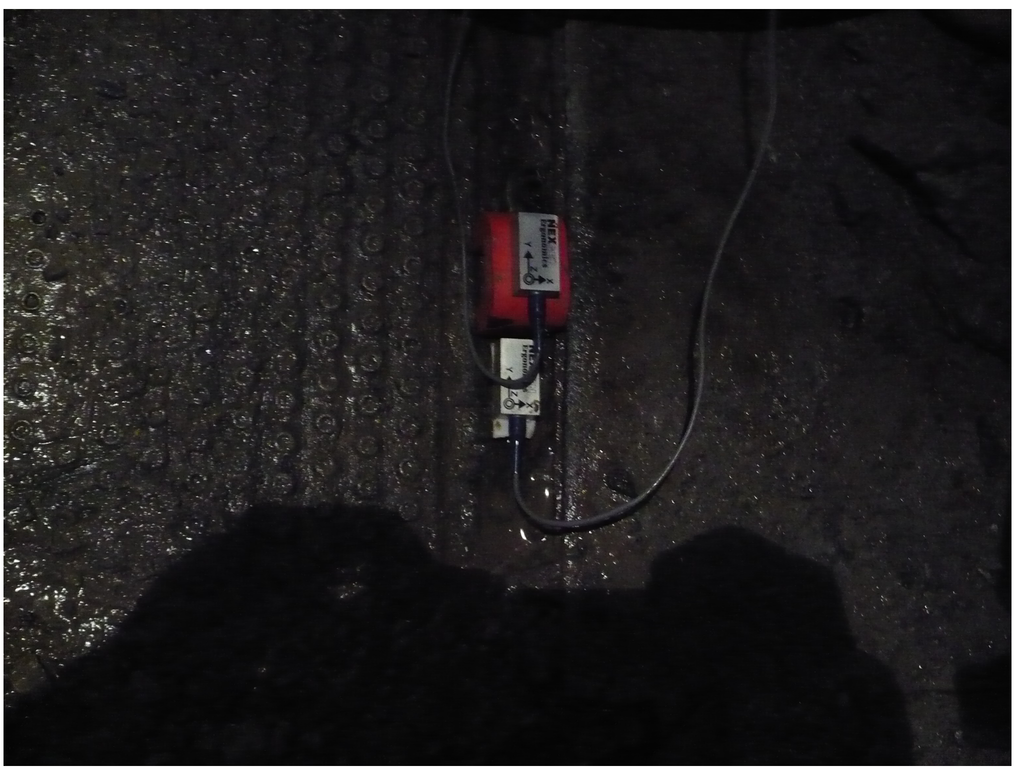


Figure 10: Accelerometer set-up for Bolter Drill 8 – Boart.

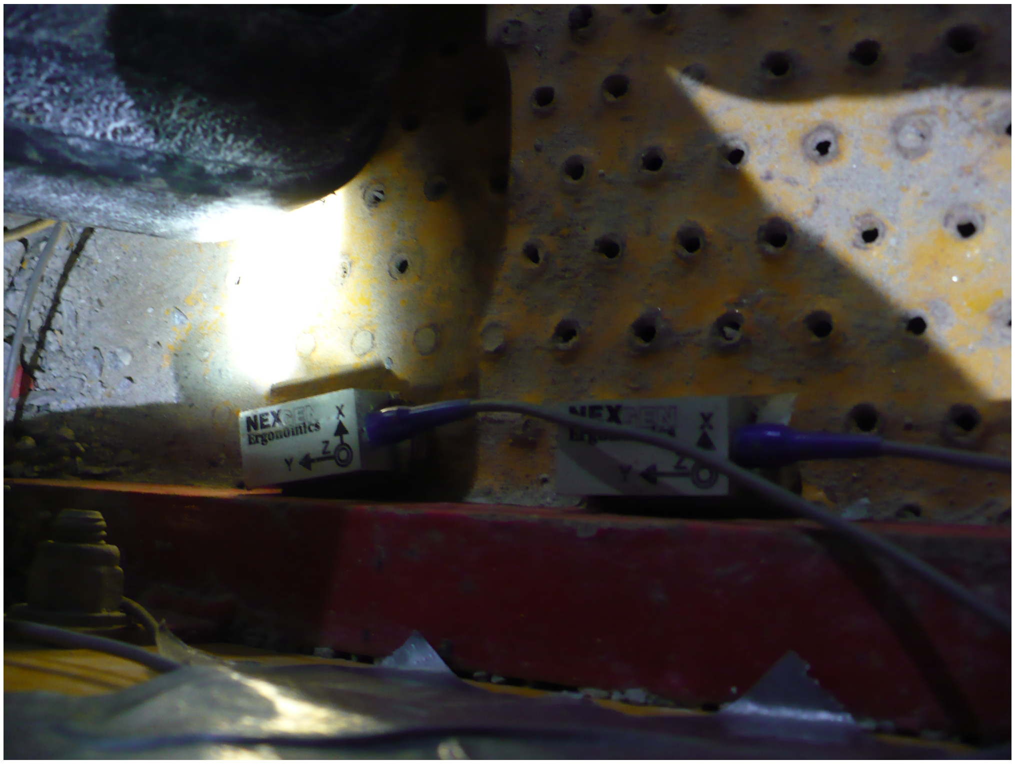


Figure 11: Accelerometer set-up for Bolter Drill 9 – RDH.

Figure 12: Accelerometer set-up for Jumbo Drill 1.

Figure 13: Accelerometer set-up for Jumbo Drill 2.

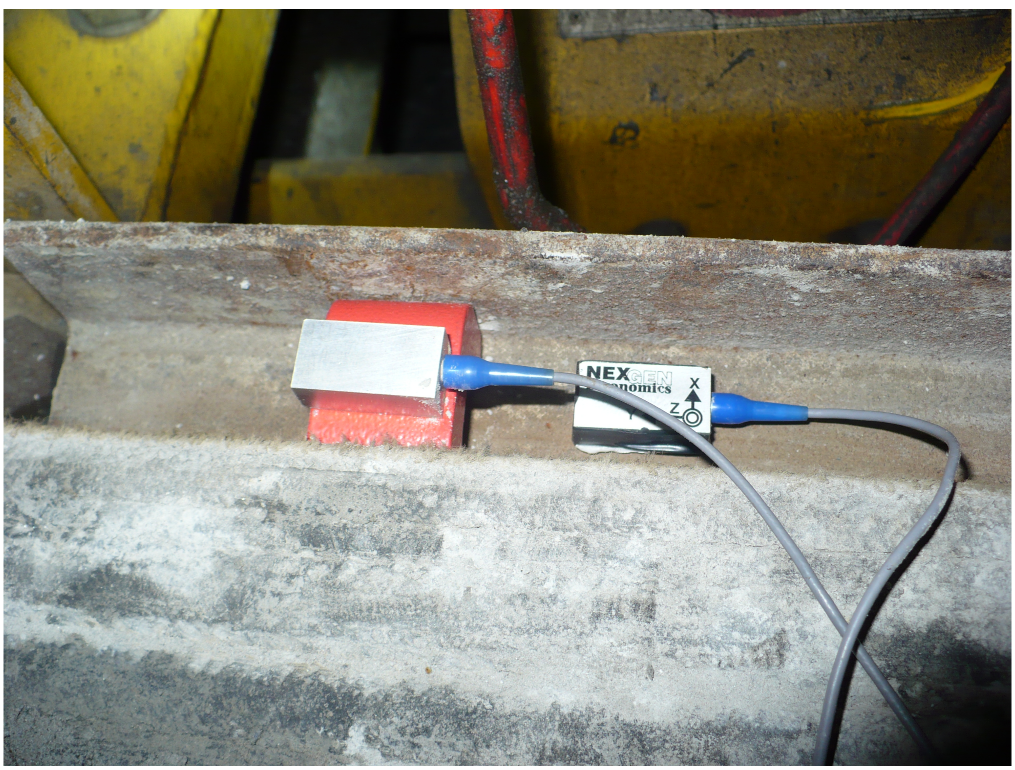


Figure 14: Accelerometer set-up for Jumbo Drill 3.

Figure 15: Accelerometer set-up for Jumbo Drill 4.

Figure 16: Accelerometer set-up for Jumbo Drill 5.

Figure 17: Accelerometer set-up for Jumbo Drill 6.

APPENDIX C

Recruitment Poster,

Consent Form,

Questionnaires for Chapter 3

Recruitment Poster

Participants wanted for a study on Foot-Transmitted-Vibration

Males between the ***ages of 20-65*** *with no history of a lower body musculoskeletal injury in the past 6-months, vasculopathy, neuropathy, motion sickness, diabetes, or head injury are eligible to participate.*

Participants will be required to stand on an exercise vibration platform (Power Plate North American, Inc., Irvine, CA) that will generate 8 different frequencies of vibration, including: 15hz, 20Hz, 25Hz, 30Hz, 35 Hz 40Hz, 45Hz and 50Hz. The participant will be randomly exposed to the 8 frequencies. Each vibration exposure period will last 60 seconds, followed by a 60 second rest period. Total vibration exposure will be 8 minutes.

If you are interested in participating in a study on foot-transmitted vibration (vibration from standing on a vibrating exercise platform) please contact the lead researcher Katie Goggins ***(Email: kx_goggins@laurentian.ca; Phone: (705) 626-5028)***.

Consent Form

Foot Transmitted Vibration: Exposure characteristics and the bio-dynamic response of the foot

I, ____, am interested in participating in the study on the **Foot Transmitted Vibration (FTV): Exposure characteristics and the bio-dynamic response of the foot** conducted by Masters student Katie Goggins and Professor Tammy Eger, Associate Professor in the School of Human Kinetics. The purpose of this research is to understand how the foot responds to FTV. We are also interested in determining if the response of the foot is influenced by mass and/or foot arch type. The result of the study will help to understand injury mechanisms associated with exposure to FTV.

I understand I am eligible to participate if I have not had a history of a lower body musculoskeletal injury in the past 6-months, or a history of, vasculopathy, neuropathy, motion sickness, diabetes, or head injury. I will also be asked to complete a brief questionnaire indicating previous MSD history and previous vibration exposure history.

If I agree to participate, the research team will attach two accelerometers designed to measure vibration. One will be secured to my ankle and another on the top of my big toe. I will be asked to stand on an exercise vibration platform on the area of the platform that the research team has secured two accelerometers. I will be exposed to 60 seconds of vibration at 15, 20, 25, 30, 35, 40, 45, and 50 hertz (for a total of 8 minutes of vibration exposure). I will have 1-minute of rest between each exposure.

I have been informed that only members of the research team will have access to the data collected. **My participation is strictly voluntary** and I am free to withdraw from the study at any moment or refuse to participate without any penalty. I have received assurance from the researcher that all data collected will remain strictly confidential. My individual results will not be reported. All collected data will be coded with a subject number and stored in a locked filing cabinet or on a password secured laptop that only members of the research team have access to. After a period of 7 years paper documents collected will be shredded. Vibration data will be kept in a database if I give permission for this – otherwise the electronic data files will be erased after 7 years.

I understand that I will receive no immediate benefit from my participation. Findings from the study will improve understanding of FTV. This information could be used in the future to improve vibration measurement standards and design of boots and insoles from workers exposed to FTV.

There are two copies of this consent form; one which the researcher keeps and one that I keep.

If I have any questions or concerns about the study or about being a participant, I may contact

Professor Tammy Eger via email teger@laurentian.ca, if I am concerned about the ethics of this study I can contact the Laurentian University Research Office at 705-675-1151 ext. 3213.

If I would like to receive a copy of the study results I can contact Professor Tammy Eger anytime after May 1, 2013.

I give permission to members of the research team to keep vibration data collected during this study in a vibration database for comparison with future vibration data collected.

□ No □ Yes

I agree to participate in this study.

Participant's Signature: ______________________ Date: _________________________

Researcher's Signature: ______________________ Date: _________________________

THANK YOU FOR YOUR PARTICIPATION.

Participant History

Musculoskeletal Disorder Questionnaire

Participant History

Musculoskeletal Disorder Questionnaire

Part A: Background Information

1. What is your current age? _____________

2. What is your current weight? (lbs) _____________

3. What is your current height? (feet/inches) _____________

4. Gender: ____________

Part B: Vibration Exposure History

5. Have you been exposed to vibration before? ____________

IF yes, what kind of vibration? Or what type of equipment?

____

____

____

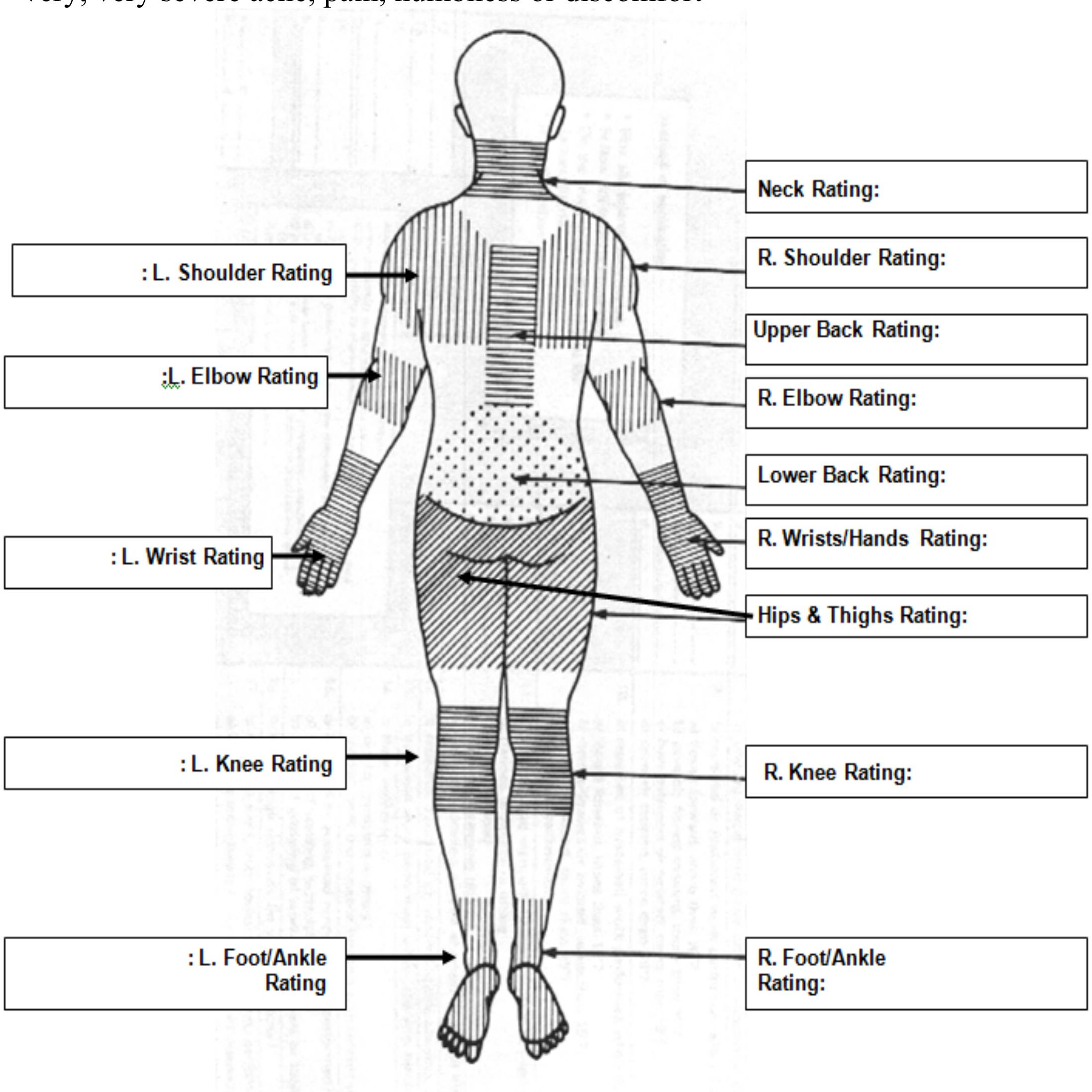
____

Musculoskeletal Disorders

The body has been divided into fourteen different regions (right). For each body region please indicate if you have had any trouble (**ache, pain, numbness or discomfort**) in the region in the last 6 months. If you have had trouble in the area in the last 6 months rate the severity of the trouble, at the worst episode that you felt.

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



Thank-you for your time. Your participation in this project is greatly appreciated.

APPENDIX D

ADXL326 Operating Manual

ADXL326

Operating Manual

Katie Goggins

Dr. Tammy Eger (MHK Candidate)

Laurentian University

Preface

The three principal categories of vibration exposure are: (1) whole-body vibration (WBV), which occurs when the human body is supported on a surface which is vibrating; (2) hand-transmitted vibration (HTV), which occurs when vibration enters through the hands of workers utilizing vibrating tools; and (3) foot-transmitted vibration (FTV), occurring when workers stand on platforms which vibrate. Whole-body vibration and hand-transmitted vibration exposures have been studied and documented in vibration related literature sufficiently to warrant International Standards, regulating the type and amount of vibration workers can be exposed to. Respectively these Standards are ISO 2631-1 (2004) and ISO 5349-1 (1997). However, at this time there are no standards regulating the assessment of foot-transmitted vibration.

There are standard designed accelerometers to measure whole-body vibration and hand-transmitted vibration. These accelerometers each have unique accessories for easy attachment to a seat, platform, or handle. Foot-transmitted vibration is more difficult to measure directly at the foot as individuals exposed to FTV are typically wearing steel-toed boots as a mandatory requirement of personal protective equipment. Standard accelerometers are often too large and awkward to attach beneath the foot, thus jeopardizing not only the workers' comfort and safety, but also making accurate reading difficult to obtain. Consequently, the ADXL326 (teardrop) accelerometer has been created to attempt to measure foot-transmitted vibration comfortably and effectively. This new, smaller, rounded design will be used to measure foot-transmitted vibration. This manual has been created to ensure proper calibration of the ADXL326 accelerometers prior to their use in the laboratory or out in the field.

1.0 Equipment Overview

The ADXL326 (teardrop) accelerometer (Figure 1) is a ± 19 g tri-axial accelerometer custom design from the University of Windsor, ON. The ADXL326 connects to the Biometrics Ltd DataLOG (P3X8) device with the X, Y, and Z Lemo connectors. See the Analog Devices, ADXL326 data sheet for typical response (Appendix A).

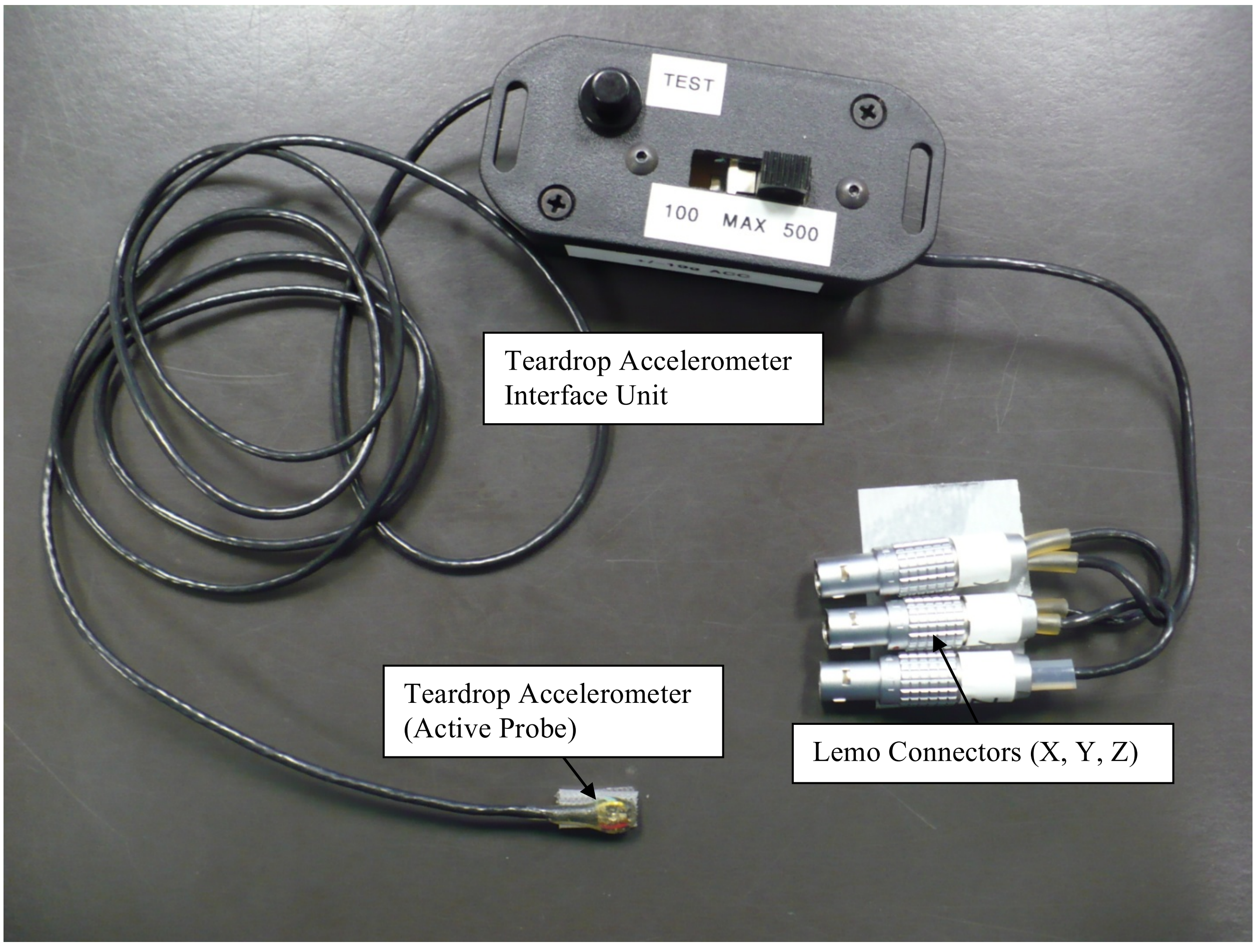


Figure 1: ADXL326 Teardrop accelerometer.

ADXL326 Accelerometer Interface Unit

The slide switch limits the bandwidth to 100 Hz or 500 Hz, or in the middle position the ADXL326 sensor chip itself limits the bandwidth to 550 Hz on Z and 1600 Hz on X and Y axes.

The Test switch applies a test command to the sensor chip.

Lemo Connectors (X, Y, Z)

Only the X channel supplies power to the accelerometer, therefore if only one channel of operation is required it must be the X channel or the unit will not function.

Orientation of Axis

The ADXL326 accelerometer has a very different orientation in comparison to the Series 2 10G tri-axial accelerometers (NexGen Ergonomics, Montreal, QC, CND), as seen in Figure 2.

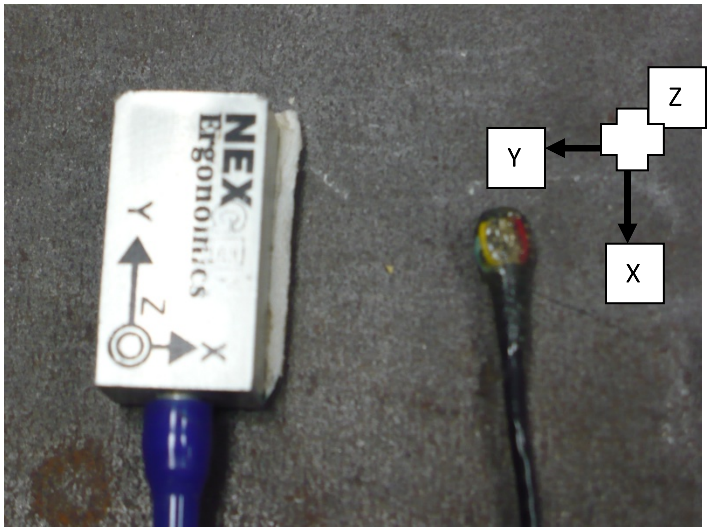


Figure 2. Comparison of orientation for S2-10G-MF accelerometer [on the left], to ADXL326 accelerometer [on the right].

2.0 DataLOG P3X8 Setup

The manufacturer of the ADXL326 accelerometers has supplied the following instructions for the DataLOG setup:

Title	Sensitivity	Rate	Excitation (mV)	Zero	Full Scale	Units
X	3V	As Required	4600	0	50*	g
Y	3V	As Required	xxxx	0	50*	g
Z	3V	As Required	xxxx	0	50*	g

OR

Title	Sensitivity	Rate	Excitation (mV)	Zero	Full Scale	Units
X	1V	As Required	4600	0	17.5*	g
Y	1V	As Required	xxxx	0	17.5*	g
Z	1V	As Required	xxxx	0	17.5*	g

xxx = don't care --> 4600 mV is OK for all channels

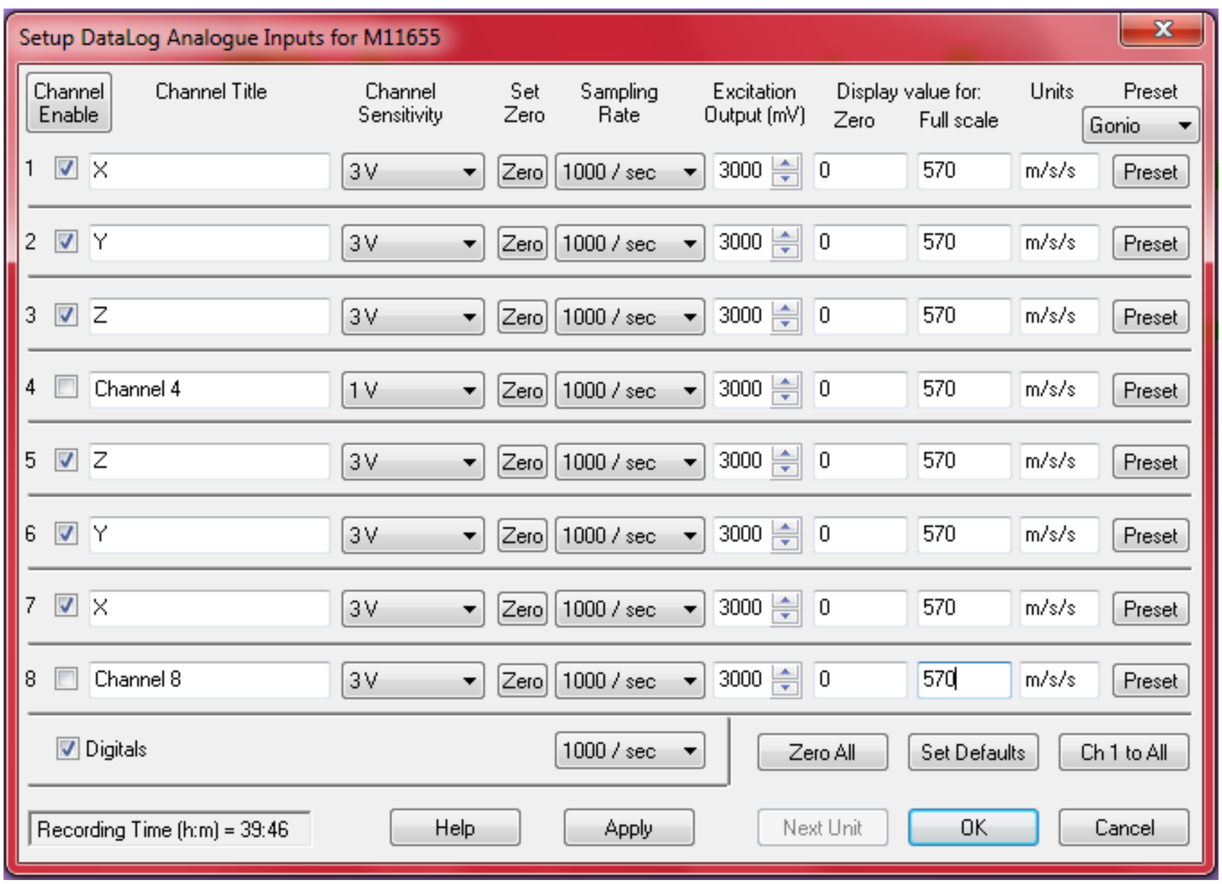
* = refine when proper calibration factors are determined

DataLog Analogue Inputs Screen

For each channel with the ADXL326 connected, setup the channel as follows:

Channel enable	check so that a black check is visible
Channel title	type in as appropriate (e.g. Accel X, Accel Y, etc.)
Channel sensitivity	± 3 V
Sampling rate	1000 / sec
Excitation output	3000 mV
Zero	0
Full scale	570
Units	m/s/s

Within the Biometrics Software and the "Analogue Inputs" screen should resemble the following:



3.0 Static Calibration (5-point)

An instrument's performance characteristics are divided into two groups: (a) static characteristics, and (b) dynamic characteristics. The static characteristics of a transducer are established by the process of static calibration. By static calibration, the relationship between the output signal and the quantity under study is experimentally determined (book reference). Static calibration is crucial to determine the coefficient matrix and zero bias of a linear modeled accelerometer before use.

To calibrate the teardrop accelerometers a 5-point static calibration was completed. This calibration incorporated three axis (x,y, and z), and five points for each axis were used (positive gravity (g), positive 45^o g, zero g, negative 45^o g, and negative). To see the orientation of the accelerometer for each measurement refer to Appendix B. A ten second measurement was obtained for each position (equivalent to approximately 10 000 samples). Three thousand samples were averaged for each axis and direction. The average values were then put into a table corresponding to their axis of measurement, with the gravity values, which were also reported as acceleration values (m/s^2), (Table 1).

Table 1. Example data table for 5-point static calibration.

X-Axis		
g	m/s/s	bits
-1	-9.81	70.85405
-45	-6.936	53.34422
0	0	1.913362
45	6.936	-49.8797
1	9.81	-71.9127

To analyze the data a regression was used comparing the acceleration values with the recorded data in bits in Microsoft Excel (2007). The R^2 values were minimally all 0.99 with varying standard error values typically below 0.4. From the regression summary output in Microsoft Excel, the x variable value (m-value) was considered the scaling factor for that axis.

Scaling Factors

After completing three separate static calibrations for each ADXL326 accelerometer, the scaling factors for each axis were found to be the following:

Table 2. Scaling factors for all ADXL326 teardrop accelerometers.

Teardrop 01		Teardrop 02		Teardrop 03		Teardrop 04	
x	0.1350	x	0.1350	X	0.1300	x	0.1334
y	0.1344	y	0.1368	y	0.1315	y	0.1353
z	0.1360	z	0.1410	z	0.1315	z	0.1317

4.0 Dynamic Calibration

Once a static calibration has been successfully completed, the accelerometers must be dynamically calibrated to ensure their performance in dynamic applications. To test the ADXL326 accelerometers they were attached directly on top of a Series 2 10G tri-axial accelerometer (NexGen Ergonomics, Montreal, QC, CND) and orientation was changed to capture all three axis (x, y, and z) on an exercise vibration platform (Power Plate North American, Inc., Irvine, CA) (Appendix C).

Data was analyzed using MatLAB 7.1 to complete the following analyses:

1) Find and remove low frequency biases.
2) Filter the data using a 4th order zero-lag Butterworth filter (can set upper and lower limits easily).
3) Scale the data according to scaling factors from the static calibration.
4) Run DFT on both the Nexgen accelerometers and the teardrop accelerometers.
5) Regression of the teardrop and Nexgen accelerometers.
6) Find the rms accelerations for both accelerometers.
7) Find the percent difference between the peak and rms values.
8) Find the absolute peak values for both accelerometers.
9) Find the percent difference between the absolute peak and rms values.
10) Repeat steps 1-9 for each axis (x, y, z).

APPENDIX E

Sample MATlab Code

```
%%%%%%%%%%%%%%%%%%%kg45plate_25hz%%%%%%%%%%%%%%%%%%%
%
% Always plug lemo connectors in X=1 Y=2 Z=3, X=5 Y=6 Z=7
%
% Loads files with XYZXYZ column assignments
%
% This code will asses transmissibility using four teardrop accelerometers
%
% Datalogger 1
%   td01=platform at big toe (Channel 1=X, 2=Y, 3=Z)
%   td02=top of big toe (Channel 5=X, 6=Y, 7=Z)
%
% Datalogger 2
%   td03=platform at heal (Channel 1=X, 2=Y, 3=Z)
%   td04=ankle bone (Channel 4=X, 5=Y, 6=Z)
%
% 6 frequencies: 25Hz, 30Hz, 35Hz, 40Hz, 45Hz, 50Hz
%
% Sample frequency= 1000Hz
%
%
%
% Created by Katie Goggins      June 6, 2012
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

close all
clear all

load kg45plate_dl1_25hz.txt
load kg45plate_dl2_25hz.txt

datalogger1=kg45plate_dl1_25hz;
datalogger2=kg45plate_dl2_25hz;

clear kg45plate_dl1_25hz
clear kg45plate_dl2_25hz

%%%%%%%%%%%Line-up data using multiple cross correlation%%%%%%%%%%%

sf=1000;

[aligned_data,shift_check]=Multi_Res_Xcorr(datalogger1,3,datalogger2,3,50,400,20,sf);

clear datalogger1
clear datalooger2
```

```
%%%%%%%%%%%find and remove low frequency biases%%%%%%%%%%%%%

aligned_data_means=mean(aligned_data);

aligned_data_bias_removed(:,1)=aligned_data(:,1)-aligned_data_means(1,1);
aligned_data_bias_removed(:,2)=aligned_data(:,2)-aligned_data_means(1,2);
aligned_data_bias_removed(:,3)=aligned_data(:,3)-aligned_data_means(1,3);
aligned_data_bias_removed(:,4)=aligned_data(:,4)-aligned_data_means(1,4);
aligned_data_bias_removed(:,5)=aligned_data(:,5)-aligned_data_means(1,5);
aligned_data_bias_removed(:,6)=aligned_data(:,6)-aligned_data_means(1,6);
aligned_data_bias_removed(:,7)=aligned_data(:,8)-aligned_data_means(1,8);
aligned_data_bias_removed(:,8)=aligned_data(:,9)-aligned_data_means(1,9);
aligned_data_bias_removed(:,9)=aligned_data(:,10)-aligned_data_means(1,10);
aligned_data_bias_removed(:,10)=aligned_data(:,11)-aligned_data_means(1,11);
aligned_data_bias_removed(:,11)=aligned_data(:,12)-aligned_data_means(1,12);
aligned_data_bias_removed(:,12)=aligned_data(:,13)-aligned_data_means(1,13);

% 4th order zero-lag Butterworth filter (fc=50hz)

[b,a]=butter(2,0.5/1000,'high');

aligned_data_bias_removed_filtered=filtfilt(b,a,aligned_data_bias_removed);

[b,a]=butter(2,100/1000,'low');

aligned_data_bias_removed_filtered=filtfilt(b,a,aligned_data_bias_removed_filtered);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Plot aligned data (column 3: z-axis datalogger 1

figure(1)
plot(aligned_data_bias_removed_filtered(:,3));
title('click on start of 30 second window')%puts title on plot
fprintf('click on start of 30 second window')%puts a string in command field

% Select the start of the 30 second window for further analysis

[X,Y]=ginput(1); %allows you to pick a data point
window_start=round(X(1,1));

aligned_data_window=aligned_data_bias_removed_filtered(window_start:window_start
+(30*sf)-1,:);

clear aligned_data_bias_removed_filtered
```

```
% Plot 30 second window of aligned data

figure(2)
plot(aligned_data_window(:,:));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Creating teardrop variables

td01=aligned_data_window(:,1:3);
td02=aligned_data_window(:,4:6);
td03=aligned_data_window(:,7:9);
td04=aligned_data_window(:,10:12);

clear aligned_data_window

% Load scaling factor document

load static_scaling_factors.txt

td01_X_sf=static_scaling_factors(1,1);
td01_Y_sf=static_scaling_factors(1,2);
td01_Z_sf=static_scaling_factors(1,3);

td02_X_sf=static_scaling_factors(2,1);
td02_Y_sf=static_scaling_factors(2,2);
td02_Z_sf=static_scaling_factors(2,3);

td03_X_sf=static_scaling_factors(3,1);
td03_Y_sf=static_scaling_factors(3,2);
td03_Z_sf=static_scaling_factors(3,3);

td04_X_sf=static_scaling_factors(4,1);
td04_Y_sf=static_scaling_factors(4,2);
td04_Z_sf=static_scaling_factors(4,3);

% Scale data with all four teardrop scaling factors

td01_scaled(:,1)=td01(:,2)*td01_Y_sf;
td01_scaled(:,2)=td01(:,1)*td01_X_sf;
td01_scaled(:,3)=td01(:,3)*-td01_Z_sf;

td02_scaled(:,1)=td02(:,2)*td01_Y_sf;
td02_scaled(:,2)=td02(:,1)*td01_X_sf;
td02_scaled(:,3)=td02(:,3)*-td01_Z_sf;
```

```
td03_scaled(:,1)=td03(:,2)*td01_Y_sf;
td03_scaled(:,2)=td03(:,1)*td01_X_sf;
td03_scaled(:,3)=td03(:,3)*-td01_Z_sf;

td04_scaled(:,1)=td04(:,2)*-td01_Y_sf;
td04_scaled(:,2)=td04(:,3)*-td01_Z_sf;
td04_scaled(:,3)=td04(:,1)*td01_X_sf;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Use WBV processing, must create variables first
sf=1000;
bpfclow=0.5;
bpfcup=100;
octbfclow=0.63;
octbfcup=80;
AT=1;
overlap=1;

% Create a time column
insf=1/sf
total_time=30000*(insf);
time=0:insf:(total_time-insf);
time=time';


%%%%%%%%%%%%%%%% WBV Processing for td01 %%%%%%%%%%%%%%%%%%

data=[time,td01_scaled,td01_scaled];

[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNweighted,
CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,running_R
MS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,MTV
V_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave_U
Nweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave_UN
weighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave_UNw
eighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_octave_UN
weighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_third_octave
_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw_third_oc
tave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectraldata_UN
weighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_DFTspectra
ldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weighted,Roll_DF
Tspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFTspectraldata_UN
weighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata_UNweighted,Yaw_D
FTspectraldata_weighted,VTV_translational_RMS_UNweighted,VTV_translational_RM
```

```
S_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RMS_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_UNweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sf,bpfclow,bpfcup,octbfclow,octbfcup,AT,overlap);
%function[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNweighted,CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,running_RMS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,MTVV_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave_UNweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave_UNweighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave_UNweighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_octave_UNweighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_third_octave_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw_third_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectraldata_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_DFTspectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weighted,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFTspectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UNweighted,VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RMS_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_UNweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sampling_frequency,band_pass_lower_freq,band_pass_upper_freq,octave_band_pass_lower_freq,octave_band_pass_upper_freq,averageing_time,moving_window_overlap)

td01_unweighted_data(1,1:3)=peak_UNweighted(1,1:3);
td01_unweighted_data(1,4:6)=RMS_UNweighted(1,1:3);
td01_unweighted_data(1,7:9)=CF_UNweighted(1,1:3);
td01_unweighted_data(1,10:12)=running_RMS_UNweighted(1,1:3);
td01_unweighted_data(1,13:15)=MTVV_UNweighted(1,1:3);
td01_unweighted_data(1,16:18)=MTVV_aw_ratio_UNweighted(1,1:3);
td01_unweighted_data(1,19)=VTV_translational_RMS_UNweighted(1,1);

td01_unweighted_3rdoctave_spectra(:,1:2)=running_RMS_X_third_octave_UNweighted(:,1:2);
td01_unweighted_3rdoctave_spectra(:,3)=running_RMS_Y_third_octave_UNweighted(:,2);
td01_unweighted_3rdoctave_spectra(:,4)=running_RMS_Z_third_octave_UNweighted(:,2);

td01_unweighted_DFT_spectra(1:101,1:2)=X_DFTspectraldata_UNweighted(1:101,1:2);
td01_unweighted_DFT_spectra(1:101,3)=Y_DFTspectraldata_UNweighted(1:101,2);
td01_unweighted_DFT_spectra(1:101,4)=Z_DFTspectraldata_UNweighted(1:101,2);
```

```
%%%%%%%%%%%%%%% WBV Processing for td02 %%%%%%%%%%%%%%%%

data=[time,td02_scaled,td02_scaled];

[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNweighted,CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,running_RMS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,MTVV_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave_UNweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave_UNweighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave_UNweighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_octave_UNweighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_third_octave_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw_third_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectraldata_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_DFTspectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weighted,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFTspectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UNweighted,VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RMS_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_UNweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sf,bpfclow,bpfcup,octbfclow,octbfcup,AT,overlap);
%function[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNweighted,CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,running_RMS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,MTVV_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave_UNweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave_UNweighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave_UNweighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_octave_UNweighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_third_octave_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw_third_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectraldata_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_DFTspectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weighted,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFTspectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UNweighted,VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RMS_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_UNweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sampling_frequency,band_pass_lower_freq,band_pass_upper_freq,octave_band_pass_lower_freq,octave_band_pass_upper_freq,averageing_time,moving_window_overlap)
```

```
td02_unweighted_data(1,1:3)=peak_UNweighted(1,1:3);
td02_unweighted_data(1,4:6)=RMS_UNweighted(1,1:3);
td02_unweighted_data(1,7:9)=CF_UNweighted(1,1:3);
td02_unweighted_data(1,10:12)=running_RMS_UNweighted(1,1:3);
td02_unweighted_data(1,13:15)=MTVV_UNweighted(1,1:3);
td02_unweighted_data(1,16:18)=MTVV_aw_ratio_UNweighted(1,1:3);
td02_unweighted_data(1,19)=VTV_translational_RMS_UNweighted(1,1);

td02_unweighted_3rdoctave_spectra(:,1:2)=running_RMS_X_third_octave_UNweighted
(:,1:2);
td02_unweighted_3rdoctave_spectra(:,3)=running_RMS_Y_third_octave_UNweighted(:,
2);
td02_unweighted_3rdoctave_spectra(:,4)=running_RMS_Z_third_octave_UNweighted(:,
2);

td02_unweighted_DFT_spectra(1:101,1:2)=X_DFTspectraldata_UNweighted(1:101,1:2);
td02_unweighted_DFT_spectra(1:101,3)=Y_DFTspectraldata_UNweighted(1:101,2);
td02_unweighted_DFT_spectra(1:101,4)=Z_DFTspectraldata_UNweighted(1:101,2);


%%%%%%%%%%%%%%% WBV Processing for td03 %%%%%%%%%%%%%%%%%

data=[time,td03_scaled,td03_scaled];

[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNweighted,
CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,running_R
MS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,MTV
V_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave_U
Nweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave_UN
weighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave_UNw
eighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_octave_UN
weighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_third_octave
_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw_third_oc
tave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectraldata_UN
weighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_DFTspectra
ldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weighted,Roll_DF
Tspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFTspectraldata_UN
weighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata_UNweighted,Yaw_D
FTspectraldata_weighted,VTV_translational_RMS_UNweighted,VTV_translational_RM
S_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_runni
ng_RMS_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_runnin
g_RMS_UNweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sf,b
pfclow,bpfcup,octbfclow,octbfcup,AT,overlap);
```

```
%function[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_U
Nweighted,CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,
running_RMS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weig
hted,MTVV_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_
octave_UNweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_o
ctave_UNweighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_oct
ave_UNweighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_oc
tave_UNweighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_thir
d_octave_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw
_third_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectral
data_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_D
FTspectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weighted
,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFTspectral
data_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata_UNweighted
,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UNweighted,VTV_translatio
nal_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_runni
ng_RMS_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_runnin
g_RMS_UNweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sam
pling_frequency,band_pass_lower_freq,band_pass_upper_freq,octave_band_pass_lower_
freq,octave_band_pass_upper_freq,averageing_time,moving_window_overlap)

td03_unweighted_data(1,1:3)=peak_UNweighted(1,1:3);
td03_unweighted_data(1,4:6)=RMS_UNweighted(1,1:3);
td03_unweighted_data(1,7:9)=CF_UNweighted(1,1:3);
td03_unweighted_data(1,10:12)=running_RMS_UNweighted(1,1:3);
td03_unweighted_data(1,13:15)=MTVV_UNweighted(1,1:3);
td03_unweighted_data(1,16:18)=MTVV_aw_ratio_UNweighted(1,1:3);
td03_unweighted_data(1,19)=VTV_translational_RMS_UNweighted(1,1);

td03_unweighted_3rdoctave_spectra(:,1:2)=running_RMS_X_third_octave_UNweighted
(:,1:2);
td03_unweighted_3rdoctave_spectra(:,3)=running_RMS_Y_third_octave_UNweighted(:,
2);
td03_unweighted_3rdoctave_spectra(:,4)=running_RMS_Z_third_octave_UNweighted(:,
2);

td03_unweighted_DFT_spectra(1:101,1:2)=X_DFTspectraldata_UNweighted(1:101,1:2);
td03_unweighted_DFT_spectra(1:101,3)=Y_DFTspectraldata_UNweighted(1:101,2);
td03_unweighted_DFT_spectra(1:101,4)=Z_DFTspectraldata_UNweighted(1:101,2);
```

```
%%%%%%%%%%%%%%% WBV Processing for td04 %%%%%%%%%%%%%%%%
data=[time,td04_scaled,td04_scaled];

[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNweighted,CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,running_RMS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,MTVV_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave_UNweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave_UNweighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave_UNweighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_octave_UNweighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_third_octave_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw_third_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectraldata_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_DFTspectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weighted,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFTspectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UNweighted,VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RMS_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_UNweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sf,bpfclow,bpfcup,octbfclow,octbfcup,AT,overlap);
%function[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNweighted,CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,running_RMS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,MTVV_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave_UNweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave_UNweighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave_UNweighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_octave_UNweighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_third_octave_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw_third_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectraldata_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_DFTspectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weighted,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFTspectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UNweighted,VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RMS_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_UNweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sampling_frequency,band_pass_lower_freq,band_pass_upper_freq,octave_band_pass_lower_freq,octave_band_pass_upper_freq,averageing_time,moving_window_overlap)
```

```
td04_unweighted_data(1,1:3)=peak_UNweighted(1,1:3);
td04_unweighted_data(1,4:6)=RMS_UNweighted(1,1:3);
td04_unweighted_data(1,7:9)=CF_UNweighted(1,1:3);
td04_unweighted_data(1,10:12)=running_RMS_UNweighted(1,1:3);
td04_unweighted_data(1,13:15)=MTVV_UNweighted(1,1:3);
td04_unweighted_data(1,16:18)=MTVV_aw_ratio_UNweighted(1,1:3);
td04_unweighted_data(1,19)=VTV_translational_RMS_UNweighted(1,1);

td04_unweighted_3rdoctave_spectra(:,1:2)=running_RMS_X_third_octave_UNweighted
(:,1:2);
td04_unweighted_3rdoctave_spectra(:,3)=running_RMS_Y_third_octave_UNweighted(:,
2);
td04_unweighted_3rdoctave_spectra(:,4)=running_RMS_Z_third_octave_UNweighted(:,
2);

td04_unweighted_DFT_spectra(1:101,1:2)=X_DFTspectraldata_UNweighted(1:101,1:2);
td04_unweighted_DFT_spectra(1:101,3)=Y_DFTspectraldata_UNweighted(1:101,2);
td04_unweighted_DFT_spectra(1:101,4)=Z_DFTspectraldata_UNweighted(1:101,2);


% The output variables of the code are as follows
%
% peak_Unweighted
%
% col 1 = X
% col 2 = Y
% col 3 = Z
%
% RMS_Unweighted --> continous band or frequency sum or vector sum
%
% col 4 = X
% col 5 = Y
% col 6 = Z
%
% CF_UNweighted
%
% col 7 = X
% col 8 = Y
% col 9 = Z
%
% running_RMS_UNweighted --> continous band or frequency sum or vector sum
%
% row 1 = mean
%
% col 10 = X
% col 11 = Y
```

```
% col 12 = Z
%
% MTVV_UNweighted
%
% row 1 = mean
%
% col 13 = X
% col 14 = Y
% col 15 = Z
%
% MTVV_aw_ratio_UNweighted
%
% row 1 = mean
%
% col 16 = X
% col 17 = Y
% col 18 = Z
%
% VTV_translational_RMS_UNweighted --> summed across axes
%
% col 19
%
% running_RMS_AXIS?_third_octave_UNweighted & weighted
%
% col 1 = 1/3 octave bin center frequency
% col 2 = X-axis mean RMS acceleration
% col 3 = Y-axis mean RMS acceleration
% col 4 = Z-axis mean RMS acceleration
%
% AXIS?_DFTspectraldata_UNweighted & weighted
%
% col 1 = DFT frequency bin
% col 2 = X-axis mean signal power
% col 3 = Y-axis mean signal power
% col 4 = Z-axis mean signal power
%
%
% NOTE: that some of the lower overlap percentages will result in some data
% at the end of the trials not being used for averaging (occurs with
% percentages less than 50%).
%
% NOTE: In the future the rotational data collected should be used to remove
% g*sin theta error will be removed from the accelerometer data
```

```
subject_unweighted_data=[td01_unweighted_data;td02_unweighted_data;td03_unweight
ed_data;td04_unweighted_data];


%%%%%%%%%%%%%%%%% Transmissibility%%%%%%%%%%%%%%%%%%%%

% Ratio of running RMS acceleration (output to input)

toe_transmissibility=(td02_unweighted_data(1,10:12))./(td01_unweighted_data(1,10:12))
;

ankle_transmissibility=(td04_unweighted_data(1,10:12))./(td03_unweighted_data(1,10:1
2));

%%%%%%%%%%%%%%%%%% Transfer Function %%%%%%%%%%%%%%%%%%%

%x-axis_toe
outputdata=td02_scaled(:,1);
inputdata=td01_scaled(:,1);
%sf
%bpfclow
%bpfcup
%AT
%overlap

[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,phase_deg_
unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfclow,bpfcup,AT,ove
rlap);

toe_modulus_size=size(modulus);
columns=toe_modulus_size(1,2);
toe_modulus(1:101,1)=(modulus(1:101,1));
toe_modulus(1:101,2)=(modulus(1:101,columns-1));

toe_coherence_size=size(modulus);
columns=toe_coherence_size(1,2);
toe_coherence(1:101,1)=(coherence(1:101,1));
toe_coherence(1:101,2)=(coherence(1:101,columns-1));

peak_modulus=max(modulus(1:101,columns-1));
[peak_rows,peak_column]=find(modulus(1:101,columns-1)==peak_modulus);
toe_dom_freq(1,1)=toe_modulus(peak_rows,1);

%y-axis_toe
outputdata=td02_scaled(:,2);
inputdata=td01_scaled(:,2);
```

```
%sf
%bpfclow
%bpfcup
%AT
%overlap

[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,phase_deg_
unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfclow,bpfcup,AT,ove
rlap);

toe_modulus_size=size(modulus);
columns=toe_modulus_size(1,2);
toe_modulus(1:101,3)=(modulus(1:101,columns-1));

toe_coherence_size=size(modulus);
columns=toe_coherence_size(1,2);
toe_coherence(1:101,3)=(coherence(1:101,columns-1));

peak_modulus=max(modulus(1:101,columns-1));
[peak_rows,peak_column]=find(modulus(1:101,columns-1)==peak_modulus);
toe_dom_freq(1,2)=toe_modulus(peak_rows,1);

%z-axis_toe
outputdata=td02_scaled(:,3);
inputdata=td01_scaled(:,3);
%sf
%bpfclow
%bpfcup
%AT
%overlap

[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,phase_deg_
unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfclow,bpfcup,AT,ove
rlap);

toe_modulus_size=size(modulus);
columns=toe_modulus_size(1,2);
toe_modulus(1:101,4)=(modulus(1:101,columns-1));

toe_coherence_size=size(modulus);
columns=toe_coherence_size(1,2);
toe_coherence(1:101,4)=(coherence(1:101,columns-1));

peak_modulus=max(modulus(1:101,columns-1));
[peak_rows,peak_column]=find(modulus(1:101,columns-1)==peak_modulus);
toe_dom_freq(1,3)=toe_modulus(peak_rows,1);
```

```
%x-axis_ankle
outputdata=td04_scaled(:,1);
inputdata=td03_scaled(:,1);
%sf
%bpfclow
%bpfcup
%AT
%overlap

[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,phase_deg_
unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfclow,bpfcup,AT,ove
rlap);

ankle_modulus_size=size(modulus);
columns=ankle_modulus_size(1,2);
ankle_modulus(1:101,1)=(modulus(1:101,1));
ankle_modulus(1:101,2)=(modulus(1:101,columns-1));

ankle_coherence_size=size(modulus);
columns=ankle_coherence_size(1,2);
ankle_coherence(1:101,1)=(coherence(1:101,1));
ankle_coherence(1:101,2)=(coherence(1:101,columns-1));

peak_modulus=max(modulus(1:101,columns-1));
[peak_rows,peak_column]=find(modulus(1:101,columns-1)==peak_modulus);
ankle_dom_freq(1,1)=ankle_modulus(peak_rows,1);

%y-axis_ankle
outputdata=td04_scaled(:,2);
inputdata=td03_scaled(:,2);
%sf
%bpfclow
%bpfcup
%AT
%overlap

[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,phase_deg_
unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfclow,bpfcup,AT,ove
rlap);

ankle_modulus_size=size(modulus);
columns=ankle_modulus_size(1,2);
ankle_modulus(1:101,3)=(modulus(1:101,columns-1));
```

```
ankle_coherence_size=size(modulus);
columns=ankle_coherence_size(1,2);
ankle_coherence(1:101,3)=(coherence(1:101,columns-1));

peak_modulus=max(modulus(1:101,columns-1));
[peak_rows,peak_column]=find(modulus(1:101,columns-1)==peak_modulus);
ankle_dom_freq(1,2)=ankle_modulus(peak_rows,1);

%z-axis_ankle
outputdata=td04_scaled(:,3);
inputdata=td03_scaled(:,3);
%sf
%bpfclow
%bpfcup
%AT
%overlap

[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,phase_deg_
unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfclow,bpfcup,AT,ove
rlap);

ankle_modulus_size=size(modulus);
columns=ankle_modulus_size(1,2);
ankle_modulus(1:101,4)=(modulus(1:101,columns-1));

ankle_coherence_size=size(modulus);
columns=ankle_coherence_size(1,2);
ankle_coherence(1:101,4)=(coherence(1:101,columns-1));

peak_modulus=max(modulus(1:101,columns-1));
[peak_rows,peak_column]=find(modulus(1:101,columns-1)==peak_modulus);
ankle_dom_freq(1,3)=ankle_modulus(peak_rows,1);

save kg45plate_25hz_unweighted_data.txt subject_unweighted_data -ASCII -TABS

save kg45plate_25hz_td01_unweighted_3rdoctave_spectra.txt
td01_unweighted_3rdoctave_spectra -ASCII -TABS
save kg45plate_25hz_td02_unweighted_3rdoctave_spectra.txt
td02_unweighted_3rdoctave_spectra -ASCII -TABS
save kg45plate_25hz_td03_unweighted_3rdoctave_spectra.txt
td03_unweighted_3rdoctave_spectra -ASCII -TABS
save kg45plate_25hz_td04_unweighted_3rdoctave_spectra.txt
td04_unweighted_3rdoctave_spectra -ASCII -TABS

save kg45plate_25hz_td01_unweighted_DFT_spectra.txt td01_unweighted_DFT_spectra
-ASCII -TABS
```

```
save kg45plate_25hz_td02_unweighted_DFT_spectra.txt td02_unweighted_DFT_spectra
-ASCII -TABS
save kg45plate_25hz_td03_unweighted_DFT_spectra.txt td03_unweighted_DFT_spectra
-ASCII -TABS
save kg45plate_25hz_td04_unweighted_DFT_spectra.txt td04_unweighted_DFT_spectra
-ASCII -TABS

save kg45plate_25hz_toe_modulus.txt toe_modulus -ASCII -TABS
save kg45plate_25hz_toe_coherence.txt toe_coherence -ASCII -TABS
save kg45plate_25hz_ankle_modulus.txt ankle_modulus -ASCII -TABS
save kg45plate_25hz_ankle_coherence.txt ankle_coherence -ASCII -TABS
save kg45plate_25hz_toe_dom_freq.txt toe_dom_freq -ASCII -TABS
save kg45plate_25hz_ankle_dom_freq.txt ankle_dom_freq -ASCII -TABS
save kg45plate_25hz_toe_transmissibility.txt toe_transmissibility -ASCII -TABS
save kg45plate_25hz_ankle_transmissibility.txt ankle_transmissibility -ASCII -TABS
```

APPENDIX F

SPSS Results from the two-way repeated-measures ANCOVA with Arch Index covariate

```
GLM A25 A30 A35 A40 A45 A50 T25 T30 T35 T40 T45 T50 WITH AI
  /WSFACTOR=Location 2 Polynomial Frequency 6 Polynomial
  /METHOD=SSTYPE(3)
  /EMMEANS=TABLES(Location) WITH(AI=MEAN)
  /EMMEANS=TABLES(Frequency) WITH(AI=MEAN)
  /EMMEANS=TABLES(Location*Frequency) WITH(AI=MEAN)
  /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY
  /CRITERIA=ALPHA(.05)
  /WSDESIGN=Location Frequency Location*Frequency
  /DESIGN=AI.
```

General Linear Model

Notes

Output Created		19-Dec-2012 22:49:16
Comments		
Input	Data	C:\Documents and Settings\Research\Desktop\Goggins Data\Transmissibility data_Log10+constant.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	30
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the model.

Syntax		GLM A25 A30 A35 A40 A45 A50 T25 T30 T35 T40 T45 T50 WITH AI /WSFACTOR=Location 2 Polynomial Frequency 6 Polynomial /METHOD=SSTYPE(3) /EMMEANS=TABLES(Location) WITH(AI=MEAN) /EMMEANS=TABLES(Frequency) WITH(AI=MEAN) /EMMEANS=TABLES(Location*Frequency) WITH(AI=MEAN) /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY /CRITERIA=ALPHA(.05) /WSDESIGN=Location Frequency Location*Frequency /DESIGN=AI.
Resources	Processor Time	00:00:00.078
	Elapsed Time	00:00:00.046

[DataSet1] C:\Documents and Settings\Research\Desktop\Goggins Data\Transmissibility data_Log10+constant.sav

Warnings

The HOMOGENEITY specification in the PRINT subcommand will be ignored because there are no between-subjects factors.

Within-Subjects Factors

Measure:MEASURE_1

Location	Frequency	Dependent Variable
1	1	A25
	2	A30

	3	A35
	4	A40
	5	A45
	6	A50
2	1	T25
	2	T30
	3	T35
	4	T40
	5	T45
	6	T50

Descriptive Statistics

	Mean	Std. Deviation	N
a25	.24512	.079807	30
a30	.24648	.083652	30
a35	.21731	.065143	30
a40	.19142	.081045	30
a45	.15441	.087993	30
a50	.12861	.088021	30
t25	.20724	.045460	30
t30	.21417	.037495	30
t35	.24429	.043048	30
t40	.26796	.037272	30
t45	.27990	.032043	30
t50	.28873	.034176	30

Multivariate Tests[b]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Location	Pillai's Trace	.001	.017[a]	1.000	28.000	.897	.001
	Wilks' Lambda	.999	.017[a]	1.000	28.000	.897	.001
	Hotelling's Trace	.001	.017[a]	1.000	28.000	.897	.001
	Roy's Largest Root	.001	.017[a]	1.000	28.000	.897	.001
Location * AI	Pillai's Trace	.011	.323[a]	1.000	28.000	.575	.011
	Wilks' Lambda	.989	.323[a]	1.000	28.000	.575	.011
	Hotelling's Trace	.012	.323[a]	1.000	28.000	.575	.011
	Roy's Largest Root	.012	.323[a]	1.000	28.000	.575	.011
Frequency	Pillai's Trace	.107	.573[a]	5.000	24.000	.720	.107
	Wilks' Lambda	.893	.573[a]	5.000	24.000	.720	.107
	Hotelling's Trace	.119	.573[a]	5.000	24.000	.720	.107
	Roy's Largest Root	.119	.573[a]	5.000	24.000	.720	.107
Frequency * AI	Pillai's Trace	.068	.349[a]	5.000	24.000	.877	.068
	Wilks' Lambda	.932	.349[a]	5.000	24.000	.877	.068
	Hotelling's Trace	.073	.349[a]	5.000	24.000	.877	.068
	Roy's Largest Root	.073	.349[a]	5.000	24.000	.877	.068
Location * Frequency	Pillai's Trace	.270	1.777[a]	5.000	24.000	.156	.270
	Wilks' Lambda	.730	1.777[a]	5.000	24.000	.156	.270
	Hotelling's Trace	.370	1.777[a]	5.000	24.000	.156	.270
	Roy's Largest Root	.370	1.777[a]	5.000	24.000	.156	.270
Location * Frequency * AI	Pillai's Trace	.184	1.080[a]	5.000	24.000	.396	.184
	Wilks' Lambda	.816	1.080[a]	5.000	24.000	.396	.184
	Hotelling's Trace	.225	1.080[a]	5.000	24.000	.396	.184
	Roy's Largest Root	.225	1.080[a]	5.000	24.000	.396	.184

a. Exact statistic

Multivariate Tests[b]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Location	Pillai's Trace	.001	.017[a]	1.000	28.000	.897	.001
	Wilks' Lambda	.999	.017[a]	1.000	28.000	.897	.001
	Hotelling's Trace	.001	.017[a]	1.000	28.000	.897	.001
	Roy's Largest Root	.001	.017[a]	1.000	28.000	.897	.001
Location * AI	Pillai's Trace	.011	.323[a]	1.000	28.000	.575	.011
	Wilks' Lambda	.989	.323[a]	1.000	28.000	.575	.011
	Hotelling's Trace	.012	.323[a]	1.000	28.000	.575	.011
	Roy's Largest Root	.012	.323[a]	1.000	28.000	.575	.011
Frequency	Pillai's Trace	.107	.573[a]	5.000	24.000	.720	.107
	Wilks' Lambda	.893	.573[a]	5.000	24.000	.720	.107
	Hotelling's Trace	.119	.573[a]	5.000	24.000	.720	.107
	Roy's Largest Root	.119	.573[a]	5.000	24.000	.720	.107
Frequency * AI	Pillai's Trace	.068	.349[a]	5.000	24.000	.877	.068
	Wilks' Lambda	.932	.349[a]	5.000	24.000	.877	.068
	Hotelling's Trace	.073	.349[a]	5.000	24.000	.877	.068
	Roy's Largest Root	.073	.349[a]	5.000	24.000	.877	.068
Location * Frequency	Pillai's Trace	.270	1.777[a]	5.000	24.000	.156	.270
	Wilks' Lambda	.730	1.777[a]	5.000	24.000	.156	.270
	Hotelling's Trace	.370	1.777[a]	5.000	24.000	.156	.270
	Roy's Largest Root	.370	1.777[a]	5.000	24.000	.156	.270
Location * Frequency * AI	Pillai's Trace	.184	1.080[a]	5.000	24.000	.396	.184
	Wilks' Lambda	.816	1.080[a]	5.000	24.000	.396	.184
	Hotelling's Trace	.225	1.080[a]	5.000	24.000	.396	.184
	Roy's Largest Root	.225	1.080[a]	5.000	24.000	.396	.184

b. Design: Intercept + AI
Within Subjects Design: Location + Frequency + Location * Frequency

Mauchly's Test of Sphericity[b]

Measure:MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Location	1.000	.000	0	.	1.000	1.000	1.000
Frequency	.016	107.940	14	.000	.390	.434	.200
Location * Frequency	.058	74.275	14	.000	.431	.485	.200

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept + AI
Within Subjects Design: Location + Frequency + Location * Frequency

Tests of Within-Subjects Effects

Measure:MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Location	Sphericity Assumed	.000	1	.000	.017	.897	.001
	Greenhouse-Geisser	.000	1.000	.000	.017	.897	.001
	Huynh-Feldt	.000	1.000	.000	.017	.897	.001
	Lower-bound	.000	1.000	.000	.017	.897	.001
Location * AI	Sphericity Assumed	.005	1	.005	.323	.575	.011
	Greenhouse-Geisser	.005	1.000	.005	.323	.575	.011
	Huynh-Feldt	.005	1.000	.005	.323	.575	.011
	Lower-bound	.005	1.000	.005	.323	.575	.011
Error(Location)	Sphericity Assumed	.455	28	.016			
	Greenhouse-Geisser	.455	28.000	.016			
	Huynh-Feldt	.455	28.000	.016			
	Lower-bound	.455	28.000	.016			

Frequency	Sphericity Assumed	.002	5	.000	.219	.954	.008
	Greenhouse-Geisser	.002	1.951	.001	.219	.798	.008
	Huynh-Feldt	.002	2.170	.001	.219	.821	.008
	Lower-bound	.002	1.000	.002	.219	.643	.008
Frequency * AI	Sphericity Assumed	.003	5	.001	.342	.886	.012
	Greenhouse-Geisser	.003	1.951	.002	.342	.706	.012
	Huynh-Feldt	.003	2.170	.002	.342	.729	.012
	Lower-bound	.003	1.000	.003	.342	.563	.012
Error(Frequency)	Sphericity Assumed	.267	140	.002			
	Greenhouse-Geisser	.267	54.615	.005			
	Huynh-Feldt	.267	60.748	.004			
	Lower-bound	.267	28.000	.010			
Location * Frequency	Sphericity Assumed	.040	5	.008	3.243	.008	.104
	Greenhouse-Geisser	.040	2.156	.019	3.243	.042	.104
	Huynh-Feldt	.040	2.426	.016	3.243	.036	.104
	Lower-bound	.040	1.000	.040	3.243	.083	.104
Location * Frequency * AI	Sphericity Assumed	.009	5	.002	.693	.630	.024
	Greenhouse-Geisser	.009	2.156	.004	.693	.514	.024
	Huynh-Feldt	.009	2.426	.004	.693	.530	.024
	Lower-bound	.009	1.000	.009	.693	.412	.024
Error(Location*Frequency)	Sphericity Assumed	.345	140	.002			
	Greenhouse-Geisser	.345	60.375	.006			
	Huynh-Feldt	.345	67.918	.005			
	Lower-bound	.345	28.000	.012			

Tests of Within-Subjects Contrasts

Measure:MEASURE_1

Source	Location	Frequency	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Location	Linear		.000	1	.000	.017	.897	.001
Location * AI	Linear		.005	1	.005	.323	.575	.011
Error(Location)	Linear		.455	28	.016			
Frequency		Linear	8.398E-5	1	8.398E-5	.016	.901	.001
		Quadratic	2.261E-5	1	2.261E-5	.014	.907	.000
		Cubic	.001	1	.001	.526	.474	.018
		Order 4	.001	1	.001	2.420	.131	.080
		Order 5	1.657E-5	1	1.657E-5	.035	.854	.001
Frequency * AI		Linear	.001	1	.001	.171	.683	.006
		Quadratic	.000	1	.000	.297	.590	.011
		Cubic	.001	1	.001	.577	.454	.020
		Order 4	.001	1	.001	2.017	.167	.067
		Order 5	8.407E-7	1	8.407E-7	.002	.967	.000
Error(Frequency)		Linear	.151	28	.005			
		Quadratic	.046	28	.002			
		Cubic	.044	28	.002			
		Order 4	.013	28	.000			
		Order 5	.013	28	.000			
Location * Frequency	Linear	Linear	.037	1	.037	4.812	.037	.147
		Quadratic	.001	1	.001	.479	.494	.017
		Cubic	4.973E-6	1	4.973E-6	.006	.939	.000
		Order 4	.002	1	.002	2.562	.121	.084
		Order 5	.000	1	.000	.466	.500	.016
Location * Frequency * AI	Linear	Linear	.005	1	.005	.655	.425	.023
		Quadratic	.001	1	.001	.291	.594	.010
		Cubic	.000	1	.000	.402	.531	.014

		Order 4	.002	1	.002	3.542	.070	.112
		Order 5	.000	1	.000	.313	.580	.011
Error(Location*Frequency)	Linear	Linear	.214	28	.008			
		Quadratic	.063	28	.002			
		Cubic	.023	28	.001			
		Order 4	.018	28	.001			
		Order 5	.026	28	.001			

Tests of Between-Subjects Effects

Measure:MEASURE_1
Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	.711	1	.711	63.246	.000	.693
AI	.011	1	.011	.973	.332	.034
Error	.315	28	.011			

Estimated Marginal Means

1. Location

Measure:MEASURE_1

Location	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	.197[a]	.012	.173	.221
2	.250[a]	.004	.242	.259

a. Covariates appearing in the model are evaluated at the following values: AI = .25.

2. Frequency

Measure:MEASURE_1

Frequency	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	.226[a]	.008	.210	.242
2	.230[a]	.009	.213	.248
3	.231[a]	.006	.218	.244
4	.230[a]	.007	.216	.244
5	.217[a]	.008	.202	.233
6	.209[a]	.008	.192	.225

a. Covariates appearing in the model are evaluated at the following values: AI = .25.

3. Location * Frequency

Measure:MEASURE_1

Location	Frequency	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	1	.245[a]	.015	.215	.275
	2	.246[a]	.016	.215	.278
	3	.217[a]	.012	.193	.242
	4	.191[a]	.015	.161	.222
	5	.154[a]	.016	.121	.188
	6	.129[a]	.016	.095	.162
2	1	.207[a]	.008	.190	.225
	2	.214[a]	.007	.200	.228
	3	.244[a]	.008	.228	.261
	4	.268[a]	.007	.254	.282
	5	.280[a]	.006	.268	.292
	6	.289[a]	.006	.277	.301

a. Covariates appearing in the model are evaluated at the following values: AI = .25.

APPENDIX G

SPSS Results from the two-way repeated-measures ANCOVA with Mass covariate

```
GLM A25 A30 A35 A40 A45 A50 T25 T30 T35 T40 T45 T50 WITH Mass
 /WSFACTOR=Location 2 Polynomial Frequency 6 Polynomial
 /METHOD=SSTYPE(3)
 /EMMEANS=TABLES(Location) WITH(Mass=MEAN)
 /EMMEANS=TABLES(Frequency) WITH(Mass=MEAN)
 /EMMEANS=TABLES(Location*Frequency) WITH(Mass=MEAN)
 /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY
 /CRITERIA=ALPHA(.05)
 /WSDESIGN=Location Frequency Location*Frequency
 /DESIGN=Mass.
```

General Linear Model

Notes

Output Created		19-Dec-2012 22:52:03
Comments		
Input	Data	C:\Documents and Settings\Research\Desktop\Goggins Data\Transmissibility data_Log10+constant.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	30
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the model.

Syntax		GLM A25 A30 A35 A40 A45 A50 T25 T30 T35 T40 T45 T50 WITH Mass /WSFACTOR=Location 2 Polynomial Frequency 6 Polynomial /METHOD=SSTYPE(3) /EMMEANS=TABLES(Location) WITH(Mass=MEAN) /EMMEANS=TABLES(Frequency) WITH(Mass=MEAN) /EMMEANS=TABLES(Location*Frequency) WITH(Mass=MEAN) /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY /CRITERIA=ALPHA(.05) /WSDESIGN=Location Frequency Location*Frequency /DESIGN=Mass.
Resources	Processor Time	00:00:00.031
	Elapsed Time	00:00:00.016

[DataSet1] C:\Documents and Settings\Research\Desktop\Goggins Data\Transmissibility data_Log10+constant.sav

Warnings

The HOMOGENEITY specification in the PRINT subcommand will be ignored because there are no between-subjects factors.

Within-Subjects Factors

Measure:MEASURE_1

Location	Frequency	Dependent Variable
1	1	A25
	2	A30

	3	A35
	4	A40
	5	A45
	6	A50
2	1	T25
	2	T30
	3	T35
	4	T40
	5	T45
	6	T50

Descriptive Statistics

	Mean	Std. Deviation	N
a25	.24512	.079807	30
a30	.24648	.083652	30
a35	.21731	.065143	30
a40	.19142	.081045	30
a45	.15441	.087993	30
a50	.12861	.088021	30
t25	.20724	.045460	30
t30	.21417	.037495	30
t35	.24429	.043048	30
t40	.26796	.037272	30
t45	.27990	.032043	30
t50	.28873	.034176	30

Multivariate Tests[b]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Location	Pillai's Trace	.006	.165[a]	1.000	28.000	.687	.006
	Wilks' Lambda	.994	.165[a]	1.000	28.000	.687	.006
	Hotelling's Trace	.006	.165[a]	1.000	28.000	.687	.006
	Roy's Largest Root	.006	.165[a]	1.000	28.000	.687	.006
Location * Mass	Pillai's Trace	.033	.959[a]	1.000	28.000	.336	.033
	Wilks' Lambda	.967	.959[a]	1.000	28.000	.336	.033
	Hotelling's Trace	.034	.959[a]	1.000	28.000	.336	.033
	Roy's Largest Root	.034	.959[a]	1.000	28.000	.336	.033
Frequency	Pillai's Trace	.191	1.134[a]	5.000	24.000	.370	.191
	Wilks' Lambda	.809	1.134[a]	5.000	24.000	.370	.191
	Hotelling's Trace	.236	1.134[a]	5.000	24.000	.370	.191
	Roy's Largest Root	.236	1.134[a]	5.000	24.000	.370	.191
Frequency * Mass	Pillai's Trace	.116	.627[a]	5.000	24.000	.680	.116
	Wilks' Lambda	.884	.627[a]	5.000	24.000	.680	.116
	Hotelling's Trace	.131	.627[a]	5.000	24.000	.680	.116
	Roy's Largest Root	.131	.627[a]	5.000	24.000	.680	.116
Location * Frequency	Pillai's Trace	.131	.727[a]	5.000	24.000	.610	.131
	Wilks' Lambda	.869	.727[a]	5.000	24.000	.610	.131
	Hotelling's Trace	.151	.727[a]	5.000	24.000	.610	.131
	Roy's Largest Root	.151	.727[a]	5.000	24.000	.610	.131
Location * Frequency * Mass	Pillai's Trace	.041	.203[a]	5.000	24.000	.958	.041
	Wilks' Lambda	.959	.203[a]	5.000	24.000	.958	.041
	Hotelling's Trace	.042	.203[a]	5.000	24.000	.958	.041
	Roy's Largest Root	.042	.203[a]	5.000	24.000	.958	.041

a. Exact statistic

Multivariate Tests[b]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Location	Pillai's Trace	.006	.165[a]	1.000	28.000	.687	.006
	Wilks' Lambda	.994	.165[a]	1.000	28.000	.687	.006
	Hotelling's Trace	.006	.165[a]	1.000	28.000	.687	.006
	Roy's Largest Root	.006	.165[a]	1.000	28.000	.687	.006
Location * Mass	Pillai's Trace	.033	.959[a]	1.000	28.000	.336	.033
	Wilks' Lambda	.967	.959[a]	1.000	28.000	.336	.033
	Hotelling's Trace	.034	.959[a]	1.000	28.000	.336	.033
	Roy's Largest Root	.034	.959[a]	1.000	28.000	.336	.033
Frequency	Pillai's Trace	.191	1.134[a]	5.000	24.000	.370	.191
	Wilks' Lambda	.809	1.134[a]	5.000	24.000	.370	.191
	Hotelling's Trace	.236	1.134[a]	5.000	24.000	.370	.191
	Roy's Largest Root	.236	1.134[a]	5.000	24.000	.370	.191
Frequency * Mass	Pillai's Trace	.116	.627[a]	5.000	24.000	.680	.116
	Wilks' Lambda	.884	.627[a]	5.000	24.000	.680	.116
	Hotelling's Trace	.131	.627[a]	5.000	24.000	.680	.116
	Roy's Largest Root	.131	.627[a]	5.000	24.000	.680	.116
Location * Frequency	Pillai's Trace	.131	.727[a]	5.000	24.000	.610	.131
	Wilks' Lambda	.869	.727[a]	5.000	24.000	.610	.131
	Hotelling's Trace	.151	.727[a]	5.000	24.000	.610	.131
	Roy's Largest Root	.151	.727[a]	5.000	24.000	.610	.131
Location * Frequency * Mass	Pillai's Trace	.041	.203[a]	5.000	24.000	.958	.041
	Wilks' Lambda	.959	.203[a]	5.000	24.000	.958	.041
	Hotelling's Trace	.042	.203[a]	5.000	24.000	.958	.041
	Roy's Largest Root	.042	.203[a]	5.000	24.000	.958	.041

b. Design: Intercept + Mass
Within Subjects Design: Location + Frequency + Location * Frequency

Mauchly's Test of Sphericity[b]

Measure:MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	Df	Sig.	Epsilon[a] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Location	1.000	.000	0	.	1.000	1.000	1.000
Frequency	.018	105.227	14	.000	.398	.443	.200
Location * Frequency	.064	71.551	14	.000	.439	.495	.200

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept + Mass
Within Subjects Design: Location + Frequency + Location * Frequency

Tests of Within-Subjects Effects

Measure:MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Location	Sphericity Assumed	.003	1	.003	.165	.687	.006
	Greenhouse-Geisser	.003	1.000	.003	.165	.687	.006
	Huynh-Feldt	.003	1.000	.003	.165	.687	.006
	Lower-bound	.003	1.000	.003	.165	.687	.006
Location * Mass	Sphericity Assumed	.015	1	.015	.959	.336	.033
	Greenhouse-Geisser	.015	1.000	.015	.959	.336	.033
	Huynh-Feldt	.015	1.000	.015	.959	.336	.033
	Lower-bound	.015	1.000	.015	.959	.336	.033
Error(Location)	Sphericity Assumed	.445	28	.016			
	Greenhouse-Geisser	.445	28.000	.016			
	Huynh-Feldt	.445	28.000	.016			
	Lower-bound	.445	28.000	.016			

Frequency	Sphericity Assumed	.016	5	.003	1.734	.131	.058
	Greenhouse-Geisser	.016	1.988	.008	1.734	.186	.058
	Huynh-Feldt	.016	2.216	.007	1.734	.182	.058
	Lower-bound	.016	1.000	.016	1.734	.199	.058
Frequency * Mass	Sphericity Assumed	.011	5	.002	1.244	.292	.043
	Greenhouse-Geisser	.011	1.988	.006	1.244	.296	.043
	Huynh-Feldt	.011	2.216	.005	1.244	.298	.043
	Lower-bound	.011	1.000	.011	1.244	.274	.043
Error(Frequency)	Sphericity Assumed	.259	140	.002			
	Greenhouse-Geisser	.259	55.670	.005			
	Huynh-Feldt	.259	62.053	.004			
	Lower-bound	.259	28.000	.009			
Location * Frequency	Sphericity Assumed	.026	5	.005	2.108	.068	.070
	Greenhouse-Geisser	.026	2.194	.012	2.108	.126	.070
	Huynh-Feldt	.026	2.473	.011	2.108	.118	.070
	Lower-bound	.026	1.000	.026	2.108	.158	.070
Location * Frequency * Mass	Sphericity Assumed	.005	5	.001	.367	.870	.013
	Greenhouse-Geisser	.005	2.194	.002	.367	.713	.013
	Huynh-Feldt	.005	2.473	.002	.367	.738	.013
	Lower-bound	.005	1.000	.005	.367	.549	.013
Error(Location*Frequency)	Sphericity Assumed	.349	140	.002			
	Greenhouse-Geisser	.349	61.431	.006			
	Huynh-Feldt	.349	69.244	.005			
	Lower-bound	.349	28.000	.012			

Tests of Within-Subjects Contrasts

Measure:MEASURE_1

Source	Location	Frequency	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Location	Linear		.003	1	.003	.165	.687	.006
Location * Mass	Linear		.015	1	.015	.959	.336	.033
Error(Location)	Linear		.445	28	.016			
Frequency		Linear	.010	1	.010	1.856	.184	.062
		Quadratic	.005	1	.005	3.035	.092	.098
		Cubic	.002	1	.002	1.081	.307	.037
		Order 4	4.253E-6	1	4.253E-6	.008	.928	.000
		Order 5	6.009E-5	1	6.009E-5	.126	.725	.004
Frequency * Mass		Linear	.007	1	.007	1.303	.263	.044
		Quadratic	.003	1	.003	1.982	.170	.066
		Cubic	.002	1	.002	1.063	.311	.037
		Order 4	2.369E-5	1	2.369E-5	.047	.830	.002
		Order 5	2.754E-5	1	2.754E-5	.058	.812	.002
Error(Frequency)		Linear	.145	28	.005			
		Quadratic	.043	28	.002			
		Cubic	.043	28	.002			
		Order 4	.014	28	.001			
		Order 5	.013	28	.000			
Location * Frequency	Linear	Linear	.024	1	.024	3.139	.087	.101
		Quadratic	.000	1	.000	.048	.828	.002
		Cubic	.001	1	.001	1.548	.224	.052
		Order 4	.000	1	.000	.275	.604	.010
		Order 5	.000	1	.000	.516	.479	.018
Location * Frequency * Mass	Linear	Linear	.003	1	.003	.430	.517	.015
		Quadratic	.000	1	.000	.124	.727	.004
		Cubic	.001	1	.001	.655	.425	.023

		Order 4	7.945E-5	1	7.945E-5	.112	.740	.004
		Order 5	.000	1	.000	.382	.542	.013
Error(Location*Frequency)	Linear	Linear	.216	28	.008			
		Quadratic	.064	28	.002			
		Cubic	.023	28	.001			
		Order 4	.020	28	.001			
		Order 5	.026	28	.001			

Tests of Between-Subjects Effects

Measure:MEASURE_1
Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	.557	1	.557	51.551	.000	.648
Mass	.023	1	.023	2.106	.158	.070
Error	.303	28	.011			

Estimated Marginal Means

1. Location

Measure:MEASURE_1

Location	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	.197[a]	.011	.174	.221
2	.250[a]	.004	.242	.259

a. Covariates appearing in the model are evaluated at the following values: Mass = 188.84.

2. Frequency

Measure:MEASURE_1

Frequency	Mean	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
1	.226[a]	.008	.210	.242
2	.230[a]	.008	.214	.247
3	.231[a]	.006	.219	.243
4	.230[a]	.007	.216	.243
5	.217[a]	.008	.202	.233
6	.209[a]	.008	.192	.226

a. Covariates appearing in the model are evaluated at the following values: Mass = 188.84.

3. Location * Frequency

Measure:MEASURE_1

Location	Frequency	Mean	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
1	1	.245[a]	.014	.216	.275
	2	.246[a]	.015	.217	.276
	3	.217[a]	.012	.194	.241
	4	.191[a]	.015	.161	.222
	5	.154[a]	.016	.121	.188
	6	.129[a]	.016	.095	.162
2	1	.207[a]	.008	.190	.225
	2	.214[a]	.007	.200	.228
	3	.244[a]	.008	.228	.260
	4	.268[a]	.007	.254	.282
	5	.280[a]	.006	.268	.292
	6	.289[a]	.006	.276	.302

3. Location * Frequency

Measure:MEASURE_1

Location	Frequency	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	.245[a]	.014	.216	.275
	2	.246[a]	.015	.217	.276
	3	.217[a]	.012	.194	.241
	4	.191[a]	.015	.161	.222
	5	.154[a]	.016	.121	.188
	6	.129[a]	.016	.095	.162
2	1	.207[a]	.008	.190	.225
	2	.214[a]	.007	.200	.228
	3	.244[a]	.008	.228	.260
	4	.268[a]	.007	.254	.282
	5	.280[a]	.006	.268	.292
	6	.289[a]	.006	.276	.302

a. Covariates appearing in the model are evaluated at the following values: Mass = 188.84.

APPENDIX H

SPSS Results from the two-way repeated-measures ANOVA,
T-tests to follow-up significant location main effect,
T-tests to follow-up significant frequency main effect,
T-tests to follow-up significant location*frequency interaction

```
GET FILE='C:\Documents and Settings\Research\Desktop\Goggins Data\Transmissibility data_Log10+constant.sav'.
DATASET NAME DataSet0 WINDOW=FRONT.
GLM A25 A30 A35 A40 A45 A50 T25 T30 T35 T40 T45 T50
  /WSFACTOR=Location 2 Polynomial Frequency 6 Polynomial
  /METHOD=SSTYPE(3)
  /EMMEANS=TABLES(Location)
  /EMMEANS=TABLES(Frequency)
  /EMMEANS=TABLES(Location*Frequency)
  /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY
  /CRITERIA=ALPHA(.05)
  /WSDESIGN=Location Frequency Location*Frequency.
```

General Linear Model

Notes

Output Created		19-Dec-2012 22:34:01
Comments		
Input	Data	C:\Documents and Settings\Research\Desktop\Goggins Data\Transmissibility data_Log10+constant.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	30
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the model.

Syntax		GLM A25 A30 A35 A40 A45 A50 T25 T30 T35 T40 T45 T50 /WSFACTOR=Location 2 Polynomial Frequency 6 Polynomial /METHOD=SSTYPE(3) /EMMEANS=TABLES(Location) /EMMEANS=TABLES(Frequency) /EMMEANS=TABLES(Location*Frequency) /PRINT=DESCRIPTIVE ETASQ HOMOGENEITY /CRITERIA=ALPHA(.05) /WSDESIGN=Location Frequency Location*Frequency.
Resources	Processor Time	00:00:00.109
	Elapsed Time	00:00:00.172

[DataSet1] C:\Documents and Settings\Research\Desktop\Goggins Data\Transmissibility data_Log10+constant.sav

Warnings

The HOMOGENEITY specification in the PRINT subcommand will be ignored because there are no between-subjects factors.

Within-Subjects Factors

Measure:MEASURE_1

Location	Frequency	Dependent Variable
1	1	A25
	2	A30
	3	A35
	4	A40

	5	A45
	6	A50
2	1	T25
	2	T30
	3	T35
	4	T40
	5	T45
	6	T50

Descriptive Statistics

	Mean	Std. Deviation	N
a25	.24512	.079807	30
a30	.24648	.083652	30
a35	.21731	.065143	30
a40	.19142	.081045	30
a45	.15441	.087993	30
a50	.12861	.088021	30
t25	.20724	.045460	30
t30	.21417	.037495	30
t35	.24429	.043048	30
t40	.26796	.037272	30
t45	.27990	.032043	30
t50	.28873	.034176	30

Multivariate Tests[b]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Location	Pillai's Trace	.356	16.032[a]	1.000	29.000	.000	.356
	Wilks' Lambda	.644	16.032[a]	1.000	29.000	.000	.356
	Hotelling's Trace	.553	16.032[a]	1.000	29.000	.000	.356
	Roy's Largest Root	.553	16.032[a]	1.000	29.000	.000	.356
Frequency	Pillai's Trace	.487	4.754[a]	5.000	25.000	.003	.487
	Wilks' Lambda	.513	4.754[a]	5.000	25.000	.003	.487
	Hotelling's Trace	.951	4.754[a]	5.000	25.000	.003	.487
	Roy's Largest Root	.951	4.754[a]	5.000	25.000	.003	.487
Location * Frequency	Pillai's Trace	.754	15.365[a]	5.000	25.000	.000	.754
	Wilks' Lambda	.246	15.365[a]	5.000	25.000	.000	.754
	Hotelling's Trace	3.073	15.365[a]	5.000	25.000	.000	.754
	Roy's Largest Root	3.073	15.365[a]	5.000	25.000	.000	.754

a. Exact statistic

b. Design: Intercept
Within Subjects Design: Location + Frequency + Location * Frequency

Mauchly's Test of Sphericity[b]

Measure:MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Location	1.000	.000	0	.	1.000	1.000	1.000
Frequency	.016	111.818	14	.000	.390	.418	.200
Location * Frequency	.063	74.935	14	.000	.436	.473	.200

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept
Within Subjects Design: Location + Frequency + Location * Frequency

Tests of Within-Subjects Effects

Measure:MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Location	Sphericity Assumed	.254	1	.254	16.032	.000	.356
	Greenhouse-Geisser	.254	1.000	.254	16.032	.000	.356
	Huynh-Feldt	.254	1.000	.254	16.032	.000	.356
	Lower-bound	.254	1.000	.254	16.032	.000	.356
Error(Location)	Sphericity Assumed	.460	29	.016			
	Greenhouse-Geisser	.460	29.000	.016			
	Huynh-Feldt	.460	29.000	.016			
	Lower-bound	.460	29.000	.016			
Frequency	Sphericity Assumed	.024	5	.005	2.609	.027	.083
	Greenhouse-Geisser	.024	1.952	.012	2.609	.084	.083
	Huynh-Feldt	.024	2.091	.012	2.609	.079	.083
	Lower-bound	.024	1.000	.024	2.609	.117	.083
Error(Frequency)	Sphericity Assumed	.270	145	.002			
	Greenhouse-Geisser	.270	56.595	.005			
	Huynh-Feldt	.270	60.626	.004			
	Lower-bound	.270	29.000	.009			
Location * Frequency	Sphericity Assumed	.502	5	.100	41.271	.000	.587
	Greenhouse-Geisser	.502	2.180	.230	41.271	.000	.587

		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
	Huynh-Feldt	.502	2.364	.213	41.271	.000	.587
	Lower-bound	.502	1.000	.502	41.271	.000	.587
Error(Location*Frequency)	Sphericity Assumed	.353	145	.002			
	Greenhouse-Geisser	.353	63.228	.006			
	Huynh-Feldt	.353	68.563	.005			
	Lower-bound	.353	29.000	.012			

Tests of Within-Subjects Contrasts

Measure:MEASURE_1

Source	Location	Frequency	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Location	Linear		.254	1	.254	16.032	.000	.356
Error(Location)	Linear		.460	29	.016			
Frequency		Linear	.014	1	.014	2.694	.112	.085
		Quadratic	.009	1	.009	5.932	.021	.170
		Cubic	2.746E-5	1	2.746E-5	.018	.895	.001
		Order 4	.000	1	.000	.783	.383	.026
		Order 5	.000	1	.000	.716	.404	.024
Error(Frequency)		Linear	.152	29	.005			
		Quadratic	.046	29	.002			
		Cubic	.045	29	.002			
		Order 4	.014	29	.000			
		Order 5	.013	29	.000			
Location * Frequency	Linear	Linear	.491	1	.491	64.975	.000	.691

		Quadratic	.002	1	.002	.876	.357	.029
		Cubic	.008	1	.008	10.049	.004	.257
		Order 4	.001	1	.001	1.930	.175	.062
		Order 5	.001	1	.001	.586	.450	.020
Error(Location*Frequency)	Linear	Linear	.219	29	.008			
		Quadratic	.064	29	.002			
		Cubic	.024	29	.001			
		Order 4	.020	29	.001			
		Order 5	.027	29	.001			

Tests of Between-Subjects Effects

Measure:MEASURE_1
Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	18.032	1	18.032	1.606E3	.000	.982
Error	.326	29	.011			

Estimated Marginal Means

1. Location

Measure:MEASURE_1

Location	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	.197	.012	.174	.221

1. Location

Measure:MEASURE_1

Location	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	.197	.012	.174	.221
2	.250	.004	.242	.259

2. Frequency

Measure:MEASURE_1

Frequency	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	.226	.008	.210	.242
2	.230	.009	.213	.248
3	.231	.006	.218	.244
4	.230	.007	.216	.244
5	.217	.007	.202	.232
6	.209	.008	.192	.225

3. Location * Frequency

Measure:MEASURE_1

Location	Frequency	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	.245	.015	.215	.275
	2	.246	.015	.215	.278
	3	.217	.012	.193	.242
	4	.191	.015	.161	.222
	5	.154	.016	.122	.187
	6	.129	.016	.096	.161

2	1	.207	.008	.190	.224
	2	.214	.007	.200	.228
	3	.244	.008	.228	.260
	4	.268	.007	.254	.282
	5	.280	.006	.268	.292
	6	.289	.006	.276	.301

```
T-TEST PAIRS=T25 T30 T35 T40 T45 T50 WITH A25 A30 A35 A40 A45 A50 (PAIRED)
  /CRITERIA=CI(.9500)
  /MISSING=ANALYSIS.
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T-Test

Notes

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	Cases Used	Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis.

Syntax		T-TEST PAIRS=T25 T30 T35 T40 T45 T50 WITH A25 A30 A35 A40 A45 A50 (PAIRED) /CRITERIA=CI(.9500) /MISSING=ANALYSIS.
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[DataSet1] C:\Documents and Settings\Research\Desktop\Goggins Data\Transmissibility data_Log10+constant.sav

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	t25	.20724	30	.045460	.008300
	a25	.24512	30	.079807	.014571
Pair 2	t30	.21417	30	.037495	.006846
	a30	.24648	30	.083652	.015273
Pair 3	t35	.24429	30	.043048	.007859
	a35	.21731	30	.065143	.011893
Pair 4	t40	.26796	30	.037272	.006805
	a40	.19142	30	.081045	.014797
Pair 5	t45	.27990	30	.032043	.005850
	a45	.15441	30	.087993	.016065
Pair 6	t50	.28873	30	.034176	.006240
	a50	.12861	30	.088021	.016070

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	t25 & a25	30	-.149	.432
Pair 2	t30 & a30	30	.043	.820

Pair 3	t35 & a35	30	-.221	.240
Pair 4	t40 & a40	30	-.400	.028
Pair 5	t45 & a45	30	-.369	.045
Pair 6	t50 & a50	30	-.159	.403

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	t25 - a25	-.037879	.097560	.017812	-.074308	-.001449	-2.127	29	0.042087219
Pair 2	t30 - a30	-.032306	.090172	.016463	-.065977	.001365	-1.962	29	0.059386732
Pair 3	t35 - a35	.026979	.085654	.015638	-.005005	.058962	1.725	29	0.095140618
Pair 4	t40 - a40	.076541	.101856	.018596	.038507	.114574	4.116	29	0.000291778
Pair 5	t45 - a45	.125491	.104153	.019016	.086599	.164382	6.599	29	0.000000312
Pair 6	t50 - a50	.160124	.099344	.018138	.123028	.197220	8.828	29	0.000000001

```
T-TEST PAIRS=A25 A25 A25 A25 A25 A30 A30 A30 A30 A35 A35 A35 A40 A40 A45 T25 T25 T25 T25 T25 T30 T30 T30 T30 T35 T35 T35 T40 T40 T45
  WITH A30 A35 A40 A45 A50 A35 A40 A45 A50 A40 A45 A50 A45 A50 A50 T30 T35 T40 T45 T50 T35 T40 T45 T50 T40 T45 T50 T45 T50
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T-Test

Notes

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Missing Value Handling	Definition of Missing	User defined missing values are treated as missing.
	Cases Used	Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis.
Syntax		T-TEST PAIRS=A25 A25 A25 A25 A25 A30 A30 A30 A30 A35 A35 A35 A40 A40 A45 T25 T25 T25 T25 T25 T30 T30 T30 T30 T35 T35 T35 T40 T40 T45 WITH A30 A35 A40 A45 A50 A35 A40 A45 A50 A40 A45 A50 A45 A50 A50 T30 T35 T40 T45 T50 T35 T40 T45 T50 T40 T45 T50 T45 T50 T50 (PAIRED) /CRITERIA=CI(.9500) /MISSING=ANALYSIS.
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Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	a25	.24512	30	.079807	.014571
	a30	.24648	30	.083652	.015273
Pair 2	a25	.24512	30	.079807	.014571
	a35	.21731	30	.065143	.011893
Pair 3	a25	.24512	30	.079807	.014571
	a40	.19142	30	.081045	.014797
Pair 4	a25	.24512	30	.079807	.014571
	a45	.15441	30	.087993	.016065
Pair 5	a25	.24512	30	.079807	.014571
	a50	.12861	30	.088021	.016070
Pair 6	a30	.24648	30	.083652	.015273
	a35	.21731	30	.065143	.011893
Pair 7	a30	.24648	30	.083652	.015273
	a40	.19142	30	.081045	.014797
Pair 8	a30	.24648	30	.083652	.015273
	a45	.15441	30	.087993	.016065
Pair 9	a30	.24648	30	.083652	.015273
	a50	.12861	30	.088021	.016070
Pair 10	a35	.21731	30	.065143	.011893
	a40	.19142	30	.081045	.014797
Pair 11	a35	.21731	30	.065143	.011893
	a45	.15441	30	.087993	.016065
Pair 12	a35	.21731	30	.065143	.011893
	a50	.12861	30	.088021	.016070
Pair 13	a40	.19142	30	.081045	.014797
	a45	.15441	30	.087993	.016065
Pair 14	a40	.19142	30	.081045	.014797
	a50	.12861	30	.088021	.016070
Pair 15	a45	.15441	30	.087993	.016065
	a50	.12861	30	.088021	.016070
Pair 16	t25	.20724	30	.045460	.008300
	t30	.21417	30	.037495	.006846
Pair 17	t25	.20724	30	.045460	.008300
	t35	.24429	30	.043048	.007859
Pair 18	t25	.20724	30	.045460	.008300
	t40	.26796	30	.037272	.006805
Pair 19	t25	.20724	30	.045460	.008300
	t45	.27990	30	.032043	.005850
Pair 20	t25	.20724	30	.045460	.008300
	t50	.28873	30	.034176	.006240
Pair 21	t30	.21417	30	.037495	.006846
	t35	.24429	30	.043048	.007859
Pair 22	t30	.21417	30	.037495	.006846
	t40	.26796	30	.037272	.006805

Pair 23	t30	.21417	30	.037495	.006846
	t45	.27990	30	.032043	.005850
Pair 24	t30	.21417	30	.037495	.006846
	t50	.28873	30	.034176	.006240
Pair 25	t35	.24429	30	.043048	.007859
	t40	.26796	30	.037272	.006805
Pair 26	t35	.24429	30	.043048	.007859
	t45	.27990	30	.032043	.005850
Pair 27	t35	.24429	30	.043048	.007859
	t50	.28873	30	.034176	.006240
Pair 28	t40	.26796	30	.037272	.006805
	t45	.27990	30	.032043	.005850
Pair 29	t40	.26796	30	.037272	.006805
	t50	.28873	30	.034176	.006240
Pair 30	t45	.27990	30	.032043	.005850
	t50	.28873	30	.034176	.006240

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	a25 & a30	30	.681	.000
Pair 2	a25 & a35	30	.512	.004
Pair 3	a25 & a40	30	.542	.002
Pair 4	a25 & a45	30	.276	.140
Pair 5	a25 & a50	30	.183	.332
Pair 6	a30 & a35	30	.626	.000
Pair 7	a30 & a40	30	.500	.005
Pair 8	a30 & a45	30	.187	.324
Pair 9	a30 & a50	30	.055	.772
Pair 10	a35 & a40	30	.776	.000
Pair 11	a35 & a45	30	.653	.000
Pair 12	a35 & a50	30	.540	.002
Pair 13	a40 & a45	30	.831	.000
Pair 14	a40 & a50	30	.742	.000
Pair 15	a45 & a50	30	.915	.000
Pair 16	t25 & t30	30	.517	.003
Pair 17	t25 & t35	30	.061	.749
Pair 18	t25 & t40	30	-.182	.335
Pair 19	t25 & t45	30	-.278	.137
Pair 20	t25 & t50	30	-.154	.417
Pair 21	t30 & t35	30	.736	.000
Pair 22	t30 & t40	30	.417	.022
Pair 23	t30 & t45	30	.074	.698
Pair 24	t30 & t50	30	-.144	.449
Pair 25	t35 & t40	30	.730	.000
Pair 26	t35 & t45	30	.410	.024
Pair 27	t35 & t50	30	.055	.772
Pair 28	t40 & t45	30	.619	.000

Pair 29	t40 & t50	30	.180	.342
Pair 30	t45 & t50	30	.652	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	a25 - a30	-.001357	.065388	.011938	-.025774	.023059	-.114	29	0.910254829
Pair 2	a25 - a35	.027811	.072762	.013284	.000641	.054981	2.094	29	0.045159362
Pair 3	a25 - a40	.053702	.076958	.014051	.024965	.082438	3.822	29	0.000647165
Pair 4	a25 - a45	.090713	.101185	.018474	.052930	.128496	4.910	29	0.000032540
Pair 5	a25 - a50	.116515	.107433	.019614	.076398	.156631	5.940	29	0.000001877
Pair 6	a30 - a35	.029169	.066503	.012142	.004336	.054001	2.402	29	0.022916628
Pair 7	a30 - a40	.055059	.082358	.015036	.024306	.085812	3.662	29	0.000993822
Pair 8	a30 - a45	.092071	.109516	.019995	.051177	.132965	4.605	29	0.000075999
Pair 9	a30 - a50	.117872	.118034	.021550	.073798	.161947	5.470	29	0.000006881
Pair 10	a35 - a40	.025890	.051173	.009343	.006782	.044999	2.771	29	0.009649413
Pair 11	a35 - a45	.062902	.067098	.012250	.037847	.087957	5.135	29	0.000017443
Pair 12	a35 - a50	.088703	.076144	.013902	.060271	.117136	6.381	29	0.000000564
Pair 13	a40 - a45	.037011	.049629	.009061	.018480	.055543	4.085	29	0.000317690
Pair 14	a40 - a50	.062813	.061124	.011160	.039989	.085637	5.629	29	0.000004432
Pair 15	a45 - a50	.025801	.036252	.006619	.012265	.039338	3.898	29	0.000527046
Pair 16	t25 - t30	-.006931	.041343	.007548	-.022368	.008507	-.918	29	0.366100282
Pair 17	t25 - t35	-.037046	.060671	.011077	-.059701	-.014391	-3.344	29	0.002288238
Pair 18	t25 - t40	-.060718	.063824	.011653	-.084550	-.036886	-5.211	29	0.000014124
Pair 19	t25 - t45	-.072657	.062481	.011407	-.095987	-.049326	-6.369	29	0.000000581
Pair 20	t25 - t50	-.081488	.060934	.011125	-.104241	-.058735	-7.325	29	0.000000046
Pair 21	t30 - t35	-.030116	.029712	.005425	-.041210	-.019021	-5.552	29	0.000005483
Pair 22	t30 - t40	-.053787	.040359	.007369	-.068858	-.038717	-7.300	29	0.000000049
Pair 23	t30 - t45	-.065726	.047485	.008670	-.083457	-.047995	-7.581	29	0.000000023
Pair 24	t30 - t50	-.074557	.054238	.009902	-.094810	-.054305	-7.529	29	0.000000027
Pair 25	t35 - t40	-.023672	.029983	.005474	-.034867	-.012476	-4.324	29	0.000164825

Pair 26	t35 - t45	-.035610	.041810	.007633	-.051223	-.019998	-4.665	29	0.000064297
Pair 27	t35 - t50	-.044442	.053469	.009762	-.064407	-.024476	-4.553	29	0.000087815
Pair 28	t40 - t45	-.011939	.030606	.005588	-.023367	-.000510	-2.137	29	0.041199389
Pair 29	t40 - t50	-.020770	.045818	.008365	-.037879	-.003661	-2.483	29	0.019061900
Pair 30	t45 - t50	-.008831	.027701	.005058	-.019175	.001512	-1.746	29	0.091367048

```
T-TEST PAIRS=Frequency25 Frequency25 Frequency25 Frequency25 Frequency25 Frequency30 Frequency30 Frequency30 Frequency30 Frequency35
    Frequency35 Frequency35 Frequency40 Frequency40 Frequency45 WITH Frequency30 Frequency35 Frequency40 Frequency45
    Frequency50 Frequency35 Frequency40 Frequency45 Frequency50 Frequency40 Frequency45 Frequency50 Frequency45 Frequency50 Frequenc
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T-Test

Notes

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	Cases Used	Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis.
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Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	t25-a25	-.0379	30	.09756	.01781
	t30-a30	-.0323	30	.09017	.01646
Pair 2	t25-a25	-.0379	30	.09756	.01781
	t35-a35	.0270	30	.08565	.01564
Pair 3	t25-a25	-.0379	30	.09756	.01781
	t40-a40	.0765	30	.10186	.01860
Pair 4	t25-a25	-.0379	30	.09756	.01781
	t45-a45	.1255	30	.10415	.01902
Pair 5	t25-a25	-.0379	30	.09756	.01781
	t50-a50	.1601	30	.09934	.01814
Pair 6	t30-a30	-.0323	30	.09017	.01646
	t35-a35	.0270	30	.08565	.01564
Pair 7	t30-a30	-.0323	30	.09017	.01646
	t40-a40	.0765	30	.10186	.01860
Pair 8	t30-a30	-.0323	30	.09017	.01646
	t45-a45	.1255	30	.10415	.01902
Pair 9	t30-a30	-.0323	30	.09017	.01646
	t50-a50	.1601	30	.09934	.01814
Pair 10	t35-a35	.0270	30	.08565	.01564
	t40-a40	.0765	30	.10186	.01860
Pair 11	t35-a35	.0270	30	.08565	.01564
	t45-a45	.1255	30	.10415	.01902
Pair 12	t35-a35	.0270	30	.08565	.01564
	t50-a50	.1601	30	.09934	.01814
Pair 13	t40-a40	.0765	30	.10186	.01860
	t45-a45	.1255	30	.10415	.01902
Pair 14	t40-a40	.0765	30	.10186	.01860
	t50-a50	.1601	30	.09934	.01814
Pair 15	t45-a45	.1255	30	.10415	.01902
	t50-a50	.1601	30	.09934	.01814

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	t25-a25 & t30-a30	30	.709	.000
Pair 2	t25-a25 & t35-a35	30	.372	.043
Pair 3	t25-a25 & t40-a40	30	.275	.141
Pair 4	t25-a25 & t45-a45	30	.109	.567
Pair 5	t25-a25 & t50-a50	30	-.068	.720
Pair 6	t30-a30 & t35-a35	30	.557	.001
Pair 7	t30-a30 & t40-a40	30	.561	.001
Pair 8	t30-a30 & t45-a45	30	.302	.105
Pair 9	t30-a30 & t50-a50	30	.091	.631
Pair 10	t35-a35 & t40-a40	30	.837	.000
Pair 11	t35-a35 & t45-a45	30	.738	.000
Pair 12	t35-a35 & t50-a50	30	.534	.002
Pair 13	t40-a40 & t45-a45	30	.797	.000
Pair 14	t40-a40 & t50-a50	30	.578	.001
Pair 15	t45-a45 & t50-a50	30	.850	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	t25-a25 - t30-a30	-5.57313E-3	.07190	.01313	-3.24192E-2	2.12729E-2	-.425	29	0.674275419
Pair 2	t25-a25 - t35-a35	-6.48574E-2	.10314	.01883	-1.03370E-1	-2.63451E-2	-3.444	29	0.001764169
Pair 3	t25-a25 - t40-a40	-1.14420E-1	.12010	.02193	-1.59265E-1	-6.95743E-2	-5.218	29	0.000013829
Pair 4	t25-a25 - t45-a45	-1.63370E-1	.13474	.02460	-2.13682E-1	-1.13057E-1	-6.641	29	0.000000279
Pair 5	t25-a25 - t50-a50	-1.98003E-1	.14392	.02628	-2.51742E-1	-1.44263E-1	-7.536	29	0.000000026
Pair 6	t30-a30 - t35-a35	-5.92843E-2	.08289	.01513	-9.02364E-2	-2.83323E-2	-3.917	29	0.000500492
Pair 7	t30-a30 - t40-a40	-1.08846E-1	.09060	.01654	-1.42678E-1	-7.50151E-2	-6.580	29	0.000000329
Pair 8	t30-a30 - t45-a45	-1.57797E-1	.11539	.02107	-2.00883E-1	-1.14711E-1	-7.490	29	0.000000030
Pair 9	t30-a30 - t50-a50	-1.92429E-1	.12792	.02335	-2.40194E-1	-1.44665E-1	-8.240	29	0.000000004
Pair 10	t35-a35 - t40-a40	-4.95621E-2	.05579	.01019	-7.03933E-2	-2.87309E-2	-4.866	29	0.000036805
Pair 11	t35-a35 - t45-a45	-9.85123E-2	.07079	.01293	-1.24947E-1	-7.20772E-2	-7.622	29	0.000000021
Pair 12	t35-a35 - t50-a50	-1.33145E-1	.09013	.01646	-1.66800E-1	-9.94904E-2	-8.091	29	0.000000006
Pair 13	t40-a40 - t45-a45	-4.89501E-2	.06570	.01200	-7.34831E-2	-2.44172E-2	-4.081	29	0.000321099
Pair 14	t40-a40 - t50-a50	-8.35830E-2	.09247	.01688	-1.18111E-1	-4.90550E-2	-4.951	29	0.000029071
Pair 15	t45-a45 - t50-a50	-3.46328E-2	.05596	.01022	-5.55278E-2	-1.37378E-2	-3.390	29	0.002033307