EXAMINATION OF VIBRATION CHARACTERISTICS AND TRANSMISSIBILITY PROPERTIES OF "ANTI-VIBRATION" MATS FOR WORKERS EXPOSED TO VIBRATION VIA THE FEET

by
MALLORIE G. LEDUC

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School of Graduate Studies
Laurentian University
Sudbury, Ontario

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Abstract

Miners are exposed to vibration at the feet when driving locomotives and standing on vibration drilling platforms. Case reports suggest these workers are reporting pain, discomfort and blanching in the toes more often than their co-workers who are not exposed to vibration via the feet (Thompson et al., 2010). The purpose of the field study was to document the frequency and amplitude characteristics of vibration experienced at the feet under typical mining equipment operation. Health guidance caution zone limits (ISO, 1997) were used to determine the potential health risk to the workers as a result of the vibration. Two categories of underground mining equipment, primary (locomotives) and secondary (jumbo drill, bolter, wood and metal raise platforms), were distinguished by their origin of vibration. Measurements were collected using a tri-axial accelerometer mounted according to the ISO 2631-1 standards, at the location where the worker stood to complete the required job task (ISO, 1997). Musculoskeletal disorder history, work history, and demographic information were also collected.

Vibration resulting from a primary source exposure had a dominant frequency below 6.3 Hz. However, the dominant frequency recorded from secondary source exposures were predominantly in the 31.5 to 40 Hz range. All workers reported discomfort in their lower limbs. The wooden raise platform and the metal raise platform exposed the workers to vibration levels at the feet that placed them above the ISO 2631-1 health guidance caution zone, when the 8-hour frequency-weighted root-mean-square acceleration exposure levels were considered (ISO, 1997). Workers standing on the jumbo drill and raise platforms experienced dominant frequency vibration known to be

associated with hand-arm vibration syndrome. The jumbo drill operator and a raise miner have been diagnosed with vibration induced white feet. The dominant frequency recorded at the feet of the locomotive operators was in the range associated with resonance of the spine and pelvis. Further investigation is warranted to determine long-term health effects resulting from vibration exposure via the feet.

As a result of the field study, it was shown that miners are exposed to vibration levels at the feet that are above the ISO 2631-1 health guidance caution zone for an 8 hour shift (Leduc, 2011; ISO, 1997). Anecdotal evidence suggests mats could be used to attenuate vibration. The purpose of the laboratory study was to evaluate the transmissibility properties and comfort of 'anti-vibration' mats. Ten participants experienced four mat conditions and three vibration conditions. Three commercially available mats and a no mat condition were randomly evaluated while participants stood on a vibrating platform with an exposure set to 5.0 m/s^2 (dominant frequency of 4 Hz) for V1a and 15 m/s^2 (dominant frequency of 30 Hz) for V1b, and a no vibration condition, V2. Participants provided a discomfort rating on a 9 point scale following each mat condition. Vibration was measured at the feet using a tri-axial accelerometer according to ISO 2631-1 (1997) and ISO 5349-1(1986) standards.

During the high frequency vibration condition (V2), all mats provided some attenuation in the z-axis. Mat 2 had the lowest mean discomfort rating for both vibration conditions (V1 and V2) and the greatest attenuation of vibration in the z-axis. No significance was found in participant reported discomfort between mats; however, exposure to the high vibration profile (V2) significantly increased participant reported discomfort. Based on the lab findings, longer duration testing should take place in the field to determine if mats will attenuate vibration and decrease worker discomfort.

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Chapter 3: Leduc, M., Eger, T., Godwin, A., and Dickey, J. EVALUATION OF TRANSIMISSIBILITY PROPERTIES AND COMFORT OF 'ANTI-VIBRATION' MATS USED BY WORKERS EXPOSED TO VIBRATION VIA THE FEET.

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Glossary

Abbreviation	Long Form
A(8)	8-hour energy equivalent vibration total value
ANOVA	analysis of variance
a_{wx}	frequency-weighted r.m.s. acceleration in the x-axis
a_{wy}	frequency-weighted r.m.s. acceleration in the y-axis
a_{wz}	frequency-weighted r.m.s. acceleration in the z-axis
DF	dominant frequency
HAV	hand arm vibration
HAVS	hand arm vibration syndrome
HGCZ	health guidance caution zone
ISO	International Organization for Standardization
M1	Mat 1
M2	Mat 2
M3	Mat 3
M4	Mat 4 (no mat)
MASHA	Mines and Aggregates Safety and Health Association
MEAT	mat effective amplitude transmissibility
NIOSH	National Institute for Occupational Safety and Health
r.m.s.	root-mean-square
SEAT	seat effective amplitude transmissibility
SD	standard deviation
V1	Vibration condition 1 (low vibration, ~3 Hz)
V2	Vibration condition 2 (high vibration, ~30 Hz)
V3	No vibration condition
VATS	vibration analysis tool-set
VDV	vibration dose value
WBV	whole-body vibration
W_d	weighting factor, applied to the x & y axes, as described in IS0 2631-1
W_k	weighting factor, applied to the z-axis, as described in IS0 2631-1

Vibration Terminology and Definitions

An attempt has been made to list and define the vibration vocabulary used throughout this thesis below. However, for a complete listening of common terminology related to mechanical vibration and shock the reader should refer to the 1997, ISO 5805 (Mechanical vibration and shock – Human exposure – vocabulary) document and the 1990, ISO 2041 (Vibration and shock – Vocabulary) document.

***A*(8)** - The 8-hour energy equivalent vibration total value for a worker in meters per second squared (m/s^2), including all whole-body vibration exposures during the day.

Amplification: A signal is said to be amplified if it increases in amplitude and intensity

Attenuation: Attenuation is the reduction in amplitude and intensity of a signal. For example, a vibration signal may be attenuated as it is transmitted through the body.

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.

Damping: The dissipation of energy with time or distance (i.e. the amplitude of the vibration signal decreases).

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. For whole-body vibration, the frequencies thought to be most important range from 0.5-80Hz. However, because the risk of damage is not equal at all frequencies a *frequency-weighting* is used to represent the likelihood of damage from the different frequencies.

ISO 2631-1: The International Standard used to describe the effects of whole body vibration exposure on human health.

Resonance Frequency: The frequency at which resonance occurs. At the resonant frequency of a system, maximal oscillation will occur.

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

Transmissibility: The unit-less ratio of the response amplitude of a system, in steady-state forced vibration, to the excitation amplitude. A value greater than one would indicate the vibration was amplified as it travelled from the input location to the "output" locations whereas a value less than one would indicate attenuation.

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

Vibration: An oscillatory motion about a fixed reference point

VDV: The vibration dose value is a cumulative measure of the vibration and shock received by a person during a specified measurement period. It is given by the fourth root of the integral of the fourth power of the frequency-weighted acceleration.

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 1:
REVIEW OF LITERATURE

1.1 Introduction

It is widely known and accepted that exposure to long-term whole body vibration places workers' health at an increased risk (Fritz, 2000). The majority of the current body of vibration literature has examined whole body vibration while seated although vibration exposure is not only a concern for workers who operate equipment from a seated position. There are many different types of equipment that require workers to perform tasks from a standing position and as a result, the workers are exposed to vibration via the feet (Eger et al., 2006).

Characteristics of vibration, including frequency content and acceleration amplitude, must be known in order to determine potential health effects to the human body. Researchers have yet to classify and characterize the frequency spectrum to which the workers on standing vibration platforms or machinery are being exposed; however, vibration characteristics need to be documented in order to determine the associated health effects on the human body (Cardinale & Rittweger, 2006). Thus, a lack of information in regards to the vibration exposure also leads to questions surrounding the health effects associated with standing vibration. In mining applications, vibration that enters the body via the feet is often initiated with vibration from a hand-tool that has caused a working platform (that a worker is standing on) to vibrate. A range of effects from the vibration are then received through two points of entry to the body. There is the potential for overall whole-body health effects, localized damage within the feet, or a combination of both. Matting products and damping platforms are prevention strategies that are currently being used in industry to attenuate vibration. However, there have yet to be any controlled research studies that have evaluated the effectiveness of such products.

This literature review will seek to provide the reader with an understanding of vibration and the characteristics of vibration that are important when measuring vibration exposure. Vibration exposure sources and levels across occupational fields will be mentioned. The mining industry will be highlighted as it is the focus industry of the current project. Expanding further on the sources of vibration exposure, both whole-body vibration and hand-arm vibration field studies will be examined. Standing vibration and the connection to whole-body vibration and hand-arm vibration will also be examined. More importantly, the health effects as a result of the vibration sources will be explored, and to that end, the current vibration standards and strategies aimed at reducing vibration will be mentioned. Lastly, the objectives of the research project will be outlined.

1.2 Vibration Basics

Vibration is an oscillatory motion about a reference point that is characterized by the frequency, magnitude and duration of exposure (Griffin, 1990). These vibration characteristics need to be understood and documented in order to determine the associated health effects on the body (Cardinale & Rittweger, 2006). However, the exact role of the frequency, magnitude, direction, and duration of the vibration exposure in the causation of documented damage and injury is not known with certainty (Griffin, 1998).

The frequency of vibration refers to the number of cycles per second. When discussing frequency, the resonant frequencies of the object being vibrated must also be examined. The resonant frequency within the body occurs when movement is amplified and maximum displacement occurs between the organs and the skeletal system; thereby, inducing strain on the surrounding structures (Matsumoto & Griffin, 2001; Randall et al., 1997). Different segments within the body have different natural resonant frequencies.

With respect to standing, the resonant frequency of a person peaks between 8-10 hertz (Hz) and again at 20 Hz (Randall et al., 1997; Miwa, 1975). Due to the differences in resonant frequencies across the various regions of the body, and more specifically in the comparison of the hand-arm system and the whole body, vibration exposure will have different effects on different locations within the body. As such, the lumbar region is susceptible to vibration induced back pain and disk degeneration caused by vibration in the frequency range of 4-8 Hz, while the hands are at a greater risk with frequency in the range of 20-25 Hz, and greater than 100 Hz for the fingers (Griffin, 1990; Dong et al., 2004).

Similar to other areas in vibration research, measurements related to the body's resonant frequency have been recorded on seated persons while driving (Randall et al., 1997). Understanding the body's response to vibration while seated is valuable when considering the response of the body to vibration when standing (Matsumoto & Griffin, 2000). According to previous vibration studies in a seated posture, the main resonance occurs between 4-6 Hz, with a secondary resonance zone occurring around 8-10 Hz (Kim et al., 2005). Body weight and posture while sitting (normal or erect) have not resulted in a large effect on altering the body's resonant frequency (Randall et al., 1997). However, muscle tension can result in a higher resonant frequency while tense (Randall et al., 1997). While most regions of the body have had their respective dominant frequencies documented, the resonance frequency of the feet remains unknown.

An understanding of the resonant frequency response is critical to the understanding of health effects; however, it is also important to report the magnitude of vibration exposure (Mansfield, 2005). The magnitude will provide details of the intensity and energy of the vibration exposure and is characterized by its average acceleration (Bovenzi, 2005).

The duration of vibration exposure also needs to be noted when documenting the characteristics of a vibration exposure. Therefore reports of occupational exposure to vibration should include: duration, magnitude and frequency information.

1.3 Epidemiological Evidence

Vibration exposure poses health concerns to workers in a wide variety of industries such as construction, forestry, agriculture, public utilities, and mining (Bovenzi, 2005). In the United States, it is estimated that 7 million workers are exposed to occupational whole body vibration (Wasserman et al., 1997). Further, Palmer and colleagues (2000) surveyed the general population in Great Britain and found that approximately 2% of adults have consulted a physician for Raynaud's phenomenon. One third of males who have consulted with a physician and been diagnosed with Raynaud's phenomenon have developed it as a result of their occupational exposure to hand arm vibration (Palmer et al., 2000).

Vibration research in the past has focused on whole-body vibration and hand-arm vibration, which are distinguishable by their contact points and health effects. Whole-body vibration occurs when the worker is being supported by a surface that is vibrating and the vibration enters the body via the supporting contact point(s) (Bovenzi, 2005). Hand-arm vibration occurs when the worker is using a vibrating tool and the vibration enters the body through the workers hands (Bovenzi, 2005).

1.4 Whole-Body Vibration

Workers exposed to whole-body vibration are at an increased risk for having health problems (Fritz, 2000). The typical health effects seen as a result of whole-body vibration affect a wide range of systems and areas of the body. When the human body is exposed to whole-body vibration, the entire system composed of the skeleton, muscles, and organs, are exposed to the vibration (Cardinale & Pope, 2003). There is often degeneration and deviation of bones and tissues, affecting the normal shape of the vertebral column (Seidel & Heide, 1986). Whole-body vibration is also associated with the increased likelihood of developing low back pain and intervertebral disc disorders (Bovenzi, 2005). In accordance with hand-arm vibration, disorders of the peripheral nervous system are also prevalent (Seidel & Heide, 1986). There is also an increased risk of disorders of the digestive system, female reproductive system, and vestibular system (Abercromby et al., 2007; Seidel & Heide, 1986).

1.5 Hand-Arm Vibration

Hand-arm vibration must also be examined to gain further understanding of the potential health risks for workers exposed to standing vibration. Prolonged exposure to hand-transmitted vibration has been shown to cause debilitating vascular, neurological, and musculoskeletal problems to both the hand and arm (Bovenzi, 1998; Cohen et al., 1995). It has been postulated that workers who are exposed to vibration via the feet could also be at risk for similar health problems (Cooke & Marshall, 2005). Taking a closer look at the mining context may reveal risks to the worker that are an indirect result of hand-tool usage. Hand-tool use is associated with high frequency vibration and prolonged use can cause hand-arm vibration syndrome. In the mining context, workers often perform tasks using these hand-tools while standing on a platform. Frequency characteristics of the vibration exposure may not be altered as the vibration travels from the hand-tool through the standing platform to the worker's feet. It is then reasonable to suspect health effects, typically seen in the hands, could also occur to the toes and feet of workings exposed to the higher frequency vibration generated by the hand-tools.

1.6 Standing Vibration

Vibration exposure via the feet can result in physical discomfort and musculoskeletal injury. However, it is thought that damping properties in the legs would allow for attenuation of ground reaction forces while performing activities of daily living (Fritz, 2000). However, suggested decreases in health risk when exposed to vibration in a standing posture have yet to be corroborated (Fritz, 2000).

Body posture is a strong determinant when calculating both the amount of physical contact with the vibrating surface and the amount of tension found within muscles of the trunk and extremities (Harazin & Grzesik,1998). Changes in posture may affect the damping capabilities of the body which can then result in differences in the transmission characteristics of vibration (Harazin & Grzesik, 1998). Transmissibility studies have examined the differences in vibration exposure while standing compared to a seated posture (Matsumoto & Griffin, 2000). Research has shown that exposure to vibration via the feet while standing leads to peak vertical transmissibility of vibration occurring at a higher frequency than when compared to what is experienced in the seated posture (Matsumoto & Griffin, 2000).

Understanding both whole-body vibration and hand-arm vibration provides insight into studying standing vibration. The vibration that is generated by the same sources, mobile equipment motors or drills, may remain unchanged as it travels into the body through the feet. Since there is minimal research examining the health effects of standing vibration, the health effects of whole-body and hand-arm vibration warn that harmful levels of certain frequencies may cause health effects both locally in the feet and throughout the whole body.

There has been evidence of workers experiencing whole-body health effects as a result of vibration exposure in a standing posture: one of the most common complaints is motion sickness (Cardinale & Rittweger, 2006). Animal models have also pointed to the degeneration of muscle fibres (Necking et al., 1996). Vibration exposure has been shown to cause structural damage in the muscles fibres of animals; thus, leading to impairment in their functional abilities (Curry et al., 2002). A particular interest of the study is the localized health risks in the feet of miners exposed to vibration.

1.7 Vibration and the Feet

Raynaud's phenomenon is caused by a lack of blood flow to the fingers and toes and can be the result of prolonged exposure to vibration. As such, it has become an established disorder amongst vibration exposed hands of miners (Cooke & Marshall, 2005; Hedlund, 1989). It has been documented that there is an association between long term standing whole body vibration and Raynaud's phenomenon in the toes (Hedlund, 1989). In a study conducted by Hedlund (1989), six of the 27 miners displayed Raynaud's phenomenon in their feet after having stood on platforms with attached drills. A case study from Korea also presents the findings of a rock drill operator experiencing Raynaud`s phenomenon of the toes or "vibration-induced white toes" (Choy, 2008).

There is conflicting evidence as to the exact cause of vascular disorders within the feet (Schweigert, 2002). Schweigert (2002) suggests that the vascular changes within the feet are a result of the changes occurring in the hands from vibration exposure to the hand arm system. One model proposes that a centrally mediated sympathetic mechanism causes repeated acute vasoconstriction in the hands and may extend to the feet (Schweigert, 2002). Vibration exposure to one hand has been found to lower skin temperature in all four extremities (Sakakibara, 1994). Chain saw operators with vibration induced white finger were studied by Sakakibara and colleagues (1991), and were found to have lower skin temperatures in their fingers and toes; therefore, suggesting that circulatory disturbances also occur in the lower extremities of individuals with vibration induced white fingers. Furthermore, additional research by Sakakibara (1994), found that chain saw operators presenting with circulatory disturbances within their feet did not have direct vibration exposure at the feet but rather substantial hand arm vibration exposure. These disturbances in the feet were then attributed to the hand-arm vibration transmitted through the sympathetic nervous system (Sakakibara, 1994).

Toibana and colleagues (1994) also studied eleven cases of chain saw operators with Raynaud's phenomenon within the toes. The case studies indicated that both the chain saw operators who had experienced limited direct vibration exposure to the feet and the rock drill operators who received direct vibration exposure to the feet developed Raynaud's phenomenon within the toes (Toibana et al., 1994).

Construction workers exposed to hand-arm vibration with limited exposure to the feet were examined by House and colleagues (2010). The digital plethysmography results revealed that 99.5% of the 191 workers had evidence of at least mild vascular damage in the feet (House et al., 2010). Also, severe vascular changes within the feet were best predicted by the extent of vascular change within the hands (House et al., 2010). Therefore, the results are in accordance with the evidence presented by Schweigert (2002), in suggesting there is a link between vibration induced white fingers from hand arm vibration exposure and the similar effects occurring in the feet that had not previously been directly exposed to vibration.

Studies examining the pathology in the feet as a result of vibration exposure are limited. Hashiguchi and colleagues (1994) investigated the pathological changes in the toes and fingers of individuals with vibration syndrome. Fourteen of 21 individuals had operated rock drills, and the other seven worked with chain saw, grinders, and bush cutters (Hashiguchi et al., 1994). In comparison to the referent, thickening of the medial muscle layer of the small artery and an increase in the number of collagen fibres in connective tissue was observed in the fingers and toes of the individual with vibration syndrome (Hashiguchi et al., 1994). The changes within the toes are displayed in Figure 1. The pathological changes were found in all individuals and not solely amongst the rock drill operators who had direct vibration exposure to the feet (Hashiguchi et al., 1994).

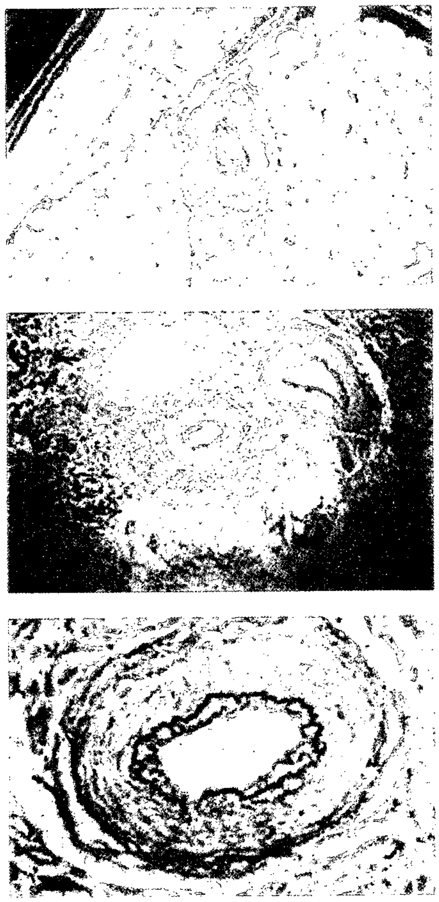

Figure 1.0: Thickening of the medial muscle layer and an increased number of collagen fibers in the toes. Top: referent, 25X; middle, 60 year old individual, 25X; bottom, 60 year old individual, 100X (Hashiguchi et al., 1994).

The neurological effects seen in the upper limbs as a result of hand-arm vibration may be expected to be reproduced in the lower limbs when exposed to similar vibration; however, some studies are still reporting conflicting results (Griffin, 2008; Kerschan-Schindl et al., 2001). Animal models continue to display permanent nerve damage as a result of direct vibration exposure (Chang et al., 1994). Furthermore, animal models continue to indicate that vascular responses as a result of vibration are frequency dependent (Krajnak et al., 2010). The greatest potential for vascular disorders in rats occurs at 250 Hz (Krajnak et al., 2010).

The first case study highlighting vibration-white foot in the absence of symptoms in the hands is documented by Thompson and colleagues (2010). The miner presented in the case report had direct vibration exposure to the feet associated with the operation of underground drills on platforms and bolters for 18 years (Thompson et al., 2010). The worker presented the inverse of symptoms typically seen in workers with hand arm vibration syndrome in that vibration-white foot was diagnosed with no damage to the hands (Thompson et al., 2010). The case report by Thompson (2010) challenges Schweigert's model (2002), which suggests that vascular changes in the feet are a result of the vascular changes in the hands. However, the two models are not mutually exclusive.

1.8 Evaluating Health Effects

The International Organization for Standardization (ISO) provides guidelines for vibration exposure and measurement in *ISO 2631-1: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements.* The guidelines are applicable to situations where the individual is exposed to vibration while in a seated, standing, or recumbent position (ISO, 1997). The ISO 2631-1 provides health guidance caution zones for vibration exposure in Annex B based on duration of vibration exposure. The caution zone for an individual's health for a vibration exposure of four to eight hours lies between 0.45 m/s^2 and 0.9 m/s^2. Any values that are within this zone may result in health risks to the worker. Values that are below this range have not been shown to cause any health effects and values above this zone likely guarantee a detrimental effect on an individual's health.

The International Organization for Standardization provides further guidelines applied solely to the hand-arm vibration exposure; *ISO 5349: Mechanical vibration – Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration* (1986). The standards are in place to protect workers who are exposed to vibration via their hands and arms through the use of tools and machinery. According to the standard, symptoms of hands-transmitted vibration are rare for a vibration total value less than 2 m/s^2.

The lumbar region is susceptible to vibration induced back pain and disk degeneration caused by vibration in the frequency range of 4-8 Hz, while the hands and feet are at a greater risk with frequency in the range of 20-25 Hz (Griffin, 1990). The differences in the frequencies related to health risks are related to the resonant frequency of these structures within the body. As the vibration exposure approaches the resonant frequency ranges of the structures there is an increased risk of damage from the body structures resonating. It can be noted that there is a large difference between the resonant frequency of the hands and feet in comparison to the back and lumbar region (Griffin, 1990). Therefore, ISO 2631-1 whole-body vibration standards, which place the greatest emphasis on lower frequency ranges, may not adequately address the health risks at the feet. Thompson and colleagues (2010), caution that ISO 2631-1 may not provide workers with the necessary protection against health effects localized in the feet. Consequently, it may be more appropriate to determine the health risks associated with vibration exposures at the feet by referring to the guidance in ISO 5349-1, hand-arm vibration standards, and not just ISO 2631-1, whole body vibration standards.

1.9 Transmissibility

The resultant vibration which the worker experiences through their feet while standing on the platform may be amplified in certain frequency ranges; whereas, attenuated in others (van Niekerk et al., 2003). Amplification and attenuation are dependent on the structural resonances occurring in the transmission path of the vibration travelling from the drill through to the platform and to the worker (van Niekerk et al., 2003). The characteristics of the vibration are altered by the transmission path through the structure from the source (drill) to the feet of the worker standing on the platform (van Niekerk et al., 2003). Therefore, matting products are currently being utilized on top of platforms that are vibrating as measures to modify the vibration along the transmission path.

Transmissibility is a non-dimensional ratio of the vibration exposure at two different locations. For example, the transmissibility property of an "anti-vibration" mat is determined by comparing the vibration on the floor surface and the vibration levels measured on top of the mat where the worker would stand.

Past research examining the transmissibility properties of vibration has primarily focused on seats in equipment and vehicles. The methodology adopted for evaluating seat transmissibility is to use the seat effective amplitude transmissibility (SEAT) value (Griffin, 1990). The SEAT value is calculated as a percentage comparing the vibration exposure at the base of the seat to the vibration exposure on the seat surface (Griffin, 1990). A SEAT value greater than 100% indicates that the vibration is amplified and there may be an increase in discomfort. SEAT values less than 100% suggest a reduction in the vibration exposure. The ratio generated to examine the differences at the two locations is termed the Mat Effective Amplitude Transmissibility (M.E.A.T) value (Boileau and Rakheja, 1990). A M.E.A.T value less than 100% indicates an decrease in vibration above the mat; thus, decreasing the potential for adverse health effects. A M.E.A.T value greater than 100% indicate the mat is amplifying the vibration and the worker is at a greater risk for health effects.

1.10 Anti-vibration Mats

Currently, 'anti-vibration' mats are a method used in industry to decrease the risk of health effects related to vibration. The transmissibility properties of the mats are of equal importance as the structural resonance of the platform the mats are placed on. The mats must be specifically designed for the frequency spectrum of the vibration exposure for the unique situation in order to prevent amplification. Anti-vibration gloves had a similar problem as initial glove models amplified the vibration entering the hand at the frequencies associated with localized health effects to the hand-arm system (Mansfield, 2005).

There have been no controlled experiments to evaluate the discomfort or transmissibility of mats used as personal protective equipment to attenuate vibration. However, seats have been researched in great length when discussing transmissibility of vibration from a piece of equipment or vehicle to an operator. In examining seat research, the density and firmness properties of the foam emerge as two of the commonly researched entities as they affect subjective measures of comfort, accommodation for different anthropometric characteristics, and the durability (Kolich et al., 2005). High density (1378 g) and high firmness (164 N at 25% compression) were found to produce the optimal condition for driving (Kolich et al., 2005). It is important that the seat have a natural resonant frequency that does not overlap with the resonant frequency of the platform or vehicle and provides adequate attenuation in the frequency range that is associated with health effects and discomfort (Kolich et al., 2005). The dynamic ability of anti-vibration gloves to attenuate vibration is dependent upon the frequency of the vibration exposure (Griffin, 1998). In addition, within anti-vibration glove research, the effects of wear and tear through the usage of the product may influence the amount of transmissibility; however, the decrease in performance has yet to be examined (Hewitt, 1998).

Mats need to be tested under controlled conditions similar to the requirements for gloves that were required for them to receive the designation of being an 'anti-vibration glove'. However, research is still lacking as frequency information is not provided for the anti-vibration gloves to determine suitable application and protection (Hewitt, 1998).

However, anti-vibration glove testing has revealed that the comparison of field and laboratory results did not produce the same ranking of gloves (Pinto et al., 2001). Further testing of the effectiveness of the mats to attenuate vibration should be carried out in an applied context; namely, that of an underground mine. Workers may be at a greater risk utilizing the mats if the mat is amplifying the vibration levels and increasing the likelihood of health effects similar to previous documentation within the hand-arm vibration and anti-vibration glove literature (Mansfield, 2005).

1.11 Discomfort

The physical comfort of workers is a basic ergonomic requirement in the workplace (Sherwin et al., 2004). However, as previously defined in seat discomfort studies, the subjective rating is defined as 'discomfort' as opposed to 'comfort', due to the nature of the vibration exposure contributing to a participants discomfort rather than comfort (Ebe & Griffin, 2000). Research regarding seat discomfort and vibration has suggested that overall seat discomfort is influenced by both static factors of the seat (stiffness) and dynamic factors (magnitude of vibration exposure) (Ebe & Griffin, 2000). Sensitivity to vibration exposure is a function of both the frequency and direction of the vibration (van Niekerk et al., 2003). Previous seat research has demonstrated that during vibration exposure there is a correlation between the objective vibration measurements collected and the subjective participant evaluation of the exposure as 60% of the seat choices selected by participants were correlated with the standards set in ISO 2631 (van Nierkerk et al., 2003). The combination of SEAT values and subjective discomfort ratings has been used in research to determine the seat with the lowest percent of transmissibility with the intention that the seat will receive the lowest discomfort rating (van Nierkerk et al., 2003).

Previous research has demonstrated that during vibration exposure there is a correlation between the objective vibration measurements collected and the subjective participant evaluation of the exposure (van Nierkerk et al., 2003). A previous study examining seat discomfort concluded that 60% of the seat choices selected by the participants are correlated with the standards set by in ISO 2631 (van Nierkerk et al., 2003). Also, females consistently rate vibration exposure discomfort as more severe than males (Dickey et al., 2006). Furthermore, specific subsets of participants may respond differently to vibration exposure; for example, physically fit individuals that had off-road driving experience reported lower discomfort scores when compared with other participants (Dickey et al., 2006).

1.12 Strategies to Reduce Vibration

As a result of the discomfort and health problems arising from standing vibration, mining companies and workers have started to use "anti-vibration" mats and insoles in an effort to reduce harmful vibration levels. As previously outlined, the workers may be at a greater risk utilizing the mats if the mat is amplifying the vibration levels and increasing the likelihood of health effects. Therefore, it is important to document the vibration spectrum of the pieces of mobile equipment and tools that are exposing workers to vibration in a standing posture. The characteristics of the matting products must also be known to provide a specific mat for the various situations in order to avoid amplifying the vibration and putting the workers health at a greater risk. Modifications may also be made to the equipment to either decrease the amount of vibration produced or provide dampening along the transmission path.

Within the field environment, the vibration may change as a result of the varying rock and terrain, road maintenance, as well as, equipment factors (drill or mobile equipment) (Sherwin et al., 2004). Therefore, studying human responses to vibration in a laboratory setting is essential for evaluating the response in a controlled environment (Dickey et al., 2006).

1.13 Thesis Outline

The purpose of the project was to learn more about the characteristics of vibration entering the feet in order to identify potential injury risks and the efficacy of interventions such as "anti-vibration mats" for attenuating potentially harmful vibrations.

1. Chapter 1 – Literature Review: The purpose of the chapter is to provide background knowledge on relevant vibration concepts and terms. Furthermore an attempt

was made to showcase previous research that has been conducted within the field; thereby, indicating the justification for the current research project.

2. Chapter 2 – Manuscript I: The objectives of the study were as follows: (1) to measure and document both the acceleration characteristics (x, y, z) and dominant frequency of vibration that enter the body via the feet under typical mining working conditions; (2) to determine if the vibration is above health guidance caution zone limits (ISO 2631); (3) to determine differences in operator musculoskeletal discomfort between primary and secondary source machine exposure.

3. Chapter 3 – Manuscript II: The objectives of the study were 1) to determine the transmissibility properties (MEAT) of three mats currently used within the mining industry; 2) to determine if the mats alter predicted injury risk according to ISO 2631-1 and ISO 5349-1 guidelines; 3) to determine if participants discomfort differs between mats.

4. Chapter 4 – General Discussion: The findings of Chapters Two and Three are summarized and linked. The relevance is discussed with respect to the workers, the mining industry, and mat manufacturers.

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CHAPTER 2:

EXAMINATION OF VIBRATION CHARACTERISTICS, AND REPORTED MUSCULOSKELETAL DISCOMFORT FOR WORKERS EXPOSED TO VIBRATION VIA THE FEET

Miners are exposed to vibration at the feet when driving locomotives and standing on vibration drilling platforms. Previous studies suggest these workers are reporting pain, discomfort and blanching in the toes more often than their co-workers who are not exposed to vibration via the feet. The purpose of this study was to document the frequency and amplitude characteristics of vibration experienced at the feet under typical mining equipment operation. Health guidance caution zone limits, as reported in ISO 2631-1 (ISO, 1997), were used to determine the potential health risk to the workers as a result of the vibration.

Two categories of underground mining equipment, primary (locomotives) and secondary (jumbo drill, bolter, wood and metal raise platforms), were distinguished by the origin of the source vibration. The vibration exposure from the primary sources occurred as a result of the moving vehicle. Secondary sources had a drill attached or supported on the surface of the platform which caused the vibration. Measurements were collected using a tri-axial accelerometer mounted according to the ISO 2631-1 standard, at the location where the worker stood to complete the required job task (ISO, 1997). Musculoskeletal and vascular disorder history, work history and demographic information were also collected from the participating workers.

Vibration resulting from a primary source exposure had a dominant frequency below 6.3 Hz. However, the dominant frequency recorded from secondary source exposures were predominantly in the 31.5 to 40 Hz range. All workers reported discomfort in their lower limbs. Drilling off the wooden raise platform and the metal raise platform exposed the workers to vibration levels at the feet that placed them above the ISO 2631-1 health guidance caution zone, when the 8-hour frequency-weighted RMS acceleration exposure levels were considered (ISO, 1997). Workers standing on the jumbo drill and raise platforms experienced dominant frequency vibration known to be associated with hand-arm vibration syndrome. The jumbo drill operator and a raise miner reported they had been diagnosed with white feet. The dominant frequency recorded at the feet of the locomotive operators was in the range associated with resonance of the spine and pelvis. Further investigation is warranted using both ISO 2631-1 and ISO 5341-1 standards to determine long-term health effects resulting from vibration exposure via the feet.

Key words: standing vibration, mining, health risk, white-feet, Raynaud's phenomenon, ISO-2631-1

2.1 Introduction

Workers in construction, forestry, agriculture, and mining industries are often exposed to vibration levels associated with negative health outcomes (Bovenzi, 2005; Eger et al., 2006). Detrimental health effects related to whole body vibration have been documented to include the cardiovascular, muscular, cardiopulmonary, metabolic, endocrine, nervous, and gastrointestinal systems (Thalheimer, 1996). In addition, prolonged exposure to hand-transmitted vibration has been shown to cause vascular, neurological, and musculoskeletal problems to the upper limb (Bovenzi, 1998; Cohen et al., 1995). Workers exposed to vibration through the feet could also be at risk of vascular and neurological problems of the toes and feet similar to those in the hand-arm from hand-arm vibration (Cooke & Marshall, 2005). Limited research has examined the characteristics of vibration that enters the body via the feet and even less is understood about the potential health effects resulting from occupational sources of vibration exposure at the feet.

The resonant frequency within the body occurs when movement is amplified and maximum displacement occurs between the organs and the skeletal system, thereby inducing strain on the surrounding structures (Matsumoto & Griffin, 2001; Randall et al., 1997). Health effects are more likely to occur if the vibration exposure is in the resonance frequency range for a particular body region. Due to the differences in resonant frequencies in the various regions of the body, and more specifically in the comparison of the hand-arm system and the whole body, vibration exposure will affect specific locations within the body differently. The resonant frequency of a standing person has been suggested to be between 8-10 Hz, with a second resonance peak at 20 Hz (Randall et al., 1997; Miwa, 1975). The lumbar region is susceptible to vibration induced back pain and disk degeneration caused by vibration in the frequency range of 4-8 Hz. In contrast, the hand-arm system as a whole is at a greater risk in the frequency range of 20-40 Hz, and the fingers are at greater risk at frequencies above 100 Hz (Griffin, 1990; Dong et al., 2004). When exposed to higher frequency vibration believed to be linked to HAV injury in humans, structural damage has been documented to occur within the muscle fibres of animals (Necking et al., 1996; Curry et al., 2002). Vascular responses to vibration of the tail in rats have been shown to be frequency depended, with the greatest risk of injury at 250 Hz (Krajnak et al., 2010). If miners experience localized damage to their feet from direct vibration exposure, it is likely that this would occur when the dominant frequency of vibration exposure is within the higher frequency range (i.e. similar to the frequency specificity of hand-arm vibration syndrome).

The determination of effects in the feet due to direct vibration exposure is complicated by the fact that HAVS due to hand-arm vibration may also be associated with effects in the feet (Schweigert, 2002). The hypothesized mechanism is a generalized activation of the sympathetic nervous system. Mining equipment often exposes workers through two contact entry points, their hands and feet. In a study conducted by Hedlund (1989), six of 27 miners displayed Raynaud's phenomenon in their feet after having stood on platforms with attached drills. A case study from Korea also presents the findings of a rock drill operator experiencing Raynaud`s phenomenon of the toes or "vibration-induced white toes" (Choy, 2008). The studies described by Hedlund (1989) and Choy (2008) both involved a mixture of hand and foot vibration exposure. However, a case report on "vibration-white foot" by Thompson and colleagues (2010) depicts a miner with vibration induced white feet. Thompson and colleagues (2010) describes the first case report in the

English literature in which the findings of vascular effects in the feet appear to be independent of the vascular effects in the hands.

The International Organization for Standardization (ISO) provides guidelines for vibration exposure and measurement in *ISO 2631-1: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements* (1997). The guidelines are applicable to situations where the individual is exposed to vibration while in a seated, standing, or recumbent position (ISO, 1997).

In underground mining, vibration that enters the body via the feet is often initiated by a drill that has caused a working platform (that a worker is standing on) to vibrate. Varied effects of vibration are then received through two points of entry to the body, hands (via the drill) and feet (via the platform). Researchers have yet to classify and characterize the frequency spectrum for the platforms that are vibrating in the mining industry. Preliminary case studies, as well as the health effects experienced as a result of whole-body and hand-arm vibration, warn of certain frequencies possibly causing health effects both locally in the feet and throughout the whole body (Hedlund, 1989; Thompson et al., 2010). Therefore, the primary objective of the current study was to measure and document the dominant frequency and acceleration magnitude of vibration entering the feet through the vibrating platforms. The secondary objective was to examine potential health risks based on guidance provided in ISO 2631-1 and the third objective was to determine differences in operator musculoskeletal discomfort between primary and secondary source machine operation.

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, Test Location and Equipment Selection

Seven male workers from four mines in Northern Ontario were recruited from a sample of convenience. The workers had a mean age of 36 years, a mean height of 177 cm and mean weight of 91 kg. The equipment operator's demographic information is presented in Table 1. Equipment that was primarily operated from a standing position, resulting in vibration exposure at the workers' feet, was selected for testing. Consequently, five different types of equipment were selected for testing. Tested equipment was classified as a "primary vibration source" if the vibration measured at the worker's feet was generated from an engine required to move the vehicle (locomotive, n=2). Tested equipment was classified as "secondary vibration source" if the vibration measured at the worker's feet originated from a drill or other tool attached to or resting on the surface a worker stood on; jumbo drill (n=1); metal raise platform (n=2); wood raise platform (n=1); and bolter (n=1). Vibration exposure measurements were collected under typical working conditions. Two testing conditions were performed on the metal raise platform. A typical drill and an "anti-vibration" drill were utilized during the data collection and were separated into two trials for comparison: metal raise 1 was the typical drill and metal raise 2 was the "anti-vibration" drill.

Table 1: Participant Work History and Demographic Information

Machine Operated	Age	Height (cm)	Weight (kg)	Equipment Regularly Operated	Years of Operation	Estimated Daily Exposure (hours)
Locomotive 1	20	175	73	Locomotive, rockbreaker	2	6
Locomotive 2	51	170	116	Locomotive, scoops, forklifts	33	10
Jumbo Drill	52	170	83	Jackleg, stoper, scoops, jumbo drill, scissor lift	32	2-3 Jumbo Drill, 2-3 Jackleg/Stoper
Wooden Raise	41	183	88	Stoper, jackleg, tugger, slusher	22	4-7
Metal Raise 1*	25	183	104	Jackleg, stopper, alimak	7	8
Metal Raise 2*	27	178	84	Alimak, stopper, jackleg, jumbo drill, plugger	9	8

*Metal Raise 1 and Metal Raise 2 were recorded on the same platform with both equipment operators present.

2.2.2 Testing Conditions

All equipment was measured under typical mining operating conditions. The testing conditions for each piece of equipment are further described in Table 2. The vibration exposure measured for the Jumbo Drill was conducted with only a single boom in operation. The wooden raise was measured with two drills in operation. Metal raise 1 had one typical drill in operation. The metal raise 2 measurement was collected on the same platform as metal raise 1, but the worker was utilizing an "anti-vibration" drill to perform the job task. The bolter measurement was taken on a newly engineered dampened platform where the worker stands to operate the controls. The platform was designed as an intervention strategy to reduce the vibration exposure. A typical older model also currently found within mines would not have the dampened platform.

2.2.3 Data Collection

Prior to all vibration measurements participating workers were asked to answer questions regarding their work history and musculoskeletal symptoms (pain, aches, discomfort) including severity (1 = mild; 4= very, very severe) in the last 6-months.

Table 1 highlights the equipment operators' work history as well as their daily and lifetime exposure to vibration. The equipment operators had an average of 17 years of operation and estimated their daily vibration exposure to be between 4-8 hours for all equipment. The bolter measurements were collected at an underground mine training facility and as a result no demographic or work history information was collected from the operator.

2.2.4 Vibration Measurement at the Feet

Two Series 2 10G triaxial accelerometers (NexGen Ergonomics, Montreal, QC, CND) were used to collect all vibration measurements in accordance with ISO 2631-1 standards (ISO, 1997). One of two methods was used to secure the accelerometers to the floor surface as close as possible to the location where the worker was required to stand to operate the equipment. If the floor surface was metal, an accelerometer was secured to the floor with a magnet. If the magnet could not be used to fix the accelerometer to the floor, the accelerometer was secured inside a rubber pad (seat pad as described in ISO 2631-1) and the rubber pad was taped to the floor surface and the participating worker was asked to stand on the edge of the flat rubber pad. All vibration measurements recorded by the accelerometers were stored onto a portable datalogger, DataLOG II P3X8 (Biometrics, Gwent, UK). The measurements were collected with a sampling frequency of 500 Hz, which is typically used for whole-body measurements.

The duration of each trial was dependent upon the type of equipment being tested and the duration of a typical operating cycle. However, vibration data were typically collected for approximately 10 – 60 minutes for each worker in order to ensure a representative sample for each working condition. A complete description of testing conditions and duration of measurement is provided in the results section in Table 2.

Table 2: Testing Conditions Description

Machine	Vibration Source	Condition	Duration (minutes)
Locomotive 1	Primary	3 cars	90
Locomotive 2	Primary	10 cars	78
Jumbo Drill	Secondary	1 boom	68
Wooden Raise	Secondary	2 Drills	15
Metal Raise 1	Secondary	1 Drill	17
Metal Raise 2	Secondary	Anti-vibration Drill	18
Bolter	Secondary	Dampened Platform – 1 ½ minute split sets	10

2.2.5 Data Analysis

Vibration data measured in the field was processed with Vibration Analysis Toolkit v 3.4.3 (NexGen Ergonomics, Montreal, QC, CND). The International Organization for Standardization (ISO) provides guidelines for vibration exposure and measurement in ISO 2631-1 (ISO, 1997). The guidelines apply to situations where an individual is exposed to vibration while in a seated, standing, or recumbent posture (ISO 2631-1). The vibration magnitude is reported as a frequency weighted root-mean-square acceleration (aw_x, aw_y, aw_z) which accounts for frequencies known to be associated with detrimental health effects. The ISO 2631-1 provides health guidance caution zones for an eight hour vibration exposure time period. The health caution zone (HGCZ) lies between 0.45 m/s^2 and 0.9 m/s^2. If the acceleration value in the dominant axis is below 0.45 m/s^2, health effects due to the vibration exposure are unlikely. Values within the health guidance caution zone suggest that a worker's health may be at risk and injury may occur. Furthermore, values exceeding 0.9 m/s^2 suggest that the vibration exposure is more likely to result in a detrimental effect to the worker's health. Therefore, measured vibration exposure at the feet was compared to the ISO 2631-1 HGCZ in order to determine potential injury risk.

2.3 Results

2.3.1 Standing Vibration Characteristics

The standing vibration descriptive characteristics are displayed in Table 3. The z-axis was the dominant axis, associated with the highest levels of acceleration, for all equipment. The bolter had the lowest average frequency-weighted RMS acceleration, 0.11 m/s^2 in the z-axis, compared to all other equipment. The wooden raise and metal raise-1 had the highest average frequency-weighted RMS accelerations (1.13 m/s^2 and 1.08 m/s^2). The two primary sources, the locomotives, exposed workers to similar levels of vibration, 0.43 m/s^2 and 0.36 m/s^2.

Vibration exposure resulting from a primary source had a dominant frequency below 6.3 Hz (Figure 1.0). In contrast, the dominant frequency recorded from secondary source exposures were predominantly in the 31.5 to 40 Hz range. The bolter was an exception among secondary sources, the bolter and had a measured dominant frequency of 5 Hz.

Table 3: Standing Vibration Characteristics

Machine	Vibration Source	Frequency-weighted RMS acceleration (m/s²)			Peak (m/s²)			Crest Factors			Dominant Frequency (Hz)		
		aw_x	aw_y	aw_z	X	Y	Z	X	Y	Z	X	Y	Z
Locomotive 1	Primary	0.20	0.20	0.43	4.4	4.41	11.03	21.75	22.46	25.93	2	1.6	6.3
Locomotive 2	Primary	0.18	0.24	0.36	2.53	7.65	11.39	14.02	32.25	32.04	1	1	3.15
Jumbo Drill	Secondary	0.04	0.03	0.16	1.15	1.06	2.34	31.13	30.41	14.98	1	1	31.5
Wooden Raise	Secondary	0.25	0.21	1.13	3.57	3.47	15.42	14.28	16.61	13.62	1	1	40
Metal Raise 1	Secondary	0.06	0.05	1.08	1.13	0.76	10.37	18.90	14.55	9.58	1	1	40
Metal Raise 2	Secondary	0.08	0.05	0.80	3.12	2.07	8.61	40.39	37.74	10.72	1	1	40
Bolter	Secondary	0.05	0.04	0.11	1.10	0.71	4.22	21.39	19.32	38.62	1	1	5

2.3.2 Predicted Health Risk

The A (8) values and the corresponding health risk evaluation according to the ISO 2631-1 HGCZ for the primary and secondary sources are shown in Table 4 and Figure 1.0. Two of the secondary sources, the wooden raise platform and the metal raise platform 1, exposed the workers to vibration levels at the feet that were above the health guidance caution zone, 1.13 m/s^2 and 1.08 m/s^2, respectively, when the 8-hour frequency-weighted RMS acceleration exposure levels were considered (ISO, 1997). Metal raise platform 2, under operation of the "anti-vibration" drill, produced vibration levels that were within the HGCZ, with a value of 0.8 m/s^2. The jumbo drill and the bolter were below the HGCZ. Further, the two primary sources were also below the HGCZ.

2.3.3 Musculoskeletal Discomforts and Injuries

The results from the Mining Equipment Operator Musculoskeletal Disorder Questionnaire are displayed in Figure 2.0. Two workers, the jumbo drill operator and the wooden raise miner, indicated a diagnosis of vibration white feet in conjunction with vibration white hands. All other equipment operators reported discomfort in their lower limbs. One primary source operator reported a unique concern, mild discomfort or pain in his neck and also reported lower limb discomfort.

Table 4: Operator Predicted Health Risk according to ISO 2631-1 Health Guidance Caution Zone for the estimated 8 hr frequency-weighted RMS acceleration.

Machine	Vibration Source	Dominant Frequency (Hz)	A(8) (m/s^2)	ISO 2631-1 HGCZ
Locomotive 1	Primary	6.3	0.43	Below HGCZ
Locomotive 2	Primary	3.15	0.36	Below HGCZ
Jumbo Drill	Secondary	31.5	0.16	Below HGCZ
Wooden Raise	Secondary	40	1.13	Above HGCZ
Metal Raise 1	Secondary	40	1.08	Above HGCZ
Metal Raise 2	Secondary	40	0.80	Within HGCZ
Bolter	Secondary	5	0.11	Below HGCZ

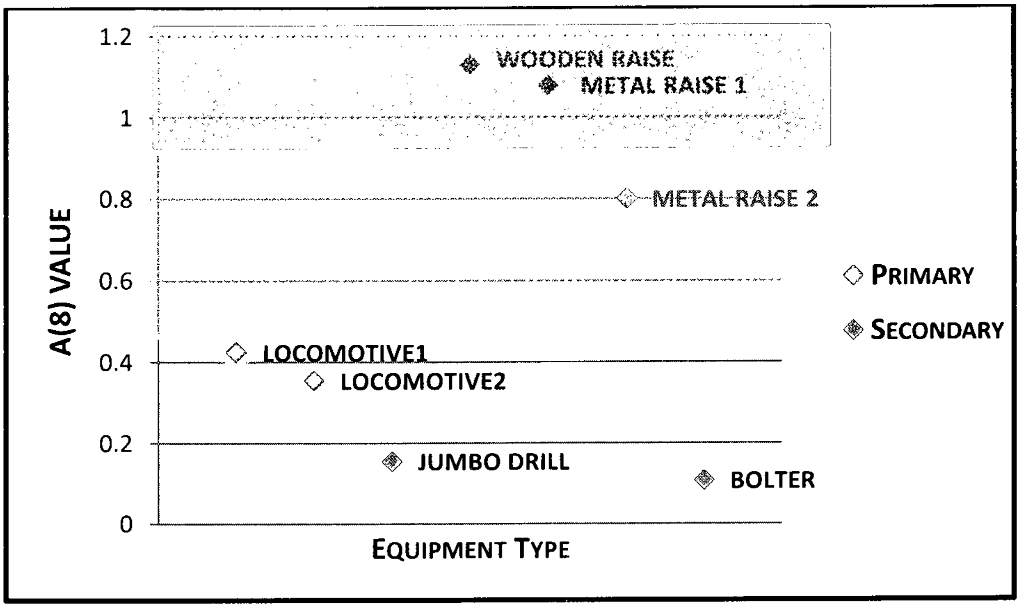

Figure 1.0: Predicted Health Risk according to the Health Guidance Caution Zone (ISO, 1997). No shading: Below 0.45 m/s^2 – health effects are unlikely. Yellow shading: 0.45 m/s^2 to 0.9 m/s^2 – HGCZ, health effects are possible. Red shading: Above 0.9 m/s^2 – health effects are likely.

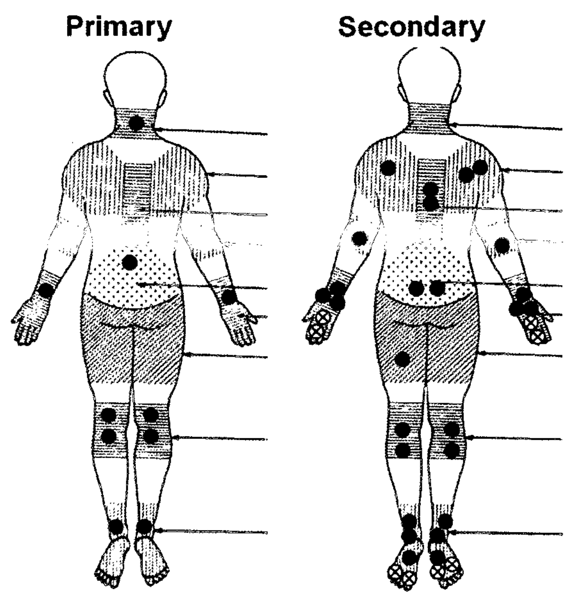

Figure 2.0: Mining Equipment Operator Musculoskeletal Disorder Questionnaire Results *Circles represent pain, ache, or discomfort in the area. Circles with an X represent a diagnosis of white hands or feet. Pain reports are grouped and include reports from 2 primary source operators and 4 secondary source operators.

2.4 Discussion

The primary objective of the study was to measure and document the dominant frequency and acceleration magnitude of vibration entering the feet. The main findings highlight the differences found in the vibration characteristics between primary (0.36 m/s^2 and 0.43 m/s^2, 3-6 Hz) and secondary sources (0.16 m/s^2 – 1.13 m/s^2, 5-40 Hz). There is a large difference in the dominant frequency produced by the two sources. Previous literature indicates the importance of dominant frequency and the impact on health if the dominant frequency is within the range of the resonant frequency of the body (Griffin, 1990; Dong et al., 2004).

Secondarily, the HGCZ was used to determine potential health risks (ISO, 1997). In addition, the differences in musculoskeletal discomfort were documented. It is suggested that the differences documented in vibration characteristics between primary and secondary sources influenced the likelihood of injury, based on ISO 2631-1, and the reported worker musculoskeletal discomfort. The two primary sources (locomotives) are below the HGCZ limits associated with eight hours of exposure. However, the two locomotives produced lower than previously reported vibration levels, which had previously placed them within the HGCZ (Eger et al., 2006). All three raise conditions (secondary sources) were within or above the HGCZ.

Despite the lower magnitudes of the vibration exposure, the dominant frequency recorded at the feet of the locomotive operators was in the range associated with detrimental "whole-body" health effects. The common finding of reported back pain or discomfort is in accordance with the increased susceptibility of the lumbar region to damage following vibration exposures in the frequency range of 4-8 Hz (Seidel & Heide, 1986; Griffin, 1990; Bovenzi, 2005). The unique reporting of pain or discomfort in the neck by the locomotive operator may suggest that with a larger sample, detrimental health effects may be reported throughout the worker's entire body.

The wooden raise miners experienced the highest levels of vibration and were above the HGCZ when the average frequency-weighted RMS acceleration levels for eight hours were considered. The standard, ISO 2631-1 (1997) suggests that workers would be likely to experience health effects as a result of the vibration exposure. The metal raise platform 1 also exposed workers to vibration levels that are above the HGCZ. When the "anti-vibration" drill was in operation on metal raise 2, the vibration exposure was decreased but remained within the HGCZ. A cautious is warranted, as health risks may still be present for workers exposed to vibration levels within the HGCZ (ISO, 1997).

The jumbo drill exposure level in the z-axis is comparable to the exposure values documented by Eger and colleagues (2006), who also reported that the jumbo drill is below the HGCZ for an eight hour exposure. However, workers standing on the jumbo drill and raise platforms experienced a dominant frequency of 40 Hz which is associated with hand-arm vibration syndrome (Griffin, 1990). Likewise, the exposure to the feet documented by Hedlund (1989), in which six of the 27 miners had Raynaud's phenomenon in their feet and 11 had typical symptoms in their hands, had a dominant frequency of 40 Hz. As a result of the dominant frequency of the vibration exposure likely corresponding with a potential resonant frequency in the feet, the health effects within the feet of these workers were exacerbated. The jumbo drill operator and one of the raise workers in this study described their diagnosis of white feet. The miner diagnosed with vibration induced white feet in the case study presented by Thompson and colleagues (2010) used similar drills while drilling off scissor lifts and operated a roof bolter for 18 years.

In comparison with other secondary sources, the bolter was found to have a lower dominant frequency. The bolter measurement was performed on a dampened platform engineered to attenuate vibration as it travels through the platform to the worker. Amplification and attenuation are dependent on the structural resonances occurring in the transmission path of the vibration between the drill and the worker (van Niekerk et al., 2003). The characteristics of the vibration are altered by the transmission path through the structure from the source (drill) to the feet of the worker standing on the platform (van Niekerk et al., 2003). As a result, the dampened platform was engineered to attenuate the vibration in the location where the worker stands. Based on the results in this study, the modified platform had lower vibration acceleration levels compared to previous reports in the literature; however, mines typically have older models of the bolter which do not include the dampened platform (Eger et al., 2006).

This study represents the first attempt to document vibration characteristics for workers exposed to standing vibration; however, limitations need to be considered given the small sample size and lack of multiple pieces of equipment for comparison within each type of equipment. Furthermore, the underground environment and conditions were also unable to be controlled during the testing of the equipment as all measurements were conducted while the workers performed their normal work requirements. In addition, the jumbo drill more consistently drills with two booms operating simultaneously as opposed to the single boom operation condition measured within the study. Likewise, there is typically more than one drill operating while multiple workers perform their job tasks on a metal raise. Further testing is needed to increase the number of pieces of equipment tested to allow for a broader comparison amongst the equipment's resulting vibration exposure and the corresponding worker's health effects. More specifically, vibration measurements from a larger sample of secondary source equipment should be collected to further our understanding of the relationship between higher frequency vibration exposure at the feet and resulting health effects to the feet and lower limbs.

Furthermore, it can be noted that there is a large difference between the resonant frequency of the hands and feet in comparison to the back and lumbar region (Griffin, 1990). Therefore, ISO 2631-1 whole-body vibration standards, which place the greatest emphasis on lower frequency ranges, may not adequately address the health risks at the feet. Consequently, it may be more appropriate to determine the health risks associated with vibration exposures at the feet by referring to the guidance in ISO 5349-1 and not solely on ISO 2631-1. Future measurements should include both methods of data collection and analysis in order to predict the likelihood of health risk more specifically to the worker's feet and toes. In the vibration-white foot case study, Thompson and colleagues (2010), also suggest that ISO 2631-1 may not be providing workers with the necessary protection against foot specific health effects. Further investigation using both ISO 2631-1 and ISO 5349-1 is warranted to determine long-term health effects resulting from vibration exposure via the feet.

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Chapter 3:

EVALUATION OF TRANSIMISSIBILITY PROPERTIES AND COMFORT OF 'ANTI-VIBRATION' MATS USED BY WORKERS EXPOSED TO VIBRATION VIA THE FEET

Field studies have shown miners are exposed to vibration levels at the feet that are within and above the ISO 2631-1 health guidance caution zone for an 8 hour shift (Leduc, 2011; ISO, 1997). The use of mats to attenuate vibration at the feet has been suggested as a possible intervention. However, controlled studies have yet to evaluate the effectiveness of mats in attenuating vibration. Therefore, the purpose of the study was to evaluate the transmissibility properties and comfort of 'anti-vibration' mats.

Ten participants experienced four mat conditions and three vibration conditions. Three commercially available mats were randomly evaluated while participants experienced vibration generated by vibrating platforms at the feet with a dominant frequency of 3 Hz and 30 Hz. Discomfort ratings on a 9 point scale were recorded following each mat condition. Vibration was measured at the feet using a tri-axial accelerometer according to ISO 2631-1 (1997) and ISO 5349-1(1986). During the high frequency vibration condition, all mats provided some attenuation in the z-axis. Participants standing on Mat 2 reported the lowest mean discomfort rating under both vibration conditions and Mat 2 had the greatest attenuation of vibration in the z-axis. There was no statistical significance in participant reported discomfort between mats; however, all participants reported the greatest discomfort under the high frequency exposure.

Key words: anti-vibration mats, standing vibration; mat transmissibility; comfort

3.1 Introduction

Miners are exposed to vibration through their hands and feet while operating locomotives and drilling off stationary platforms which may result in increased risk for whole-body health effects (Eger et al., 2006). Whole-body vibration exposure experienced by workers may negatively affect the cardiovascular, muscular, cardiopulmonary, metabolic, endocrine, nervous, and gastrointestinal systems (Thalheimer, 1996). Furthermore, the dominant frequency experienced by miners, between 3-6 Hz while operating locomotives is the same as the resonance of the pelvis and spine (Griffin, 1990).

Several case studies have reported localized health effects at the feet which may occur as a result of vibration entering the feet while performing typical mining tasks (Thompson et al., 2010; Hedlund, 1989). Moreover, several researchers have suggested that workers exposed to vibration via the feet are at risk for similar vascular and neurological problems to the toes and feet as is often the case documented in the hands and fingers of workers exposed to hand-transmitted vibration (Cooke & Marshall, 2005). Health effects presenting within the mining industry are congruent with vibration measurements collected in a field study conducted by Leduc and colleagues (Leduc, 2011). Miners drilling from stationary platforms were exposed to vibration levels at the feet that were above the ISO 2631-1 health guidance caution zone for an 8 hour shift (Leduc, 2011; ISO, 1997). In addition, the dominant frequency experienced while drilling, 40 Hz, is known to be associated with hand-arm vibration syndrome (Leduc, 2011). As a result of case studies suggesting localized effects on the feet, Mansfield

(2005) suggests that it may be more appropriate to evaluate the vibration exposure at the feet using hand-arm vibration standards. In agreement, Thompson and colleagues (2010) suggest that ISO 2631-1 is not providing workers with adequate protection against localized health effects to the feet.

Mats are currently being used as an intervention strategy to reduce the vibration entering the feet of workers. Vibration a worker experiences through their feet while standing may be amplified in certain frequency ranges and attenuated in others (van Niekerk et al., 2003). In relation to drilling platforms, amplification and attenuation are dependent on the structural resonances occurring in the path of the vibration travelling from the drill through the platform and to the worker (van Niekerk et al., 2003). In the case of mining, vibration characteristics are altered by the transmission path through the structure from the source (drill) to the feet of the worker standing on the platform (van Niekerk et al., 2003). Some "anti-vibration" gloves can significantly attenuate vibrations in the frequency spectrum ranging from 100-1600 Hz (Griffin, 1998). However, other gloves amplify vibration in the harmful frequency range transmitted to the hand-arm system (Mansfield, 2005). As a result, the mats currently being utilized within the mining industry must be evaluated to determine if they attenuate or amplify vibration in the frequency range associated with vibration exposure in underground mining. Workers may be at a greater injury risk utilizing the mats if the mat is amplifying the vibration levels as was the case when some gloves were found to amply vibration at the hand (Mansfield, 2005).

The physical comfort of workers is a basic ergonomic requirement in the workplace (Sherwin et al., 2004). However, as previously defined in seat discomfort studies, the subjective rating is defined as ‘discomfort’ as opposed to ‘comfort’, due to the nature of the vibration exposure contributing to a participants discomfort rather than comfort (Ebe & Griffin, 2000). Research regarding seat discomfort and vibration has suggested that overall seat discomfort is influenced by both static factors of the seat (stiffness) and dynamic factors (magnitude of vibration exposure) (Ebe & Griffin, 2000). Previous seat research has demonstrated that there is a correlation between the objective vibration measurements collected and the subjective participant evaluation of the exposure as 60% of the seat choices selected by participants were correlated with the standards set in ISO 2631 (van Nierkerk et al., 2003). The combination of SEAT values and subjective discomfort ratings has been used in research to determine the seat with the lowest percent of transmissibility with the intention that the seat will receive the lowest discomfort rating (van Nierkerk et al., 2003).

Matting products are currently being implemented within the mining industry as a measure to attenuate the vibration along the transmission path and decrease the associated health effects related to vibration. However, there have yet to be any controlled studies that demonstrate the effectiveness of mats for vibration attenuation. Therefore, the three primary objectives of the project were 1) to determine the transmissibility properties (MEAT) of several commercially available mats, 2) to determine if the mats alter predicted injury risk according to ISO 2631-1 and ISO 5349-1 guidelines and 3) to determine if participant reported discomfort differs when standing on the mats while exposed to foot-transmitted vibration.

3.2 Methodology

A four by three condition experimental design was used where four mat conditions (Mat 1; Mat 2; Mat 3; No Mat) by three vibration condition (low frequency exposure, high frequency exposure, and no vibration) with one repeat were tested. A schematic of the testing protocol is displayed in Figure 1.0. Each matting condition consisted of 20 seconds of no vibration and 20 seconds of vibration exposure. There was a 10 second rest period, which was selected as an adequate and appropriate time period based on previous research conducted by Dickey and colleagues (2006). During the rest period between mat conditions the verbal subjective discomfort rating was collected. In total, participants were exposed to approximately 2.5 minutes of low vibration and 2.5 minutes of high vibration. Total testing time was approximately 45 minutes.

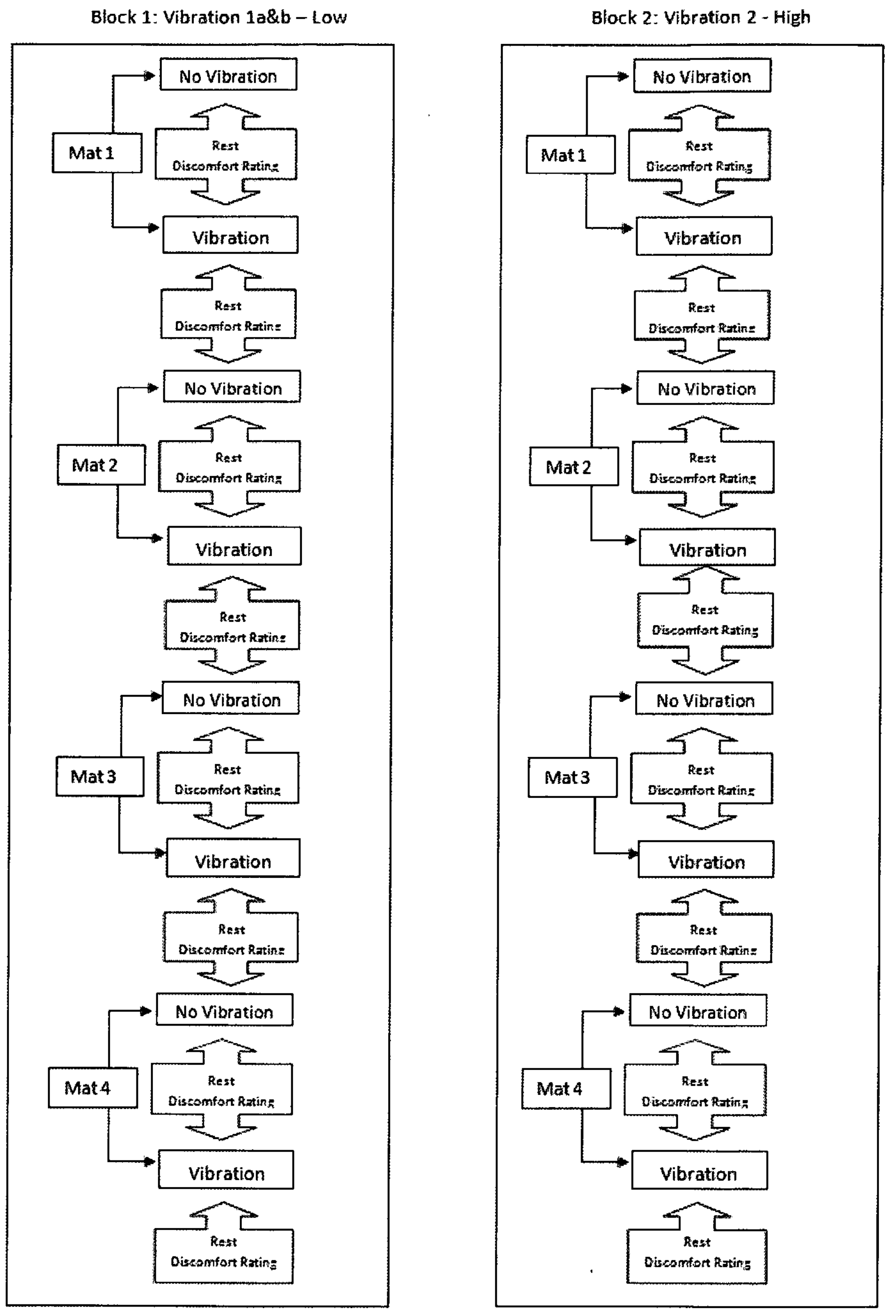

Figure 1.0: Methodology Diagram. *Vibration and No Vibration Conditions were 20 seconds. Rest periods were 10 seconds. Mats were randomized within each block during testing. Blocks 1 and 2 were repeated.

3.2.1 Vibration Generating Equipment

Two vibration sources were used to produce the vibration exposure profiles during the study: vibration 1 (V1=low) and vibration 2 (V2=high). A control condition was also included in which participants stood on the platforms but experienced no vibration. V1 was generated by a vibration simulator in the Biomechanics lab at Laurentian University. V1 had two vibration levels due to altered vibration following a required simulator repair. V1a produced 5.0 m/s^2 (4 Hz dominant frequency) and V1b was 0.70 m/s^2 (3 Hz dominant frequency). V1 was selected to replicate the dominant frequency associated with typical underground mining vibration exposure frequency generated by a locomotive or moving vehicle (Leduc, 2010). An exercise vibration platform (Power Plate North American, Inc., Irvine, CA) was used to generate the high vibration level condition (V2). The platform produced 15 m/s^2 (30 Hz dominant frequency). V2 was selected to simulate the vibration frequency experienced when standing on drilling platforms and raises used in underground mining (Leduc, 2011).

3.2.2 Mats

Four matting conditions were used during the study: Mat 1, Mat 2, Mat 3, and Mat 4 (no mat). Mat 1 was a ½ inch thick rubber floor mat with a honeycomb design. Mat 2 was a sponge mat that was 3/32 inches thick. Mat 3 was a vinyl mat z-web design that was 10.5 mm thick. Two of the three mats tested are currently being used within the Northern Ontario mining industry as a preventative strategy to attenuate the vibration exposure experienced by the miners. During the no mat condition, participants stood directly on the platform.

3.2.3 Vibration Measurement Equipment

Two T Series 2 10G MF tri-axial accelerometers (NexGen Ergonomics, Montreal, QC) were used to collect all vibration measurements. Whole-body (ISO 2631-1) and hand arm (ISO 5349) standards were used to collect the vibration measurements simultaneously. All vibration measurements recorded by the accelerometers were stored onto portable dataloggers, DataLOG II P3X8 (Biometrics, Gwent, UK). The measurements under the whole-body collection protocol were collected with a sampling frequency of 500 Hz. Measurements under the hand arm measurement protocol were collected with a sampling frequency of 5000 Hz.

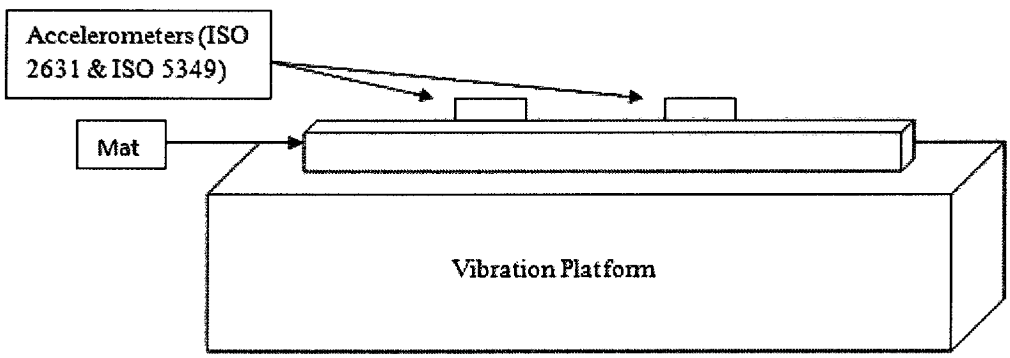

Figure 2.0 Equipment set-up and measurement location for mat conditions

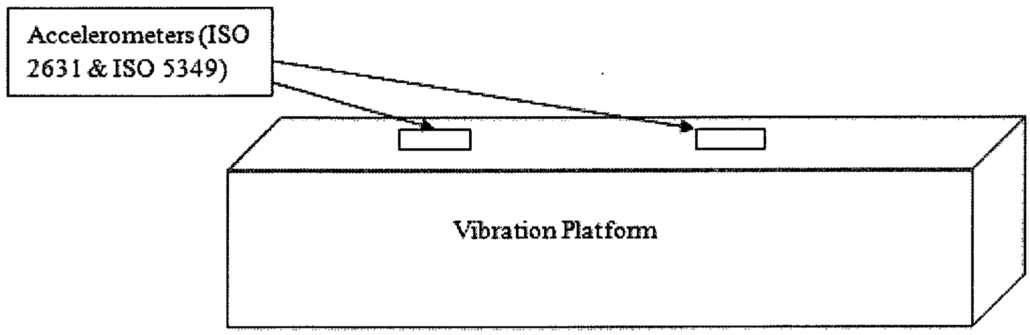

Figure 3.0 Equipment set-up and measurement location for no mat condition

3.2.4 Discomfort Measurement

A 9-point continuous discomfort scale that enables verbal reports of discomfort was utilized (Dempsey et al., 1977). Verbally reported discomfort measurements were recorded during each rest period (following each vibration exposure). Zero is the lowest rating on the scale indicating "zero discomfort" and nine is the highest, indicating "maximum discomfort" (Dempsey et al., 1977).

3.2.5 Data Collection

Ten healthy participants (5 males; 5 females) were recruited from a sample of convenience at Laurentian University (mean age of 29 years, mean height of 167.3 cm, mean weight of 68 kg) (Table 1). Participants indicated no history of a lower body musculoskeletal injury within the last six months and no previous head injury. Written informed consent was received prior to the commencement of data collection. Demographic information was collected as well as initial areas of general musculoskeletal discomfort prior to testing (Table 1). All participants completed the procedures in their entirety; however, it was not possible to analyze block 1 and block 3 for participant 1 due to equipment malfunctions. The research project was approved by the Laurentian University Research Ethics Board.

Table 1: Participant Demographic and Initial Discomfort Rating

Participant	Gender	Age	Weight (kg)	Height (cm)	Initial Discomfort
1	M	25	75	177.5	7 - R. Shoulder
2	M	27	83	173	0
3	F	38	54	156	Tender Achilles tendon
4	M	27	61	167.5	0
5	M	34	68	167.5	0
6	F	28	82	160	0
7	F	25	57	167.5	0
8	M	26	73	182.5	0
9	F	23	59	157	0
10	F	37	64	165	0

Participants did not wear shoes and were provided with a pair of typical athletic ankle socks to be worn during testing. Two tri-axial accelerometers were mounted within rubber pads, in accordance with the ISO 2631-1 standards (ISO, 1997). The accelerometer mounted under the right foot of all participants recorded vibration according to ISO 2631-1 guidelines. The accelerometer mounted under the left foot of all participants collected vibration in accordance to the ISO 5631 standard. Differences between standards will be further discussed in the Data Analysis section. Participants were asked to stand on the rubber pad in a comfortable neutral posture with a slight bend in the knees and were instructed to hold on to handles above the platform resulting in approximately a 90 degree angle at the elbow.

One block of trials consisted of four no vibration and four vibration trials with the four mat conditions (Figure 1.0). The no vibration condition occurred prior to every mat condition. All mat conditions were presented in a randomized order within each block. The vibration conditions were also randomized in that they alternated which block would be presented first.

Participants were asked to step onto the platform and experienced 20 seconds of no vibration. The no vibration condition was followed by 10 seconds of rest in which the discomfort score for the previous 20 seconds was verbally communicated to the researcher reflecting the discomfort they had felt during the previous 20 seconds. The participant was then exposed to 20 seconds of vibration followed by the 10 seconds of rest and the recording of the discomfort score. Each block took approximately 3.5 minutes to complete. Participants were given approximately 5 minutes of rest between blocks. A 20-second vibration exposure duration has been demonstrated to produce reliable self-reports of comfort (Dickey et al., 2006). Additional investigations have also demonstrated the reliability of using 20-second exposures based on field measurements for evaluating the effectiveness of suspension seating (Smith et al., 2006). This discomfort methodology allowed participants to report their discomfort following each 20 second bout of vibration; consequently, allowing them to report their discomfort as they experience the vibration as opposed to having them wait and remember their experiences over a longer duration of time (Dickey et al., 2006). The entire testing session lasted approximately 45 minutes.

3.2.6 Data Analysis

All vibration data collected were processed with Vibration Analysis Toolkit v. 5.0 (NexGen Ergonomics, Montreal, QC, CND). The data were processed under the two conditions, according to the whole body vibration standards, ISO 2631-1, and the hand arm vibration standards, ISO 5349.

The International Organization for Standardization (ISO) provides guidelines for vibration exposure and measurement in *ISO 2631-1: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements.* The guidelines are applicable to situations where the individual is exposed to vibration while in a seated, standing, or recumbent posture (ISO 2631-1). The vibration magnitude is reported as a frequency weighted root-mean-square (aRMS) acceleration which accounts for frequencies known to be associated with detrimental health effects. The weighting factors were calculated using the protocol set out in ISO 2631-1 (x-axis = W_d; y-axis = W_d; z-axis = W_k). The appropriate scaling factors used to determine health risk were also used (x-axis, k = 1.4; y-axis, k = 1.4; z-axis, k = 1.0). The ISO 2631-1 health guidance caution zone for an eight hour vibration exposure lies between 0.45 m/s^2 and 0.9 m/s^2. If the 8 hour (measured or estimated) a_w acceleration value in the dominant axis is below 0.45 m/s^2, then health effects due to the vibration exposure are unlikely. Values within the health guidance caution zone suggest that potential health risks are possible. Furthermore, values exceeding 0.9 m/s^2 suggest that the vibration exposure will likely result in a detrimental effect to the worker's health. In the current study, the vibration exposure was assumed to occur over an 8 hour period.

The ISO also provides guidelines for vibration exposure and measurement of hand-arm vibration, *ISO 5349, Mechanical Vibration – Guidelines for the measurement and assessment of human exposure to hand-transmitted vibration* (ISO, 1986). The standard indicates that health effects are rare for vibration total value less than 2 m/s^2. This value was used to determine likely health effects to the feet.

3.2.7 Mat Effective Amplitude Transmissibility (MEAT)

Vibration transmissibility properties of the mats were determined by comparing frequency weighted vibration values on the vibrating platform (directly below the mat) and above the mat at the mat/feet interface. The value inputted as the vibration platform value was taken from the M4 measurement and used in calculating the MEAT value for the three mat conditions (M1, M2, M3) within each block. The MEAT value expresses the total amount of vibration at the operator interface compared to the underlying vibrating surface (similar to SEAT method reported in Boileau and Rakheja, 1990). MEAT values less than 100% indicate vibration attenuation by the mat whereas values greater than 100% indicate that the mat has amplified the vibration.

3.2.8 Statistical Analysis

An analysis of variance was conducted to test group mean differences with a selected alpha level of 0.05. In all cases, the homogeneity of variance was assessed using Levene's test of homogeneity with a significance level set at 0.05. When homogeneity of variance was satisfied, Tukey post-hoc tests were used; when not satisfied Games-Howell post-hoc tests were used. No significant difference was found between measurements recorded on the platform between the repeated blocks during either vibration condition.

3.3 Results

3.3.1 MEAT values

Mat 2 was the only mat to provide attenuation of the vibration exposure under whole-body vibration exposure analysis procedures (Table 2). When standing on mat 2, participants experienced 96% of the vibration transmitted in the vertical axis from the platform during vibration profile 1 and 99% of the vibration transmitted from the platform during vibration profile 2. However, when MEAT values, calculated according to hand-arm vibration exposure analysis procedures were determined, all mats provided attenuated vibration in the vertical axis during the higher frequency vibration profile (V2) (Table 3). MEAT values are displayed for each participant during each matting and vibration condition in Tables 4-7 in Appendix D.

Table 2: Mean M.E.A.T. values for mat and vibration conditions determined with frequency weighted acceleration calculated according to ISO 2631-1 guidelines

Mat*	Vibration Profile	mean MEAT X (%)	SD (%)	mean MEAT Y (%)	SD (%)	mean MEAT Z (%)	SD (%)
1	1	117	17	103	16	103	6
1	2	138	37	161	76	100	5
2	1	102	15	100	9	96	5
2	2	133	44	120	27	99	2
3	1	111	9	97	11	102	5
3	2	118	26	118	34	100	4

* M4 = no mat condition (Therefore no transmissibility score is reported)

Table 3: Mean M.E.A.T values for mat and vibration conditions determined with frequency-weighted acceleration calculated according to ISO 5349-1 guidelines

Mat*	Vibration Profile	mean MEAT X (%)	SD (%)	mean MEAT Y (%)	SD (%)	mean MEAT Z (%)	SD (%)
1	1	111	19	114	20	107	12
1	2	148	56	240	50	100	11
2	1	99	16	100	11	102	9
2	2	105	22	128	27	99	6
3	1	112	9	106	11	103	8
3	2	122	33	187	60	100	7

3.3.2 Discomfort

There was no statistical significant difference found between types of mat on discomfort rating despite Mat 2 having the lowest mean discomfort rating. Controlling for the vibration condition did not alter the non significant results as Mat 2 continued to have the lowest mean discomfort rating during both vibration profile 1 (low frequency vibration) and vibration profile 2 (high frequency vibration).

The high frequency vibration profile was more uncomfortable than the low frequency vibration profile ($F_{(1,158)}$=10.777, p<0.001). Regardless of mat condition, when participants experienced the high frequency vibration (vibration 2) they reported a mean discomfort rating of 3.85 out of 9 as opposed to low frequency vibration (vibration 1), which was reported as a mean discomfort rating of 2.54 on the 9 point (Figure 4.0).

The discomfort rating was also statistically significant between participants ($F_{(9,103)}$=39.084, p<0.000), as displayed in Figure 5.0. Participant 5 had the greatest mean discomfort rating of 8.44 out of 9; therefore, reaching almost maximum discomfort and resulting in discomfort ratings that were significantly greater than all of the other participants. Additional post-hoc analyses for all participants is provided in Appendix C. Gender was also found to significantly affect discomfort rating ($F_{(1,145)}$=36.431, p<0.000). Females reported a mean discomfort rating of 2.07 out of 9; whereas, males reported a mean discomfort rating of 4.33 on the 9 point scale.

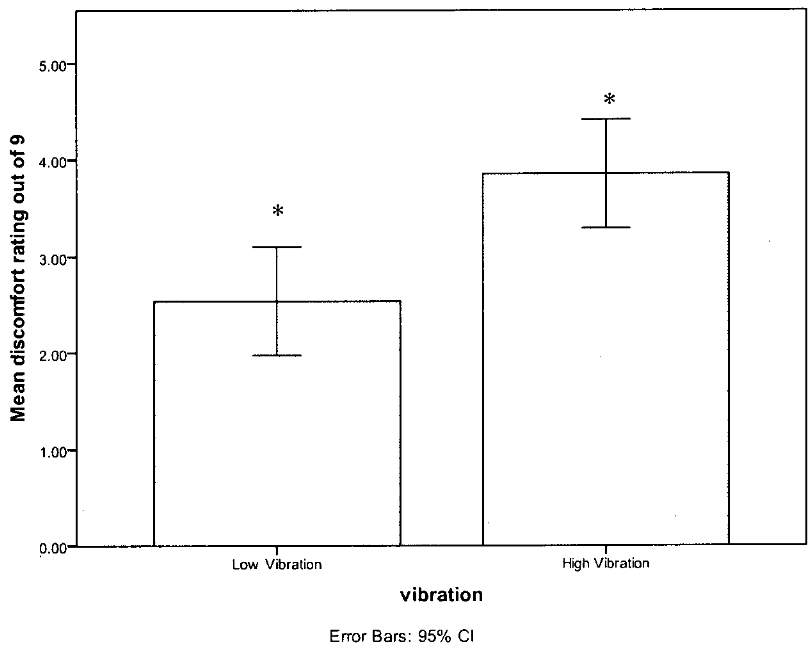

Figure 4.0: Mean reported discomfort rating for low vibration profile and high vibration profile. * indicates significant difference between conditions.

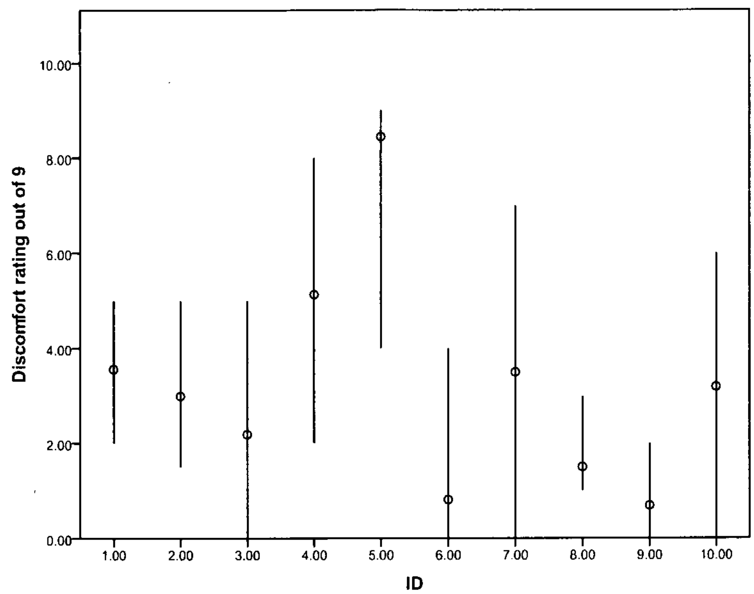

Figure 5.0: Discomfort rating mean and range for all participants

The number of specific discomfort reports was also examined for the various body regions. The number of feet and ankle discomfort reports can be found in Figure 6.0. A similar amount of specific feet and ankle discomfort reports were given during both vibration conditions and independent of mat condition. In comparison, the number of head discomfort reports is displayed in Figure 7.0. With all participants combined, there was only one discomfort reporting for the head during vibration profile 1 for each mat condition; whereas, during vibration profile 2 there were 13 reports of discomfort at the head.

3.3.3 Health Risk

According to ISO 2631-1, 8-hr exposure to vibration profile 1a and 1b would place participants within or above the health guidance caution zone during testing while exposure to vibration profile 2 would expose participants to vibration levels above the health guidance caution zone. However, no mat provided attenuation to decrease exposure levels enough to change zones. Likewise, according to ISO 5349-1, vibration profile 1a and vibration 2 would place participants at a health risk for an 8 hour period. Vibration 1b profile was below 2 m/s^2, which indicates that health effects are rare. No mat condition provided any meaningful reduction in the vibration exposure in order to decrease the health risk. Table 3 in Appendix C displays the health effects according to both whole-body (ISO 2631-1) and hand-arm vibration (ISO 5349-1) standards.

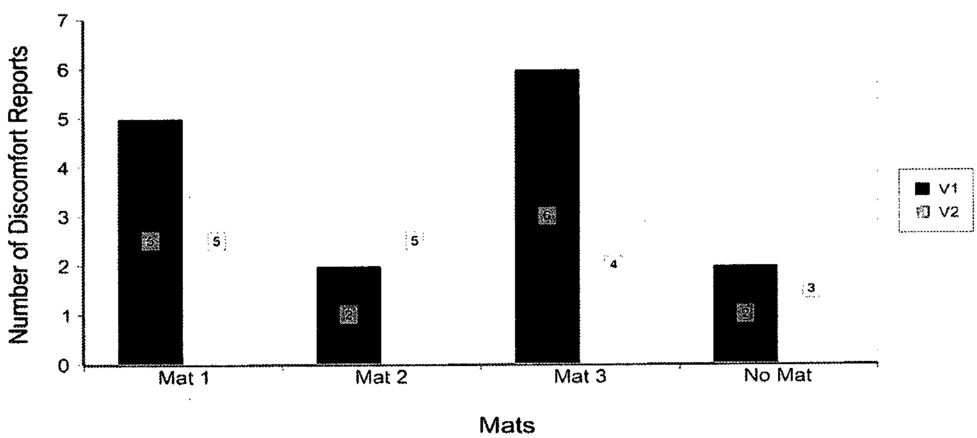

Figure 6.0: Number of discomfort reports for the feet and ankles by mat condition for low frequency vibration exposure (V1) and high frequency vibration exposure (V2).

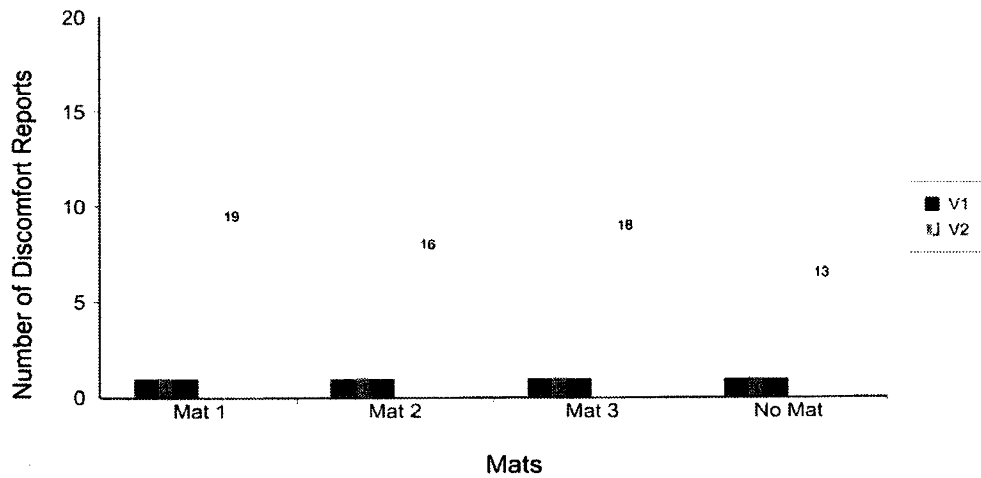

Figure 7.0: Number of discomfort reports for the head by mat condition for low frequency vibration exposure (V1) and high frequency vibration exposure (V2).

3.4 Discussion

The objectives of this study were to determine the transmissibility properties (MEAT) of three commercially available mats used in underground mining, to determine if the mats alter predicted injury risk according to ISO 2631-1 and ISO 5349-1 guidelines and to investigate if participant reported discomfort differed when exposed to vibration while standing on the mats.

Mat 2, according to ISO 2631-1 methodology, was the only mat to decrease the vibration exposure under both low and high frequency vibration conditions. However, when analyzing the data according to ISO 5349, all mats attenuated vibration in the z-direction. The mats did not provide clinically significant attenuation; in fact, they did not attenuate vibration enough to reduce the exposure below the health guidance caution zone. Therefore, the mats were not able to decrease the likelihood of a worker experiencing potential damage to their feet. Due to the differences in frequency weightings between the two ISO standards, there were slight differences in the MEAT values. The ISO 5349 guidelines may be more applicable as they place a greater emphasis on the higher frequency vibration levels. Feet are more likely to be injured at the higher frequencies (40 Hz; Thompson et al., 2010); thus, the mats need to be effective at attenuating the higher frequencies within this range. Future research should evaluate the mats under a larger range of frequencies in order to ensure the attenuation is occurring within the frequencies range that is believed to be harmful to health. A limitation of using the MEAT value is that it only produces a single value. The MEAT value does not indicate the frequencies across the spectrum in which attenuation or amplification may be occurring. It is essential to determine if amplification occurs at the frequency range that is linked to potential damage to the feet.

The significant difference in discomfort rating between vibration conditions is similar to findings in previous research which suggests that compared to a lower magnitude vibration; a higher magnitude vibration is less comfortable (Mansfield, 2000). Due to the significant effect of the vibration condition on discomfort and no significant difference between mats, participants were not able to distinguish between mats. The larger number of discomfort ratings at the head when participants were exposed the higher frequency and magnitude vibration profile may have also contributed to the significant difference in reported discomfort between vibration conditions.

There was no significant difference between mat conditions on discomfort rating. As suggested by Annett (2002), subjective measures of discomfort were reported immediately following each mat condition. However, the participants were then required to interpret their discomfort and rate it on a numerical scale from 0-9, which Annett (2002) suggests requires dependence upon their memory and previous experiences. Therefore, future work could employ a paired comparison method in order to discriminate between mats. A paired comparison methodology utilizes forced choice between two alternatives which may have helped to give an indication of mat preference (Annett, 2002).

An equal number of male and females participants were selected to participate as it has been previously documented that females rate vibration exposures as more severe than males on a consistent basis during seated whole body vibration which may be due to differences in the pelvis (Dickey et al., 2006). However, the results of the current standing vibration study show the opposite findings as females reported the vibration exposures as less severe. However, four of the five males were tested prior to the equipment malfunction; therefore, experiencing a higher vibration magnitude during vibration profile 1. There was still a significant difference in discomfort ratings between males and females during vibration profile 2 ($F_{1,72.314}=5.545$, $p<0.05$). Also, one male participant had a significantly higher mean discomfort rating than all other participants and experienced 'maximum discomfort'. Further background demographic information could be collected in order to evaluate the characteristics of the participants as certain subsets of participants respond differently to vibration exposure (Dickey et al., 2006). Previous vibration exposure and a detailed health history were not collected in this study; however, future research conducted in a laboratory setting should document the participant's previous vibration exposure and a more detailed health history. In addition, to improve transferability of the current study to an occupational setting, a sample of miners rather than university students should have been selected. The differences in mass between genders may also potentially influence the vibration transmissibility. Previous research examining load-haul-dump vehicles found the whole-body vibration exposure was greater when driving the smaller capacity vehicles and when operating the vehicle with an empty bucket as opposed to full (Village et al., 1989). Eger and colleagues (2010) also found the highest vibration exposure occurred when the bucket of the LHD was empty; therefore, decreasing the vehicle's overall mass when compared to operating with a fully loaded bucket. As a result, mass should be more carefully examined and compared in future studies examining vibration transmitted to the feet.

Although according to the MEAT values, the mats did not provide any meaningful attenuation, there may be benefits to mats from an anti-fatigue perspective. The anti-fatigue mats are designed to allow the body to naturally sway while standing (King, 2002). The mats allow small subtle movements of the calf and leg muscles to improve blood flow and reduce fatigue (King, 2002). The mats do provide benefits as the worker is able to stand on a softer surface which is less fatiguing than standing on concrete or a hard surface (King, 2002). Positive anecdotal feedback provided by miners also supports the benefits for the continued use of the mats in the workplace.

There are several limitations to the current study. Following the completion of testing participant 5, the vibration platform producing the low frequency vibration profile experienced a mechanical malfunction. The repair reduced the magnitude and dominant frequency of the low frequency vibration profile for participants 6 through 10. The initial acceleration level for V1 was 5.0 m/s^2. For the remainder of the study following the repair, the acceleration level for V1 was 0.70 m/s^2. The transmissibility of the mats is calculated as a ratio; therefore, the difference in the vibration exposure measured on the platform in comparison to above the mat yielded similar results. However, the discomfort scores may have been altered as the acceleration magnitude was decreased in the z-axis since the sensitivity to vibration exposure is a function of both the frequency and direction of the vibration (van Niekerk et al., 2003).

Caution should be exercised in generalizing the findings of this study to all situations in which vibration enters the feet. MEAT values are related to the specific vibration amplitude and frequency. As noted with SEAT values in previous research, the comfort level only reflects that particular vibration input condition (van Niekerk et al., 2003). Also, due to equipment limitations, the vibration level was only measured above the mat during the three mat conditions and compared to a measurement recorded during the no mat condition within the block. Future researchers should collect simultaneous samples using two accelerometers, above and below the mat, during each vibration sample collected. Therefore, the MEAT results cannot be generalized to all situations in which a worker experiences vibration through their feet.

Furthermore, all the mats in this study were brand new at the onset of the study. As with anti-vibration glove research, the effects of wear and tear through the usage of the product may influence the amount of transmissibility; however, the decrease in performance has yet to be examined (Hewitt, 1998). Mats need to be tested under controlled conditions similar to the requirements for gloves to receive the designation of being an anti-vibration glove. However, anti-vibration glove testing has revealed that the comparison of field and laboratory results did not produce the same ranking of gloves (Pinto et al., 2001). Further testing of the effectiveness of the mats to attenuate vibration should be carried out in an applied context; namely, that of an underground mine. The duration of vibration exposure in this experiment is also not indicative of an occupational vibration exposure. Again, future testing should consider testing the mats in the field environment over a longer duration of time that is more representative of a typical usage.

Future research in this area may look to study the physical properties of seats and anti-vibration gloves that are being used to control and attenuate vibration in order to make a possible link to matting materials. The density and firmness properties of foam in seat research are two of the commonly researched entities as they affect subjective measures of comfort, accommodation for different anthropometric characteristics, and product durability (Kolich et al., 2005). High density (1378 g) and high firmness (164 N at 25% compression) were found to produce the optimal condition for driving (Kolich et al., 2005).The same principles from seat research would apply for selecting a mat. The mat should have a natural resonant frequency that does not overlap with the resonant frequency of the platform or vehicle and provides adequate attenuation in the frequency range that is associated with health effects and discomfort (Kolich et al., 2005). Therefore, future research may also explore the aforementioned properties of mats and insoles in order to provide the utmost protection to the worker.

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CHAPTER 4:

GENERAL DISCUSSION

4.1 Linking of Previous Chapters

Several studies have reported health effects at the feet for workers exposed to foot transmitted vibration (Hedlund, 1989; Eger, et al., 2006; Thompson, et al., 2010). Chapter 2 quantified the typical vibration exposure of miners exposed to vibration through their feet. It was found that the vibration levels experienced while working on a raise platform was above the ISO 2631-1 HGCZ for an eight hour shift; however, many miners typically work a 12 hour shift. In turn, the miners are likely to experience health effects as a result of the vibration exposure. The dominant frequency of the vibration measured at the feet was also documented and reported in Chapter 2. The dominant frequency experienced by the miners while operating the locomotives fell within the range known to be associated with whole body health concerns (Griffin, 1990). Therefore, locomotive operators were more likely to experience discomfort throughout their body as the resonant frequency of the pelvis and spine is also within the same range (Griffin, 1990). The findings of the questionnaire from Chapter 2 suggest the miners exposed to vibration with a dominant frequency of approximately 3-6 Hz reported discomfort throughout their whole body with a unique indication of pain in the neck, where as drill operators exposed to a dominant frequency vibration between 30-40 Hz reported discomfort in the feet and limbs.

In Chapter 3, the simulated low vibration frequency exposure of the locomotive resulted in a significantly lower discomfort rating when compared to the higher frequency vibration profile representative of a drill operator. However, none of the mats resulted in a significant decrease in vibration exposure.

While working on raises and operating the jumbo drill, the dominant frequency is within the range associated with localized health effects to the hand-arm system. Two of the participating miners had a previous diagnosis of hand-arm vibration syndrome and vibration induced white feet as a result of the vibration exposure entering both their hands and feet while performing their required job task. The dominant frequency measured on the platforms (40 Hz) has also been documented by Hedlund (1989) and Thompson and colleagues (2010) in conjunction with vibration white feet. In Chapter 3, the participants also noted numbness and tingling within their feet during testing.

As a potential solution to vibration exposure at the feet, "anti-vibration" mats have been implemented at various mine sites across Northern Ontario. In order to evaluate the mats effectiveness, Chapter 2 was required to understand the exposure characteristics. As a result, the vibration acceleration levels and dominant frequencies were replicated (as close as possible given equipment constraints) in a laboratory setting for controlled evaluation of the mats in Chapter 3. However, the mats did not prove to be effective in attenuating vibration. Mat 2 displayed some positive characteristics; however, the mat did not attenuate the magnitude sufficiently to eliminate a worker from being within or above the HGCZ.

The findings of Chapter 2 and previous researchers have suggested that measurements recorded at the feet should be done in accordance with ISO 5349 as opposed to ISO 2631 (Thompson et al., 2010). The hand-arm vibration standards may provide a more accurate indication of the potential health effects which may occur locally at the feet as a result of the vibration exposure (Thompson et al., 2010). Furthermore, the hand and foot are structurally similar which implies they may react similarly to the vibration exposure (Mansfield, 2005). The measurements conducted in Chapter 3 were recorded simultaneously in accordance with ISO 5349 and ISO 2631 standards. There was a slight difference in their findings due to the frequency weightings as noted by the difference in attenuation recorded for each mat.

Future research examining the characteristics and health effects of vibration entering the body through the feet should also conduct their measurements and analysis using ISO 5349.

4.2 Relevance to the Mining Industry

Vibration exposure experienced by the miners working on raise platforms is above the health guidance caution zone for an 8 hour shift as recorded in Chapter 2. Based on Chapter 3 findings, installing mats to attenuate the vibration will likely provide no clinical significant reduction in vibration transmitted to the feet. However, testing was limited and as a result future testing is warranted. Future research should include additional mats and insoles. Furthermore, engineering interventions should also be explored. The bolter in Chapter 2, showed positive results, with a reduction in vibration, for the implementation of a dampened isolated platform located on the larger main platform. Also, in Chapter 2, the use of the "anti-vibration" drill while working on the metal raise also showed lower vibration magnitudes at the feet compared to a normal drill. Further research with regards to mining drills and equipment in order to reduce vibration from the source and provide dampening structures along the transmission path may help to reduce the amount of vibration reaching the worker.

4.3 Relevance to Mat Manufacturers

More controlled testing is warranted to further investigate the transmissibility properties of mats used for a personal protective application. The material properties composing the mats need to be further examined. Also, the durability and survival of the mats is important in an underground mine setting. The material needs to hold up against a harsh environment that includes water, oil, and rock. A standard should also be established for the testing of mats and insoles. As previously completed for anti-vibration gloves, each product is required to endure a systematic testing process prior to identifying the product as an "anti-vibration" product that attenuates vibration.

4.4 Relevance to the Medical Community

The medical community and occupational physicians also need to become more aware of the potential damage and injury which may occur in the feet as a result of an occupational vibration exposure. Patients presenting with a work history that involves standing vibration should be questioned about numbness and tingling within the feet. Toibana and colleagues (1994) caution that is it typically difficult to visually identify the damage occurring within the feet and fears there may well be more affected workers. Testing should be done regardless of observing HAVS symptoms.

4.5 Conclusions

The current research project has provided findings important for miners, the mining industry, manufactures, and occupational health physicians. The study documented the vibration characteristics of various types of mining equipment that exposes workers to vibration through their feet and found that differences are present amongst primary and secondary sources.

In the past, pressure to reduce occupational hand-arm vibration exposures resulted in the commercial interest in producing anti-vibration gloves (Griffin, 1998). Future research in this area may continue to communicate the need for workers and companies to take caution with respect to vibration entering the feet, as well as, to occupational physicians to become more aware, and researchers to develop adequate standards and conduct further investigations.

The documentation supports the prevalence of health effects amongst the workers and is needed to investigate a potential solution to attenuate the vibration exposure. Although, the mats were not found to significantly attenuate the vibration exposure, other materials and methods may be explored in the future in order to provide vibration attenuation benefits to the user.

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APPENDIX A

Questionnaires for Chapter 2

LaurentianUniversity
UniversitéLaurentienne

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) ____________

Part B: Equipment Operating History

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

____

____

____

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

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

____

7. What equipment type do you operate most often (please name)

____

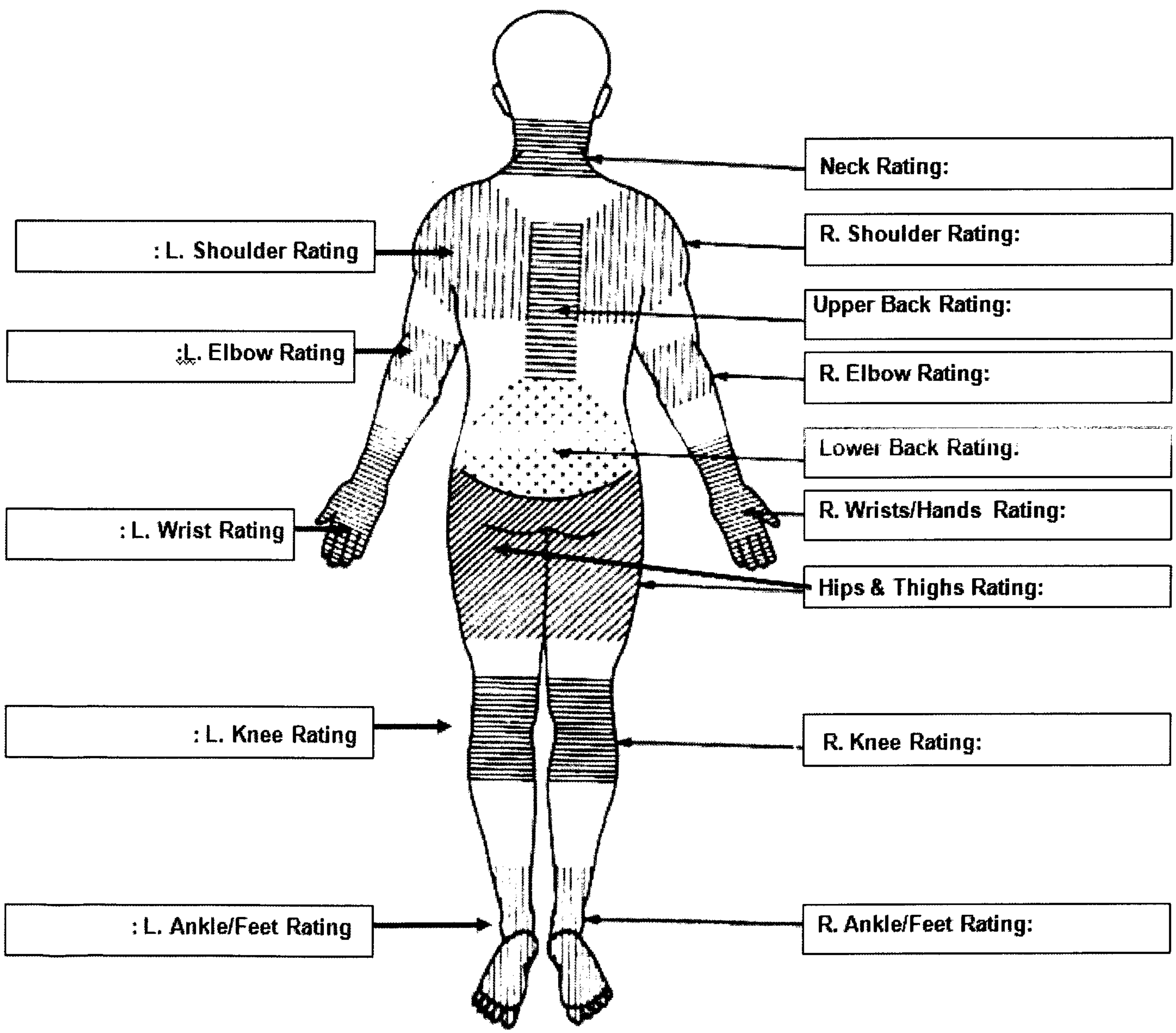
8. How many hours a day (on average) do you operate or work with equipment that exposes you to vibration? ___________

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



APPENDIX B

Figures for Chapter 2

Figure 1: Accelerometer set-up in locomotive 2

Figure 2: Accelerometer set-up on the metal raise

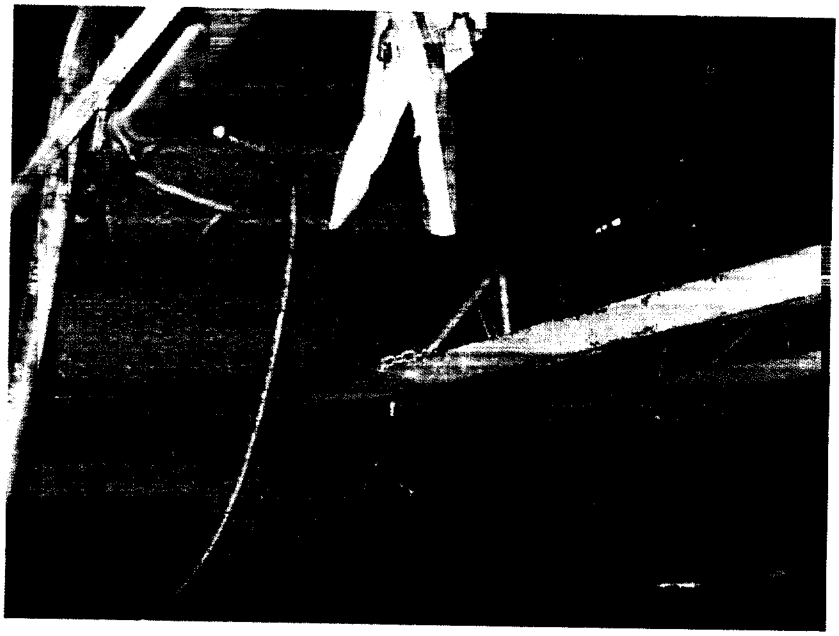


Figure 3: Metal Raise Platform

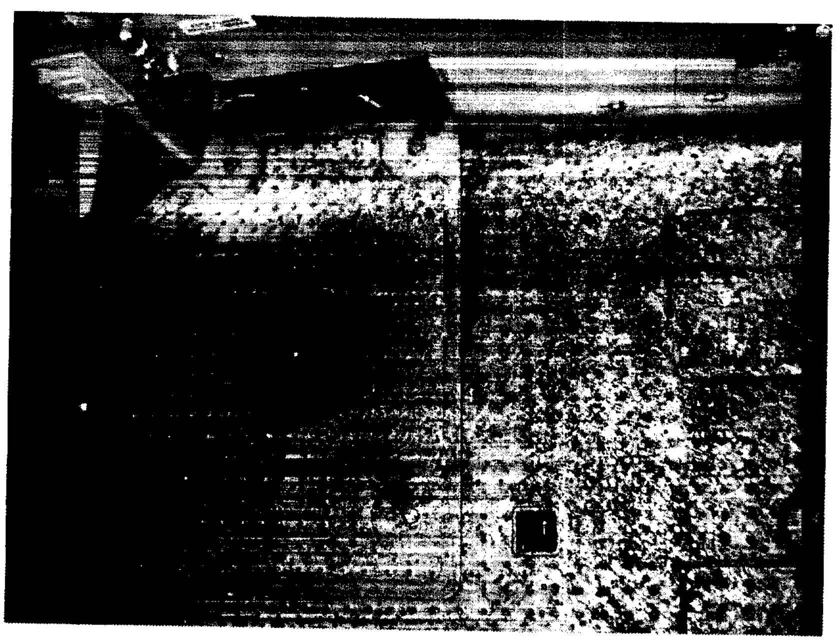


Figure 4: Accelerometer set-up on bolter dampened platform

Figure 5: Bolter platform

APPENDIX C

Questionnaires for Chapter 3

Part A: Background Information

1. Have you every sustained a head injury? ______________________
2. Have you had foot pain or back pain within the last 6 months?_______

If you have answered **NO** to **the two** questions, you may continue to participate in the research study. If you have answered **YES** to **ANY** of the questions; unfortunately, you will not be able to participate in the research study due to the potential health risks caused by the vibration.

4. What is your current age? _____________

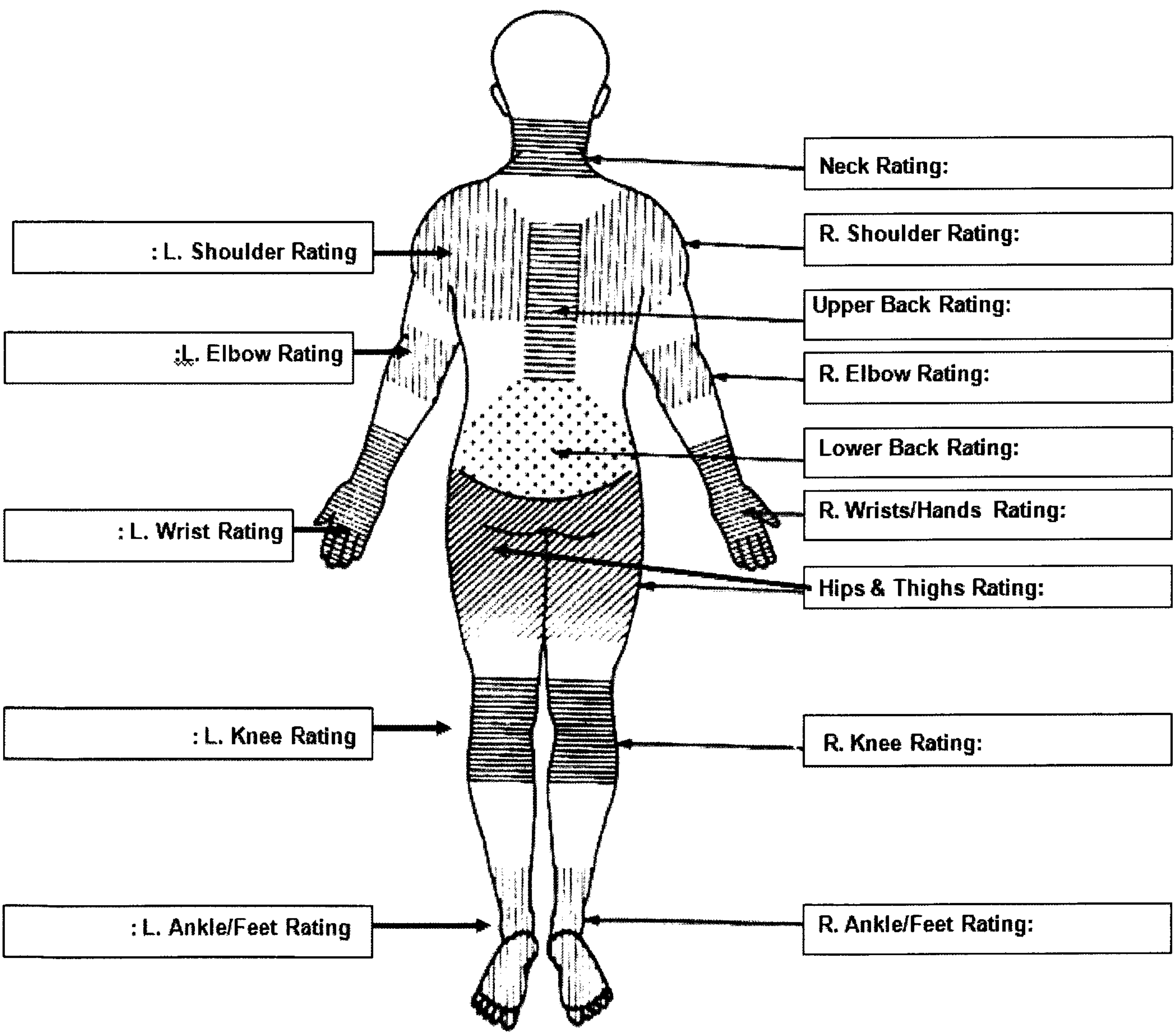
5. What is your current weight? (lbs) _____________

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

7. Gender: ____________

Part B: Discomfort

The body has been divided into fourteen different regions (right). For each body region please indicate if you feel any discomfort (**ache, pain, numbness**) in the region at the present time. If you have discomfort in an area, please rate the severity on the 9 point scale.



APPENDIX D

Tables and Figures for Chapter 3

Table 1: Mean discomfort rating for participants (Whole body vibration)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
1.00	16	3.5625	1.03078	.25769	3.0132	4.1118	2.00	5.00
2.00	16	3.0000	1.09545	.27386	2.4163	3.5837	1.50	5.00
3.00	16	2.1875	1.72119	.43030	1.2703	3.1047	.00	5.00
4.00	16	5.1250	1.92787	.48197	4.0977	6.1523	2.00	8.00
5.00	16	8.4375	1.36473	.34118	7.7103	9.1647	4.00	9.00
6.00	16	.8125	1.06262	.26566	.2463	1.3787	.00	4.00
7.00	16	3.5000	2.02485	.50621	2.4210	4.5790	.00	7.00
8.00	16	1.5000	.63246	.15811	1.1630	1.8370	1.00	3.00
9.00	16	.6875	.77190	.19298	.2762	1.0988	.00	2.00
10.00	16	3.1906	2.12087	.53022	2.0605	4.3208	.00	6.00
Total	160	3.2003	2.60639	.20605	2.7934	3.6073	.00	9.00

Table 2: Post-hoc Comparison of discomfort ratings amongst participants

Multiple Comparisons

Dependent Variable:discomfort rating out of 9

Games-Howell	1.00	2.00	.56250	.37604	.883	-.7206	1.8456
		3.00	1.37500	.50156	.212	-.3647	3.1147
		4.00	-1.56250	.54653	.175	-3.4703	.3453
		5.00	-4.87500*	.42757	.000	-6.3417	-3.4083
		6.00	2.75000*	.37011	.000	1.4874	4.0126
		7.00	.06250	.56803	1.000	-1.9260	2.0510
		8.00	2.06250*	.30233	.000	1.0152	3.1098
		9.00	2.87500*	.32194	.000	1.7703	3.9797
		10.00	.37188	.58952	1.000	-1.6973	2.4411
	2.00	1.00	-.56250	.37604	.883	-1.8456	.7206
		3.00	.81250	.51006	.840	-.9509	2.5759
		4.00	-2.12500*	.55434	.023	-4.0534	-.1966

	5.00	-5.43750*	.43750	.000	-6.9351	-3.9399
	6.00	2.18750*	.38154	.000	.8859	3.4891
	7.00	-.50000	.57554	.996	-2.5078	1.5078
	8.00	1.50000*	.31623	.003	.4009	2.5991
	9.00	2.31250*	.33502	.000	1.1600	3.4650
	10.00	-.19062	.59677	1.000	-2.2780	1.8967
3.00	1.00	-1.37500	.50156	.212	-3.1147	.3647
	2.00	-.81250	.51006	.840	-2.5759	.9509
	4.00	-2.93750*	.64610	.003	-5.1436	-.7314
	5.00	-6.25000*	.54915	.000	-8.1305	-4.3695
	6.00	1.37500	.50570	.219	-.3761	3.1261
	7.00	-1.31250	.66438	.621	-3.5832	.9582
	8.00	.68750	.45843	.876	-.9457	2.3207
	9.00	1.50000	.47159	.100	-.1628	3.1628
	10.00	-1.00312	.68285	.893	-3.3399	1.3336
4.00	1.00	1.56250	.54653	.175	-.3453	3.4703
	2.00	2.12500*	.55434	.023	.1966	4.0534
	3.00	2.93750*	.64610	.003	.7314	5.1436
	5.00	-3.31250*	.59051	.000	-5.3436	-1.2814
	6.00	4.31250*	.55033	.000	2.3947	6.2303
	7.00	1.62500	.69896	.403	-.7597	4.0097
	8.00	3.62500*	.50724	.000	1.8087	5.4413
	9.00	4.43750*	.51916	.000	2.5958	6.2792
	10.00	1.93438	.71653	.219	-.5115	4.3803
5.00	1.00	4.87500*	.42757	.000	3.4083	6.3417
	2.00	5.43750*	.43750	.000	3.9399	6.9351
	3.00	6.25000*	.54915	.000	4.3695	8.1305
	4.00	3.31250*	.59051	.000	1.2814	5.3436
	6.00	7.62500*	.43241	.000	6.1433	9.1067
	7.00	4.93750*	.61046	.000	2.8331	7.0419
	8.00	6.93750*	.37604	.000	5.6140	8.2610
	9.00	7.75000*	.39198	.000	6.3861	9.1139
	10.00	5.24688*	.63050	.000	3.0683	7.4255
6.00	1.00	-2.75000*	.37011	.000	-4.0126	-1.4874
	2.00	-2.18750*	.38154	.000	-3.4891	-.8859

		3.00	-1.37500	.50570	.219	-3.1261	.3761
		4.00	-4.31250*	.55033	.000	-6.2303	-2.3947
		5.00	-7.62500*	.43241	.000	-9.1067	-6.1433
		7.00	-2.68750*	.57168	.003	-4.6853	-.6897
		8.00	-.68750	.30915	.468	-1.7602	.3852
		9.00	.12500	.32835	1.000	-1.0031	1.2531
		10.00	-2.37812*	.59305	.017	-4.4561	-.3002
	7.00	1.00	-.06250	.56803	1.000	-2.0510	1.9260
		2.00	.50000	.57554	.996	-1.5078	2.5078
		3.00	1.31250	.66438	.621	-.9582	3.5832
		4.00	-1.62500	.69896	.403	-4.0097	.7597
		5.00	-4.93750*	.61046	.000	-7.0419	-2.8331
		6.00	2.68750*	.57168	.003	.6897	4.6853
		8.00	2.00000*	.53033	.035	.0972	3.9028
		9.00	2.81250*	.54175	.002	.8860	4.7390
		10.00	.30938	.73306	1.000	-2.1916	2.8104
	8.00	1.00	-2.06250*	.30233	.000	-3.1098	-1.0152
		2.00	-1.50000*	.31623	.003	-2.5991	-.4009
		3.00	-.68750	.45843	.876	-2.3207	.9457
		4.00	-3.62500*	.50724	.000	-5.4413	-1.8087
		5.00	-6.93750*	.37604	.000	-8.2610	-5.6140
		6.00	.68750	.30915	.468	-.3852	1.7602
		7.00	-2.00000*	.53033	.035	-3.9028	-.0972
		9.00	.81250	.24948	.072	-.0410	1.6660
		10.00	-1.69062	.55329	.136	-3.6793	.2981
	9.00	1.00	-2.87500*	.32194	.000	-3.9797	-1.7703
		2.00	-2.31250*	.33502	.000	-3.4650	-1.1600
		3.00	-1.50000	.47159	.100	-3.1628	.1628
		4.00	-4.43750*	.51916	.000	-6.2792	-2.5958
		5.00	-7.75000*	.39198	.000	-9.1139	-6.3861
		6.00	-.12500	.32835	1.000	-1.2531	1.0031
		7.00	-2.81250*	.54175	.002	-4.7390	-.8860
		8.00	-.81250	.24948	.072	-1.6660	.0410
		10.00	-2.50312*	.56424	.008	-4.5142	-.4921
	10.00	1.00	-.37188	.58952	1.000	-2.4411	1.6973

	2.00	.19062	.59677	1.000	-1.8967	2.2780
	3.00	1.00312	.68285	.893	-1.3336	3.3399
	4.00	-1.93438	.71653	.219	-4.3803	.5115
	5.00	-5.24688*	.63050	.000	-7.4255	-3.0683
	6.00	2.37812*	.59305	.017	.3002	4.4561
	7.00	-.30938	.73306	1.000	-2.8104	2.1916
	8.00	1.69062	.55329	.136	-.2981	3.6793
	9.00	2.50312*	.56424	.008	.4921	4.5142

*. The mean difference is significant at the 0.05 level.

Table 3: Health Effects according to both whole-body (ISO 2631-1) and hand-arm vibration (ISO 5349-1) standards.

Participant	Condition	Location	WBV			HAV		
			aw_z (m/s^2)	DF_z (Hz)	ISO 2631-1	aw_z (m/s^2)	DF_z (Hz)	ISO 5349-1
1	**V1-M1**	Above Mat	5.6343	4	Above	4.6481	12.5	Above
	V1-M2	Above Mat	4.7613	4	Above	19.25	12.5	Above
	V1-M3	Above Mat	5.5089	4	Above	4.0681	12.5	Above
	V1- M4	Platform	5.0621	4	Above	3.5135	12.5	Above
	V2-M1	Above Mat	9.3743	31.5	Above	13.5413	40.75	Above
	V2-M2	Above Mat	9.1691	31.5	Above	14.8814	40.75	Above
	V2-M3	Above Mat	9.0909	31.5	Above	13.6891	40.75	Above
	V2- M4	Platform	9.514	31.5	Above	14.232	40.75	Above
2	**V1-M1**	Above Mat	5.48105	4	Above	4.8911	12.5	Above
	V1-M2	Above Mat	5.07785	4	Above	4.68605	12.5	Above
	V1-M3	Above Mat	5.52825	4	Above	4.358	12.5	Above
	V1- M4	Platform	5.39765	4	Above	4.1465	12.5	Above
	V2-M1	Above Mat	9.131	31.5	Above	12.3042	31.5	Above
	V2-M2	Above Mat	8.1634	31.5	Above	10.9134	31.5	Above
	V2-M3	Above Mat	8.8435	31.5	Above	10.8774	31.5	Above
	V2- M4	Platform	8.10465	31.5	Above	9.57885	31.5	Above
3	**V1-M1**	Above Mat	3.84895	4	Above	3.04275	12.5	Above
	V1-M2	Above Mat	3.8364	4	Above	2.90125	12.5	Above
	V1-M3	Above Mat	3.82255	4	Above	2.7945	12.5	Above
	V1- M4	Platform	3.68435	4	Above	2.7745	12.5	Above
	V2-M1	Above Mat	11.62275	31.5	Above	14.3914	31.5	Above
	V2-M2	Above Mat	11.4515	31.5	Above	13.997	31.5	Above
	V2-M3	Above Mat	11.76354	31.5	Above	14.6267	31.5	Above
	V2- M4	Platform	11.5553	31.5	Above	14.2943	31.5	Above

4	**V1-M1**	Above Mat	4.89905	4	Above	3.5592	12.5	Above
	V1-M2	Above Mat	4.8133	4	Above	3.48945	12.5	Above
	V1-M3	Above Mat	4.87015	4	Above	3.36875	12.5	Above
	V1- M4	Platform	4.7564	4	Above	3.55105	12.5	Above
	V2-M1	Above Mat	11.2924	31.5	Above	14.3355	31.5	Above
	V2-M2	Above Mat	12.0636	31.5	Above	14.4234	31.5	Above
	V2-M3	Above Mat	12.3457	31.5	Above	14.6143	31.5	Above
	V2- M4	Platform	12.21515	31.5	Above	15.1638	31.5	Above
5	**V1-M1**	Above Mat	5.70775	4	Above	4.4014	12.5	Above
	V1-M2	Above Mat	5.00035	4	Above	4.2386	12.5	Above
	V1-M3	Above Mat	6.07275	4	Above	4.7756	12.5	Above
	V1- M4	Platform	5.66995	4	Above	4.47425	12.5	Above
	V2-M1	Above Mat	9.81035	31.5	Above	11.878	31.5	Above
	V2-M2	Above Mat	9.7698	31.5	Above	11.996	31.5	Above
	V2-M3	Above Mat	9.59045	31.5	Above	12.5519	31.5	Above
	V2- M4	Platform	9.7894	31.5	Above	11.8876	31.5	Above
6	**V1-M1**	Above Mat	0.8412	3.15	Within	0.7494	12.5	Below
	V1-M2	Above Mat	0.8542	3.15	Within	0.7521	12.5	Below
	V1-M3	Above Mat	0.8564	3.15	Within	0.76265	12.5	Below
	V1- M4	Platform	0.88555	3.15	Within	0.7677	12.5	Below
	V2-M1	Above Mat	9.41615	31.5	Above	13.0785	31.5	Above
	V2-M2	Above Mat	9.1761	31.5	Above	13.025	31.5	Above
	V2-M3	Above Mat	8.75215	31.5	Above	12.2129	31.5	Above
	V2- M4	Platform	9.24305	31.5	Above	14.266	31.5	Above
7	**V1-M1**	Above Mat	1.4493	5.6	Above	1.2564	12.5	Below
	V1-M2	Above Mat	1.18695	4	Above	1.13955	12.5	Below
	V1-M3	Above Mat	1.22795	3.15	Above	1.213	12.5	Below
	V1- M4	Platform	1.25235	5	Above	1.17595	12.5	Below
	V2-M1	Above Mat	12.2598	31.5	Above	16.175	31.5	Above
	V2-M2	Above Mat	11.68695	31.5	Above	14.8713	31.5	Above
	V2-M3	Above Mat	12.10375	31.5	Above	15.464	31.5	Above
	V2- M4	Platform	12.24775	31.5	Above	15.7408	31.5	Above
8	**V1-M1**	Above Mat	1.3752	5	Above	1.0095	12.5	Below
	V1-M2	Above Mat	1.2891	5	Above	0.96865	12.5	Below
	V1-M3	Above Mat	1.2949	5	Above	0.9408	12.5	Below
	V1- M4	Platform	1.3712	5	Above	1.04055	12.5	Below
	V2-M1	Above Mat	10.3633	31.5	Above	12.7255	31.5	Above
	V2-M2	Above Mat	10.5448	31.5	Above	13.279	31.5	Above
	V2-M3	Above Mat	10.8033	31.5	Above	13.6022	31.5	Above
	V2- M4	Platform	10.3077	31.5	Above	13.6142	31.5	Above

9	V1-M1	Above Mat	1.76965	5	Above	1.30715	12.5	Below
	V1-M2	Above Mat	1.74755	5	Above	1.30155	12.5	Below
	V1-M3	Above Mat	1.8081	5	Above	1.32835	12.5	Below
	V1- M4	Platform	1.7473	5	Above	1.31505	12.5	Below
	V2-M1	Above Mat	11.773	31.5	Above	14.6792	31.5	Above
	V2-M2	Above Mat	11.50625	31.5	Above	14.2254	31.5	Above
	V2-M3	Above Mat	11.65645	31.5	Above	14.65	31.5	Above
	V2- M4	Platform	12.0059	31.5	Above	14.9405	31.5	Above
10	V1-M1	Above Mat	1.44145	5	Above	1.11355	12.5	Below
	V1-M2	Above Mat	1.4013	5	Above	1.11885	12.5	Below
	V1-M3	Above Mat	1.5651	5	Above	1.23135	12.5	Below
	V1- M4	Platform	1.47075	5	Above	1.08885	12.5	Below
	V2-M1	Above Mat	10.7255	31.5	Above	13.9283	31.5	Above
	V2-M2	Above Mat	10.74435	31.5	Above	14.1113	31.5	Above
	V2-M3	Above Mat	11.031	31.5	Above	14.4429	31.5	Above
	V2- M4	Platform	11.02745	31.5	Above	14.7508	31.5	Above

Table 4: MEAT values in the z-axis for each participant during WBV collection and V1.

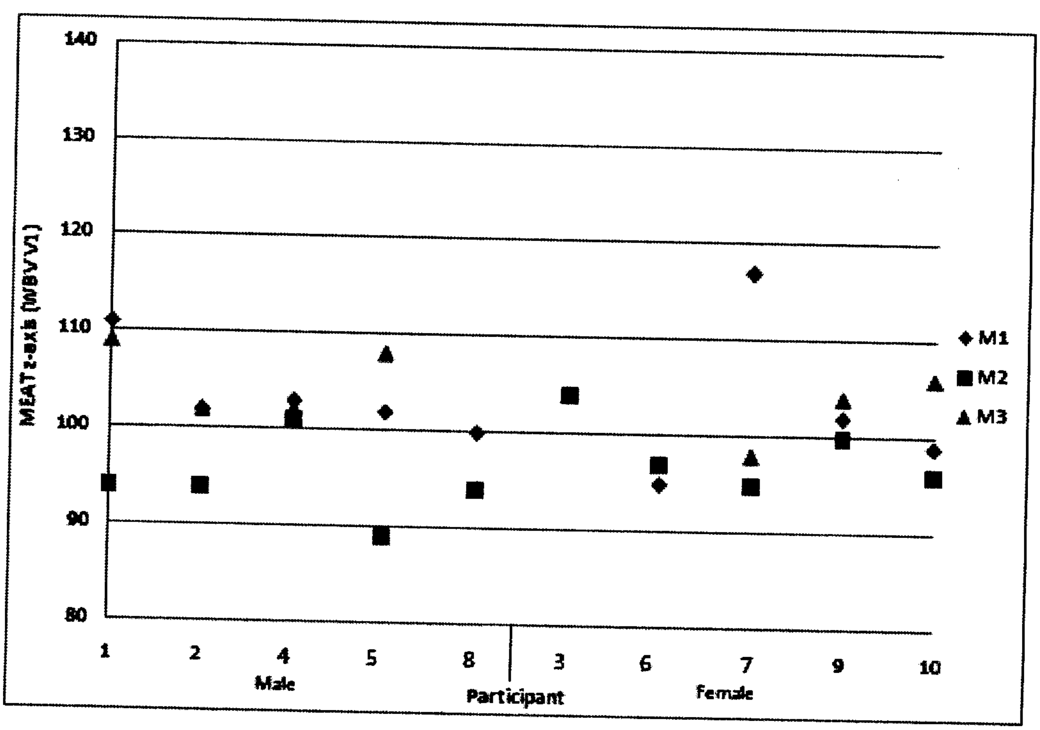


Table 5: MEAT values in the z-axis for each participant during WBV collection and V2.

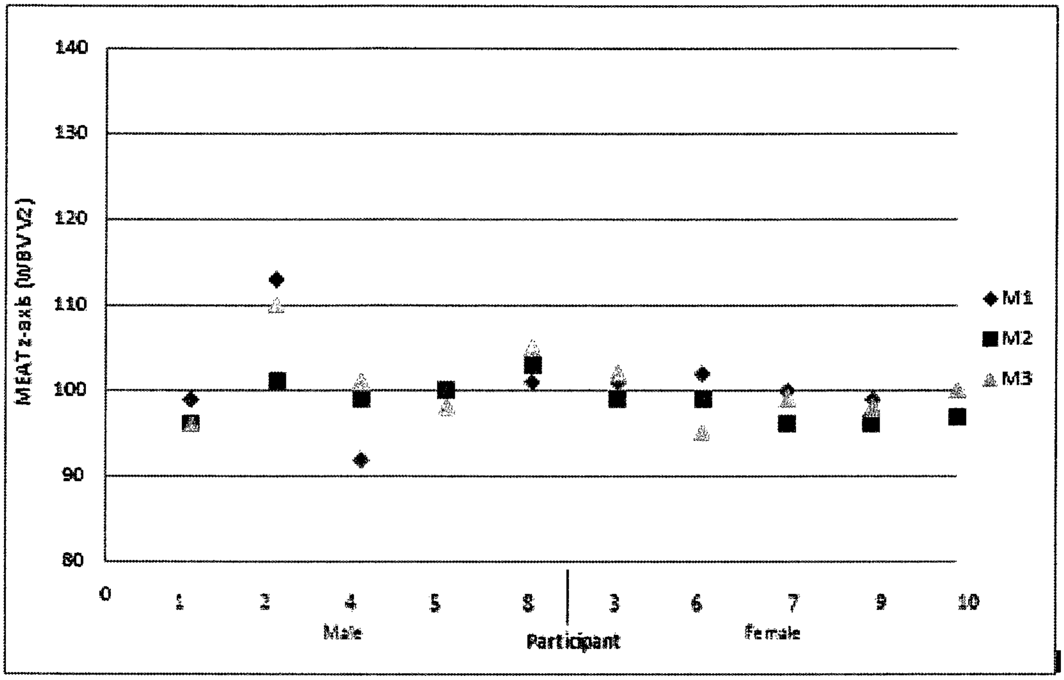


Table 6: MEAT values in the z-axis for each participant during HAV collection and V1.

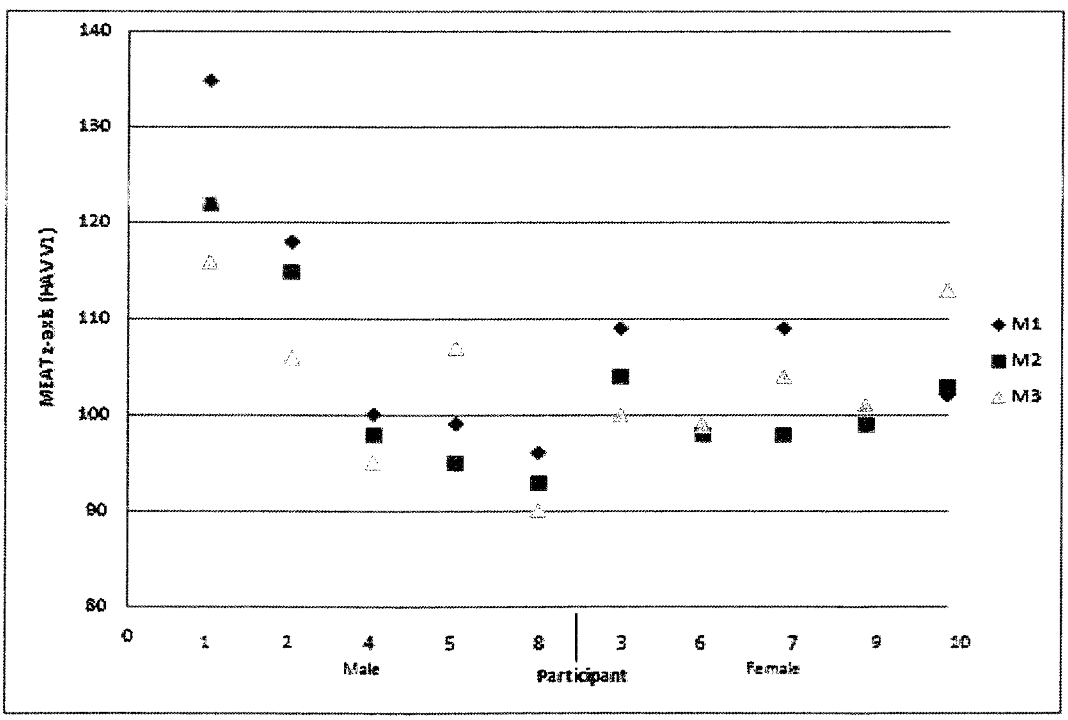
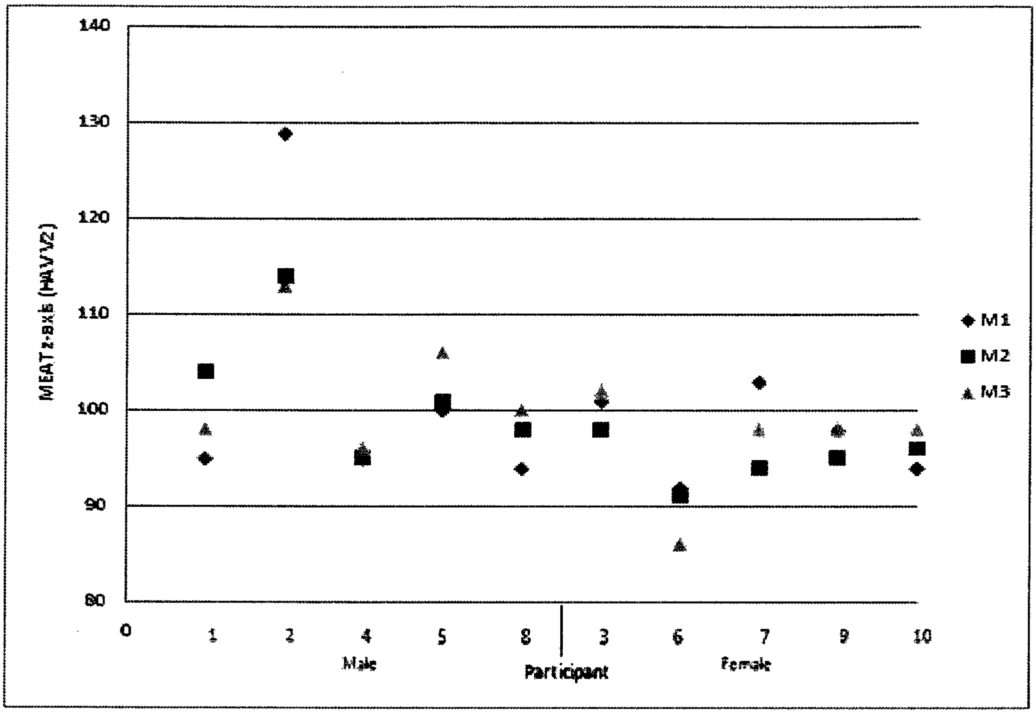


Table 7: MEAT values in the z-axis for each participant during HAV collection and V2.



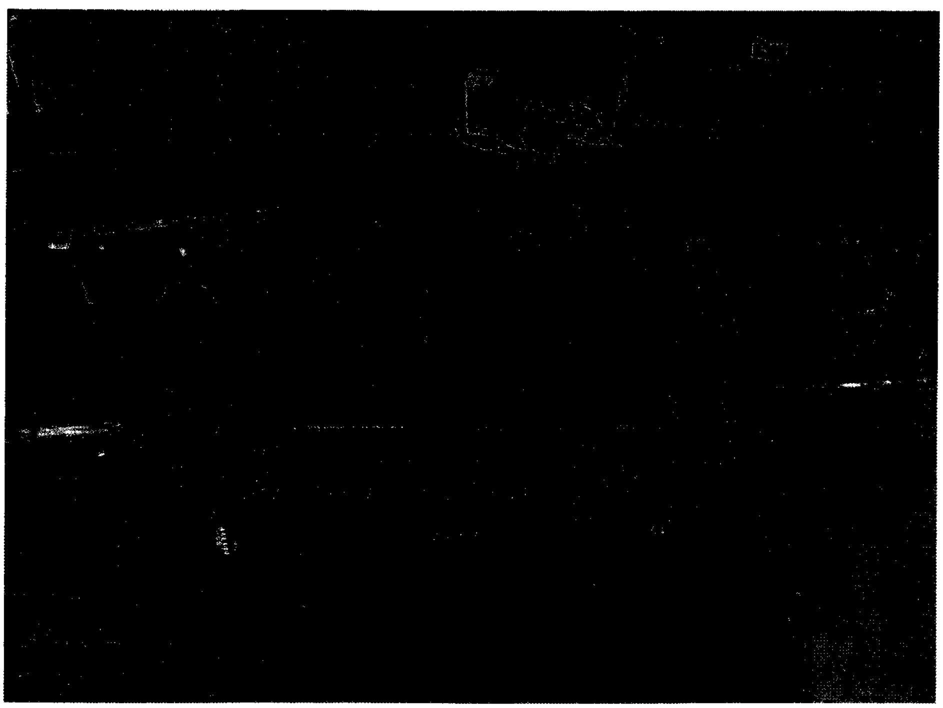


Figure 1: Vibration simulator platform used to generate vibration platform 1 (No mat condition shown)

Figure 2: Mat 2 tested on vibration profile1

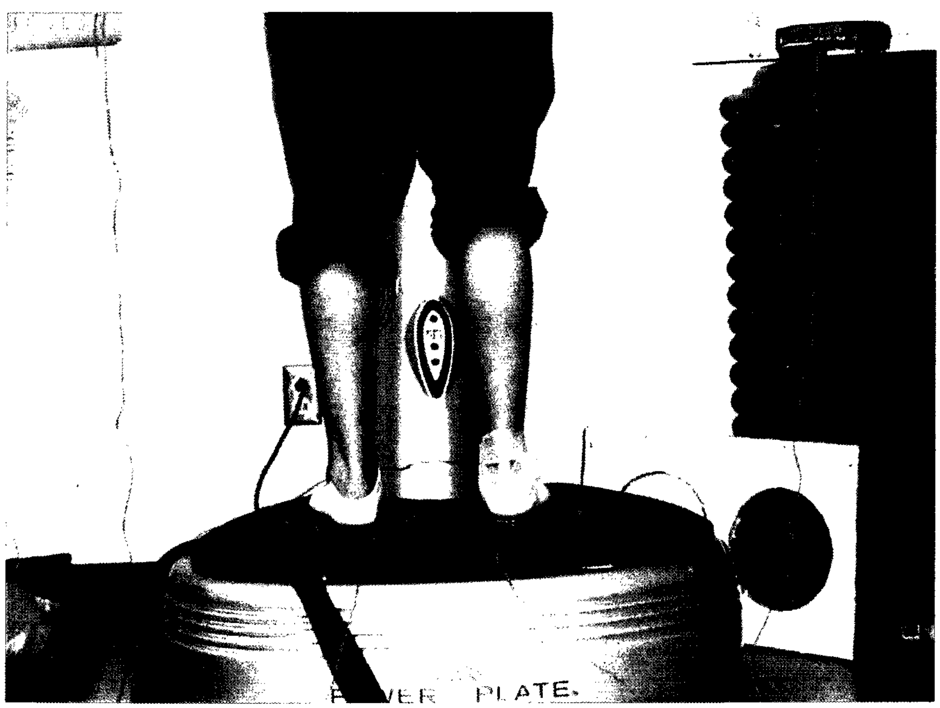


Figure 3: Mat 1 tested on vibration profile 2