Establishing a protocol for the measurement of human exposure to foot-transmitted vibration

by

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Abstract

Foot-transmitted vibration (FTV) is defined as vibration exposure where the primary route of vibration transmission is through the feet. Individuals can be exposed to FTV through a vibrating platform that they stand on or from vibrating foot-operated controls. Workers exposed to FTV are at risk of suffering from vibration white-foot, an irreversible disease with vascular, neurological and musculoskeletal symptoms. In order to understand injury risk, the transmission of vibration from a vibrating surface into the foot can be measured. The international standards for the measurement of occupational vibration exposure (ISO 2631-1, 1997; ISO 5349-1, 2001) do not provide appropriate guidance for FTV exposure measurement. Although several researchers have reported worker exposure to FTV, the reliabilities of the methods used to measure FTV have yet to be studied.

The purpose of this thesis is to propose a reliable protocol for the measurement of FTV exposure (Vance FTV Measurement Protocol, V-FTVMP). Preliminary testing was conducted to examine how factors such as location of accelerometer placement on the foot, changes in standing posture, time of day that measurements are taken, and duration of measurement, influence measures of FTV exposure. These findings were translated into the V-FTVMP. Inter-rater and intra-rater reliability of the proposed method for the measurement of FTV transmissibility were determined by testing the protocol with three raters and 12 participants. Transmissibility was measured at the toe as the ratio of vibration input (measured on the platform) to vibration output (measured on the surface of the toe), with values over one indicative of vibration amplification and less than one indicative of attenuation. Transmissibility was also calculated as a ratio at the ankle with input measured at the platform and output measured from the medial malleolus of the ankle. Mean un-weighted root-mean-squared (r.m.s.) accelerations (z-axis) for all accelerometer locations were calculated for all participants and found to be 13.01 m/s^2 (±0.87), 12.68 m/s^2 (±1.19), 8.23 m/s^2 (±2.24), and 16.05 m/s^2 (±3.81) for measures at the platform at the toe, platform at the ankle, toe at the first metatarsal head and ankle at the medial malleolus, respectively. The mean transmissibility for all participants was measured as 0.63 (±0.16) at the toe, and 1.27 (±0.30) at the ankle. The intraclass correlation tests showed good or acceptable reliability for all locations: platform location at the toe ICC =.83 (CI =.67 -.92), platform at ankle ICC =.82 (CI=.65-.92), toe ICC =.77 (CI =.37 -.81), ankle ICC =.60 (CI =.18 -.68). Based on the results of this study, it appears the V-FTVMP can generate reliable measures of FTV. Additional research led by independent groups is needed to confirm these results and to further validate the protocol.

Keywords

Vibration, standardization, standing, reliability, validation, measurement protocol.

Co-Authorship Statement

Author Contributions:

All phases of data collection and analysis were led by Brandon Vance in consultation with Dr. Eger. Dr. Oddson assisted with statistical analysis in Chapter 3 and methodological guidance for Chapters 2 and 3. Dr. Godwin provided additional support and assistance with methodological development. Dr. Eger, Dr. Oddson, and Dr. Godwin all provided editorial assistance in writing.

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Glossary

Abbreviation	**Long Form**
DF	dominant frequency
FTV	foot-transmitted vibration
FTVMP	foot-transmitted vibration measurement protocol
HAV	hand-arm vibration
HAVS	hand-arm vibration syndrome
ICC	intraclass correlation
ISO	International Organization for Standardization
MATlab	matrix laboratory
r.m.s.	root-mean-square
SD	standard deviation
VWF	vibration white finger
VWFt	vibration white foot
WBV	whole-body vibration

Terminology and Definitions

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

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

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

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

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

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

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

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

ISO 2631-1: The International Standard for Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration.

ISO 5349-1: The International Standard for Mechanical Vibration – Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration.

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

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

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

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

Vibration: An oscillatory motion about a fixed reference point.

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

Chapter 1: Literature Review

1. Vibration Basics

Vibration is a mechanical movement that oscillates about a fixed point and requires a structure through which to travel (Mansfield, 2005). Vibration can enter the body through any point in contact with a vibrating surface such as the hands when in contact with vibration tools (hand-arm vibration), the buttock when sitting on a seat (whole-body vibration), and the feet when standing on a vibrating platform (foot-transmitted vibration). The mechanical response of humans to vibration is dependent on the frequency, magnitude and direction of the vibration, as well as the person's posture and orientation (Griffin, 1990).

Vibration magnitude can be described as displacement in meters (m), velocity in meters per second (m/s) or acceleration in meters per second squared (m/s^2); it is typically expressed as the average root mean square acceleration (r.m.s. m/s^2). The direction in which the vibration is travelling at the point of contact with the human is another key component of vibration exposure. Vibration can be measured in the x (fore-aft), y, (lateral) and z (vertical) orthogonal axes as well as their rotational components in a 6-degree of freedom signal. The duration, typically measured in seconds, is another characteristic that affects the human response to vibration (Griffin, 1990). Exposure to vibration over an extended period of time may result in vibration injury, especially at higher magnitudes (Mansfield, 2005). Lastly, the frequency of vibration is defined as the number of cycles per second and is measured in Hertz (Hz). The frequency is a critical aspect to an individual’s response to vibration exposure (Griffin, 1990), as vibration at specific frequencies can cause injury to the body due to a phenomenon known as resonance (Welcome et al., 2008).

1.1. Transmissibility

Vibration transmissibility is the ratio of the measured acceleration of vibration between two points (Mansfield, 2005). In terms of describing FTV exposure, transmissibility is a ratio of vibration input and output calculated by measuring the acceleration at a vibrating platform, and measuring the acceleration on the foot segment on the heel or metatarsal, for example. A transmissibility value greater than one indicates that the vibration is being amplified, whereas a value less than one indicates vibration is attenuated. Amplification is linked with increased injury risk as it suggests exposure occurred at a frequency of resonance (Mansfield, 2005).

1.2. Resonance

The resonant frequency of a region within the human body will cause substantial displacement of the organs within the skeletal structure and cause strain on the tissues involved (Randall et al., 1997). Animal studies have shown that exposure to vibration at frequencies at which resonance occurs is linked to higher tissue damage (Welcome et al., 2008). Resonance frequencies of various body regions have been studied and discovered for individuals exposed to WBV and HAV. The frequencies of greatest concern for individuals exposed to WBV are in the range of 1-20Hz (Mansfield, 2005). For exposure to HAV, the resonance frequency of the hands and fingers exceed 100Hz (Griffin, 1990). Randall et al. (1997) found that the overall range of resonant frequencies for standing subjects to be 9-16Hz. Harazin and Grzesik (1998) investigated standing transmissibility of subjects and showed resonance at the ankle for frequencies between 4-8Hz and 25-63Hz (Harazin & Grzesik, 1998) and at the metatarsal for frequencies between 31-125Hz. Interestingly, Kiiski and colleagues (2008) investigated the effect of frequency and magnitude on vertical transmissibility while standing and found peak accelerations occurred at 10-40Hz for the ankle, 10-25Hz for the knee, and 10-20Hz for the hip. The discrepancy in reported resonance from the two studies may be due to the differences in standing posture of the participants. In Kiiski et al.'s study participants remained in a normal standing position with their knees slightly bent for all trials; In Harazin & Grzesik's study ten different standing postures were tested.

1.3. General Health Effects

Workers that operate equipment while standing on a vibrating surface are at an increased risk of suffering from vibration white-foot, an irreversible disease with vascular, neurological and musculoskeletal symptoms (Thompson et al., 2010). Vascular effects of vibration exposure involve symptoms of coldness in the extremities, changes in skin temperature, and vasospastic disease (Schweigert, 2002). Neurological damage occurs from continuous vasoconstriction and direct damage to the nerves, often resulting in numbness and tingling in the toes (Schweigert, 2002; Eger et al., 2014). Vasospastic disease is diagnosed by vibration-exposure history, symptoms of cold-intolerance in the feet, evidence of vasospasm detected by cold-provocation digital plethysmography, and symptoms of toe blanching detected and measured by the Stockholm vascular scale (House et al., 2010). It is suggested that these health effects are dependent on the frequency of the vibration exposure (Eger et al., 2014).

Exposure to whole-body vibration (WBV) in the workplace is associated with an increased risk for low-back pain, sciatic pain, and degenerative changes in the spinal column such as intervertebral disc disorders (Bovenzi, 2005). WBV can affect the spine by mechanical overloading and excessive muscular fatigue (Bovenzi, 2005).

Individuals exposed to hand-arm vibration (HAV) are at risk of suffering from hand-arm vibration syndrome (HAVS) (ISO 5349-1, 2001; Matoba, 1994). HAVS is an occupational disease involving vascular, sensorineural and musculoskeletal problems, which may all contribute to an upper-body disability (House et al, 2010).

1.4. Discomfort

Vibration discomfort, as defined by Mansfield (2005) is a point below a comfort threshold where participants exposed to vibration reported that they would not change their activity to reduce its magnitude. Exposure to FTV may contribute to discomfort, annoyance or interfere with activities. Sensations felt during vibration exposure vary in strength according to the vibration magnitude, frequency, direction and the contact conditions with the vibrating surface (Morioka & Griffin, 2010). Only a few researchers have reported the relationship between discomfort and FTV exposure characteristics. Leduc and colleagues (2011) reported discomfort values associated with FTV exposure with underground mine workers and found that jumbo drillers, bolters and raise operators, exposed to dominant frequencies between 30 and 40Hz reported higher discomfort values (Leduc et al., 2011; Eger et al., 2014). A field study by Goggins (unpublished Master's thesis, 2013) involving 17 machine operators in a mine reported musculoskeletal discomfort and injuries prior to testing. Only two of the 17 operators reported no discomfort, and five workers reported severe or very severe ache, pain, numbness or discomfort. Additionally, twelve participants specifically reported discomfort in the lower limbs (Goggins, 2013).

2. Foot-Transmitted Vibration

2.1. Epidemiological Evidence of Vibration-Induced Injury

Prevalence of injury for WBV and HAV exposure has been widely documented and published. It is estimated that 4-7% of workers in Western countries are exposed to WBV (Bovenzi & Hulshof, 1999). Approximately 1.7- 5.8% of workers in the United States, Canada, and European countries are exposed to HAV, and the prevalence of vibration white finger (VWF) varies depending on the area and climate in which they are located (Bovenzi, 2005). According to Bovenzi (2005), epidemiological studies have documented that approximately 80-100% of workers exposed to high magnitude HAV in northern and colder climates have vibration white finger. There are no estimated prevalence rates for those exposed to FTV, as there is limited research in this field. Workers that are exposed to FTV include workers in mining, forestry, agriculture, construction, public transport, and more (Hedlund 1989; Eger et al., 2006, 2014; Thompson et al., 2010; Leduc et al., 2011).

As changes in equipment design were introduced to protect workers from HAVS, workers started to experience symptoms similar to HAVS in their feet. For example, drills used in industries such as mining moved from hand-held to platform-mounted. The effort to reduce exposure in the hands led to vibration exposure transmitted through the feet via the platform. There are few studies documenting injury from FTV exposure. In one of the studies available, over twenty percent of miners working off a raise platform showed symptoms of Raynaud's phenomenon in the toes (white toes) (Hedlund, 1989). Similarly, Thompson et al. (2010) reported an underground miner with 18 years of experience operating bolters off a raise platform and scissor lift was diagnosed with vibration-induced white-feet. The diagnosis was made with plethysmographic findings post-cold stress dampening in the toes, symptoms of primary blanching in the toes, and cold-intolerance in the feet. The 54 year-old individual reported vibration exposure from a bolter as being 3-4 hours per day, 3 days a week during the previous 4 years, in addition to exposure from other equipment in the past such as scissor lifts and load-haul-dump (LHD) vehicles (Thompson et al., 2010).

In a field study of northern Ontario mines, 2 out of 7 male workers reported they had been diagnosed with vibration white-foot (Leduc et al., 2011). These individuals had a mean age of 36 years with an average work experience of 17 years operating equipment that exposed them to FTV such as bolters, jumbo drills and locomotives. A similar field study of 27 underground workers with an average age of 46 years and 22 years of work experience were also investigated, and found that 75% of raise platform workers and 57% of jumbo drillers reported pain and discomfort in their feet; additionally, one worker reported a diagnosis of vibration white-foot (Eger et al., 2014).

2.2. Exposure Characteristics associated with Vibration White-Foot

Exposure frequencies between 30Hz and 50Hz appear to be associated with onset of vibration white foot (VWFt) and vibration discomfort (Leduc et al., 2011; Eger et al., 2014; Goggins et al., 2016). In the study by Hedlund (1989) physiological symptoms of the fingers and toes for fan drillers and raise drillers that were exposed to a vibration frequency around 40Hz were measured. Other types of equipment in underground mining that expose workers to FTV include the jumbo drill, scissor lift, locomotive, bolting platform, pit drill, cavo loader, muck machine and crusher plant (Eger et al., 2006; Thompson et al., 2010). Leduc and colleagues (2011) investigated the vibration frequency characteristics for five different types of mining equipment that expose operators to FTV, and they found that drilling off of wooden and metal raise platforms exposed workers to FTV with a dominant frequency of 40Hz, which was associated with an increased injury risk. Similarly, a recent field study measured vibration characteristics of various pieces of mining equipment in 6 underground mines (Eger et al., 2014) and found that the dominant FTV exposure frequency was 40Hz when drilling off a raise platform, and 30Hz when operating a jumbo drill. Therefore, it appears that frequencies between 30 and 50Hz are most highly linked to FTV injury, and workers operating equipment that exposes them to FTV in this frequency range may be at increased risk of injury.

2.3. FTV exposure measurement methods and limitations

Since there are no standards specific to FTV measurement and evaluation, researchers are limited to using ISO 2631 or ISO 5349 for direction. ISO 2631-1:1997 ‘Mechanical vibration and shock

– Evaluation of human exposure to whole-body vibration' is the standard typically used for WBV measurement and evaluation. For WBV measurement, an accelerometer is placed in a seat pad and is fixed to the operator's seat. ISO 5349-1 (for HAV measurement) provides guidelines for the mounting location of accelerometers on vibrating tools and hands of workers. This of course, does not apply to the measurement of FTV, as the primary source of vibration exposure is the vibrating platform the worker stands on and the primary route of exposure is through the feet. Neither ISO 2631-1 nor ISO 5349-1 provide guidance on where to mount accelerometers on the feet for the measurement of FTV transmissibility.

Furthermore, the frequency-weighting curve applied in ISO 2631-1 (1997) (W_d) covers a frequency range between 0.5-80Hz, but places emphasis on frequencies below 20Hz. Several researchers have suggested this standard may not be appropriate for the measurement of exposure to vibration when standing, particularly if the dominant exposure frequency is believed to be above 20Hz (Thompson et al, 2010; Leduc et al., 2011). For example, field studies (Leduc et al., 2011; Eger et al., 2014) have shown that workers are experiencing negative health effects when being exposed to drills and equipment operating at dominant frequencies of 30 and 40Hz. Therefore, some researchers have suggested ISO 5349-1 might be more appropriate as the weighting curves in this standard place more emphasis on higher frequencies (Leduc et al., 2011; Eger et al., 2014). However, there are still limitations in using ISO 5349-1 for the assessment and evaluation of FTV. For example, the frequency weightings, although most likely better than ISO 2631-1, may not be entirely suitable for the evaluation of FTV, as the frequencies of concern for the feet have been suggested to be at or above 40Hz (Goggins et al., 2016). The frequency weighting in ISO 5439-1 & 2 for HAV measurement covers a frequency range of 8-1000Hz however, after the 16Hz range the weighting continually decreases (ISO 5349-1, 2001).

2.4. FTV Transmissibility Measurement

To measure FTV transmissibility, researchers typically mount one accelerometer on a vibrating platform and 1-3 accelerometers on the participant's foot (Eger et al., 2014). If performing a controlled laboratory experiment, the platform accelerometer is usually placed as close as possible to the foot; in field measurements this can be more difficult. In the field, such as on a drilling platform in an underground mine, the platform accelerometer is typically placed as close as possible to the foot but in an area where it would not be damaged. Previous studies of FTV exposure (Table 1.1) reveal the inconsistency of measurement locations and accelerometer attachment methods between studies. For example, of the 15 studies identified as measuring vibration exposure while standing, only two studies used the same measurement locations and they were studies led by the same author (Singh et al. (2011; Singh, 2012). Two other studies using the same measurement location were field studies led by Eger et al. (2014) and Leduc et al. (2011) where vibration was only measured on the vibrating surface. A standardized protocol for measurement of FTV is required to reduce measurement uncertainty.

Table 1.1: Review of FTV measurement methods used in previous studies

Author (year)	Title	Locations of FTV measurement	Type of study
Abercromby et al. (2007)	Vibration exposure and biodynamic responses during whole-body vibration training	- Platform - Head	Lab
Byrnell (2016) unpublished Masters thesis	Personal protective equipment as a control strategy to reduce foot-transmitted vibration	- platform - underside of heel	Lab
Caryn (2011) (unpublished Masters thesis)	Transmission of whole-body vibration from exercise platforms	- platform - greater trochanter - 5th lumbar vertebrae - frontal bone of	Lab

		skull	
Eger et al. (2014)	Vibration induced white-feet: overview and field study of vibration exposure and reported symptoms in workers	- platform	Field
Friesenbichler et al. (2014)	Vibration transmission to lower extremity soft tissues during whole-body vibration	- skin at triceps surae of the calf - quadriceps femoris	Lab
Goggins et al. (2016)	Study of the biodynamic response of the foot to vibration exposure	- two locations on the platform - first metatarsal head - lateral malleolus	Lab
Harazin & Grzesik (1998)	The transmission of vertical whole-body vibration to the body segments of standing subjects	- metatarsus (unspecified), - medial malleolus, - knee - hip - shoulder - head.	Lab
Kiiski et al. (2008)	Transmission of vertical whole body vibration to the human body	- medial malleolus - knee - hip - lumbar spine	Lab
Leduc et al. (2011)	Examination of vibration characteristics, and reported musculoskeletal discomfort for workers exposed to vibration via the feet	- platform	Field
Leduc et al. (2011)	Evaluation of transmissibility properties of anti-fatigue mats used by workers exposed to foot-transmitted vibration	- platform - surface of the mat	Lab
Matsumoto & Griffin (1998)	Dynamic response of the standing human body exposed to vertical vibration: influence of posture and vibration magnitude	- T1 - T8 - L4 - left and right iliac crests - knee	Lab
Singh et al. (2011)	Evaluation of gender differences in foot-transmitted vibration	- platform - lateral malleolus	Lab

Singh (2012) (unpublished Masters thesis)	Evaluation of foot-transmitted vibration and transmissibility characteristics of mining boots and insoles	- platform - lateral malleolus	Lab
Singh et al. (2016)	Site-specific transmission of a floor-based, high-frequency, low-magnitude vibration stimulus in children with spastic cerebral palsy	- platform - medial malleolus - lateral condyle of femur	Lab
Wee & Voloshin (2013)	Transmission of vertical vibration to the human foot and ankle	- medial malleolus - tibial tuberosity (while seated)	Lab

3. Measurement Uncertainty for Vibration Assessment

The ISO 21748:2010 states that knowing the measurement uncertainty is essential to the interpretation of results. According to Fornasini (2008), every practical physical measurement has some uncertainty; evaluating the measurement uncertainty is vital in assessing the reliability of technical procedures and to establish the validity limits of theories in research. Generally, the uncertainty in physical measurements is influenced by factors such as operating characteristics of the instrument, interaction between the instrument and system under measurement, interaction between the instrument and experimenter, measurement methodology, and environmental conditions (Fornasini, 2008). Terms related to uncertainty include reproducibility and repeatability of measurements. Repeatability is assessed under conditions where the same operator, using the same equipment within short intervals of time, obtains the measurements with the same method, on identical measurement items, in the same facility. Reproducibility on the other hand, requires measurements to be obtained with the same method on identical measurement items, in different measurement facilities, with different operators using different equipment (ISO 3534-2:2006).

According to Mansfield (2005) even with guidance on accelerometer placement outlined in ISO 5349-2, uncertainty in measurements of HAV can be as high as 40% due to variability of the vibration in the work environment and the precise mounting location for the accelerometers. It is imperative to take necessary precaution as a researcher when measuring to avoid making mistakes. Other factors that may play a role in measurement uncertainty, as per ISO 5349-1 (2001), involve the location of accelerometers, electrical interference, changes in the method of work, changes in posture of the worker, changes in the condition of the vibrating tool, and others. Furthermore, the investigator mounting the accelerometers during set-up can influence measurement error and/or uncertainty with their differences in skill and experience handling the equipment (ISO 5349-1, 2001). Hewitt (1998) explains how misalignment of the adaptor for HAV measurement is a major source of variability in measures and will result in transmissibility measurement errors. Experiments have shown that participants can rotate the adaptor off-axis up to 10-40° when mounting it to the palm, donning a glove, and gripping a hand tool; this amount of misalignment can lead to overestimation in the true transmissibility by 20% (Hewitt, 1998; Dong et al. 2002). A study by Dong et al. assessing anti-vibration gloves found that yaw misalignment of the hand-mounted adaptors contributed to the highest measurement error of glove transmissibility. The study suggests that the high inter and intra-subject variability observed was mainly due to adaptor misalignment (Dong et al., 2002).

4. Factors Influencing Transmissibility Measurement

Measurement of vibration transmissibility can be affected by several factors including (but not limited to) exposure frequency (Randall et al., 1997), accelerometer positioning (ISO 2631-1, 1997; ISO 5349-1,2, 2001), posture (Paddan & Griffin, 1993), time of day, and inter-subject variability (Laszlo & Griffin, 2011).

4.1. Exposure Frequency

It has been noted that vibration frequency can affect transmissibility, as different locations of the human body will amplify under exposure to certain frequencies (i.e. resonance), as per Randall et al. (1997), and more recently by Wee and Voloshin (2013) in a study investigating FTV exposure.

4.2. Accelerometer Location and Positioning

The location where an accelerometer is attached to the foot could affect transmissibility measures; however, it is unknown to what extent transmissibility would change as a result of the accelerometer shifting by a few degrees or by a few centimeters. As a comparison, ISO 2631-1 (1997) emphasizes that the accelerometer/seat pad alignment must be within a 15° range. For HAV measurement, experiments have shown that participants can rotate the adaptor off-axis up to 10-40° when mounting accelerometers to the palm, donning a glove, and gripping a hand tool and can alter transmissibility by 20% (Hewitt, 1998; Dong et al. 2002). ISO 5349 (2001) (Part 1 and 2) states the importance of mounting the accelerometers as close as possible to the centre of the gripping zone for any tool. The standard also emphasizes the importance of precisely reporting the location of the accelerometer and the need to mount them as rigid as possible. Even with this guidance on accelerometer placement outlined in ISO 5349-2 (2001), uncertainty in measurements of HAV can be as high as 40% due to variability of the vibration in the work environment and the mounting location for the accelerometers (Mansfield, 2005). Human factors may also tie in to this as differences in the researcher mounting the accelerometer could play a role in accelerometer positioning with their differences in skill and experience handling the equipment (ISO 5349-1, 2001). A study by Dong et al. (2002) assessing anti-vibration gloves found that the high inter and intra-subject variability observed was mainly due to adaptor misalignment.

4.3. Posture

Previous studies have measured transmissibility for standing participants exposed to vibration through the feet. Paddan and Griffin (1993) measured floor-to-head transmissibility for standing subjects across a frequency range of 0.1-50Hz for different standing postures. The authors found changes in transmissibility occurred with changes in knee joint angle. Specifically, it was reported that at frequencies beyond 8Hz, locking the knees increases transmissibility. Harazin & Grzesik (1998) found similar findings above 25Hz, as 50% of the changes observed in transmissibility were due to changes in the ten postures that were investigated. Additionally, Matsumoto and Griffin (1998) studied the influence of three postures (normal, legs bent, and one leg) on the dynamic response of the body exposed to vibration at a frequency range of 0.5 – 30Hz and found that the resonant frequencies of the apparent masses changed for each posture. Damping of mechanical energy (reducing transmission of vibration) can be achieved by compliance of the ankle, knee, and hip joints (Abercromby et al., 2007). In the experiment by Abercromby and colleagues, it was found that knee angles should be at 26-30° flexion in order to minimize damage from vibration exposure while standing on a platform vibrating at 30Hz. Standing posture can also influence vibration transmissibility due to changes in contact area on the vibrating surface. Individual differences in foot contact area and centre of pressure influences the anatomical structures in the foot and surrounding soft tissues, which changes the way vibration is transmitted (Goggins et al., 2016). Therefore, the standing posture adopted during measures of FTV exposure measurement should be controlled to minimize measurement variability.

4.4. Foot Composition and Impact of Time of Day

The foot is one of the most complex structures in the body, consisting of many small bones, ligaments, cartilages, tendons, muscles, and fat tissue to maintain structure, perform movements, and absorb impacts (Morales-Orcajo et al., 2016). Differences in foot and ankle swelling, blood volume, and water volume in the lower limbs, associated with time of day could possibly be a factor when studying FTV transmissibility. In a study by Man et al. (2004) lower limb volume was measured with an ankle volumeter on healthy, uninjured participants to determine the position that best reduces swelling in consideration for patients during physical therapy treatment. The researchers measured foot volume under different postures and found that 30 minutes of motionless standing caused the greatest increase in foot and ankle volume compared to sitting and supine lying. In a study by Noddeland & Winkel, (1988) the effect that leg activity and skin temperature had on foot swelling was investigated. Significantly more swelling was reported in the inactive foot, and in the morning compared to the afternoon. Additionally, research by Voloshin et al. (1998) and Mercer et al. (2003) suggests that muscle fatigue and physical activity significantly decreases the musculoskeletal system's ability to attenuate shock waves and impact vibrations. This raises some questions as to whether or not time of day can influence vibration transmissibility. Previous research suggests that lower limb volume can change as a function of time due to temperature, activity level, hours spent awake, inactivity, etc. (Noddeland & Winkel, 1988; Man et al., 2004). If vibration transmissibility in the feet is affected by foot and ankle swelling, physical activity, and muscle fatigue, then it would be logical to consider time of day when conducting vibration experiments to control for changes in foot composition.

4.5. Inter-subject Variability

Biological tissues, such as those that are found in the foot, experience inter-subject variability as well differences due to sex and age (Morales-Orcajo et al., 2016). Differences in individuals' anthropometrics such as foot surface area, mass, and a person's biodynamic responses could lead to variability in vibration transmissibility. Matsumoto and Griffin (1998) conducted a study on the dynamic response to standing vibration exposure and found relatively large inter-subject variability in their findings of peak transmissibility measured across 6 parts of the body. Furthermore, Laszlo and Griffin (2011) evaluated different anti-vibration gloves to quantify their vibration attenuation properties to HAV exposure and the authors found the inter-subject variability in transmissibility was as large as the variability between gloves.

Mass will also vary between individuals and has been proven to influence how vibration is transmitted through the body (Mansfield, 2005). A study by Wee and Voloshin (2013) found that resonance frequencies of the medial malleolus and tibial tuberosity varied with an increase of applied mass. These individual differences should be acknowledged when assessing FTV exposure and accurately documented when recording data.

5. Method Development and Validation

Developing and validating a method is important to ensure correct measurement and observation (Rogers, 2013). According to Rogers, key elements for method validation include determining the specificity, accuracy, precision, limit of detection, linearity & range, and robustness & ruggedness. Furthermore, Rogers (2013) went on to define accuracy as the capability of a method to determine the correct measurement; robustness as a method’s ability to produce consistent results under various normal conditions such as the use of different laboratories, researchers, and instruments; ruggedness as a method’s ability to produce results consistently when conditions have been intentionally altered; precision as the ability of a method to produce consistent results and is determined by its repeatability, intermediate precision, and reproducibility; repeatability as the consistency of results between trials run by the same researcher under all the same conditions; intermediate precision as the consistency of a second researcher within the same lab under the same conditions and reproducibility is the consistency between different laboratories and researchers (Rogers, 2013).

Reliability is defined as the degree to which measures yield consistent results and this must be assessed if research is to be truly scientific (Peter, 1979). Unreliable methods reduce the correlation between measures so if reliability is not assessed and the correlation between measures is low, the researcher would not be able to conclude whether the difference between measures is real or due to an unreliable method (Peters, 1979). An intraclass correlation statistical test (ICC) can provide a useful estimate of test-retest reliability, intra-rater reliability, and inter-rater reliability for quantitative data (Landers, 2015; Koo & Li, 2016). Inter-rater reliability "reflects the variation between two or more raters who measure the same group of subjects" and intra-rater reliability "reflects the variation of data measured by one rater across two or more trials" (Koo & Li, 2016). ICC provides a measure that represents the degree of correlation as well as the agreement between measures (Koo & Li, 2016). According to Koo and Li (2016), a research study should always involve at least three raters when evaluating the reliability of a method.

A study by Al-Masri & Amin (2005) provides an example of how a developed method can be validated using similar processes as described by Rogers (2013). Researchers compared three techniques for the determination of uranium in environmental samples by using the Eurachem guide on method validation. This was determined by identifying each method's detection limits, reproducibility, repeatability and uncertainty. The repeatability limit was identified by analyzing ten duplicates of a soil sample under repeatable conditions, with a known uranium concentration. The reproducibility limit was estimated by analyzing ten duplicates of a soil sample (with a known uranium concentration) but with at least one condition changed in the process such as the researcher, instrument, or time of day (Al-Masri & Amin, 2005). Another study by Tiryaki (2006) used a similar approach by determining limits of detection, accuracy, precision, ruggedness, and robustness to validate a method used for pesticide residue analysis. In this study, four thin layer chromatography detection methods were validated based on single-laboratory criteria (Tiryaki, 2006).

To date, no procedures have been used to establish a method for the measurement of vibration transmissibility through the foot. Hence, elements such as the robustness, ruggedness, and precision (or reliability) of the developed method should be captured in the process of validation. Furthermore, it is important to know how reliable FTV measurement methods are in order to determine the effectiveness of interventions aimed at reducing vibration exposure.

6. Thesis Objectives

The purpose of this research is to create a reliable protocol for measuring human exposure to FTV. A series of trials were conducted to develop a protocol for the measurement of FTV exposure (Vance FTV Measurement Protocol; V-FTVMP). This protocol was then evaluated. The ruggedness of the protocol was tested by observing changes in FTV measures due to alterations in the location and orientation of the measurement accelerometer, standing posture of participant, time of day that measurements were taken, and duration of measurement. The specific objectives of the experiments were to determine the effect that the independent variables (posture, trial duration, time of day, accelerometer location and orientation) had on the dependent variables (un-weighted r.m.s. accelerations, and transmissibility). Second, a detailed protocol for FTV measurement transmissibility was established and the reliability of the method was determined for the V-FTVMP.

6.1 Rationale of the Study

Accurate and reliable measurement of FTV is important in order to determine health risks associated with exposure to FTV and to determine potential benefits of controls designed to mitigate exposure to FTV. Previous methods for FTV measurement have not been evaluated for reliability, yet evidence suggests that factors such as the attachment location and orientation of the measurement accelerometer, standing posture, time of day, and duration of measurement may have an influence on FTV transmissibility measurement (Harazin & Grzesik, 1998; Abercromby et al., 2007; Paddan and Griffin, 1993; ISO 5349-1 & 2, 2001). Researchers need to know the reliability and validity of FTV measurement methods in order to improve the ability to diagnose vibration injury and test interventions aimed at reducing vibration exposure in the workplace.

6.2 Thesis Outline

To address the objectives of the study the thesis was written with the following chapters:

Chapter 1: Review of the Literature – This chapter was written to provide relevant background information to better understand the research problem. Topics such as vibration knowledge, health effects, factors associated with FTV measurement, and validation of methods are discussed.

Chapter 2: Preliminary Testing of Variables to Establish a Foot-Transmitted Vibration Measurement Protocol – The purpose of this chapter was to establish the Vance FTV Measurement Protocol by conducting a series of preliminary tests designed to understand the contribution of several factors (accelerometer location and orientation, posture, time of day, and trial duration) leading to variability of FTV measures.

Chapter 3: Manuscript: Evaluation of the Inter-Rater and Intra-Rater Reliability of a Method for the Measurement of Foot-Transmitted Vibration - The purpose of this chapter was to determine the inter-rater and intra-rater reliability of the Vance FTV Measurement Protocol. To complete this study, three research assistants independently measured three repeated trials of FTV exposure on 12 participants. The specific objective of the experiment was to determine the reliability coefficient for each of the dependent variables (r.m.s. un-weighted acceleration in z-axis, vector sum acceleration, and transmissibility in z-axis) for 4 accelerometer locations (platform [2], toe, and ankle).

Chapter 4: General Discussion – The purpose of this chapter is to discuss the relevance of this thesis in general, to workers, researchers, industry, and standards committees.

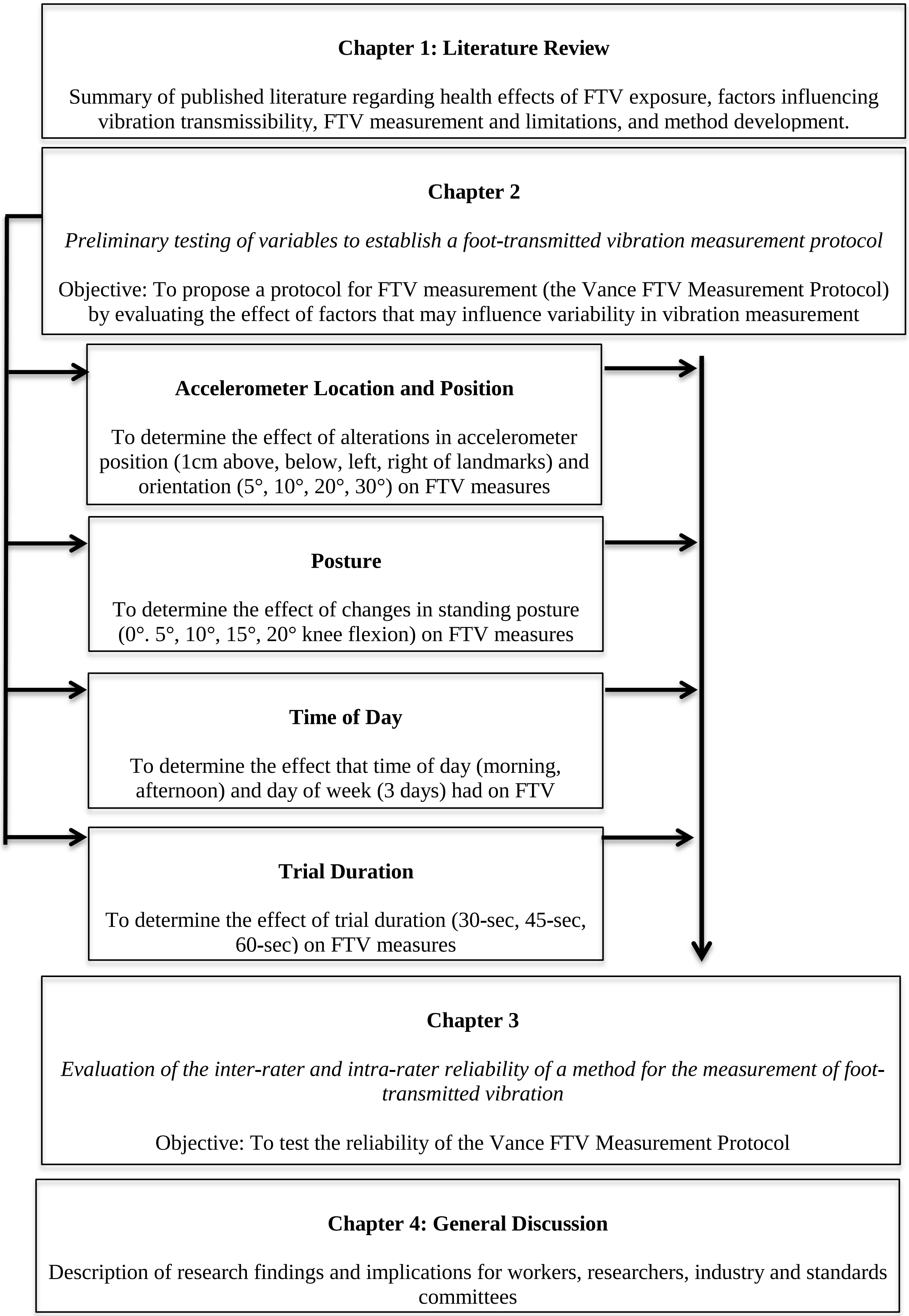

Figure 1.1: Overview of the relationship between the chapters presented in this dissertation

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Chapter 2: Preliminary Testing of Variables to Establish a Foot-Transmitted Vibration Measurement Protocol

1. Introduction

Workers in mining, construction, and agriculture can be exposed to foot-transmitted vibration (FTV) when standing on platforms that vibrate or when operating foot controls of mobile equipment (Hedlund 1989; Eger et al., 2006, 2014; Thompson et al., 2010; Leduc et al., 2011). Workers exposed to FTV can be at an increased risk of suffering from vibration white-foot, an irreversible disease with vascular, neurological and musculoskeletal symptoms (Thompson et al., 2010). In order to determine injury risk, the transmission of vibration from a vibrating surface into the foot can be measured. To measure FTV transmissibility, researchers typically mount one accelerometer to the vibrating platform and 1-3 accelerometers to the participant's foot (Eger et al., 2014). Although a standard protocol for placement does not exist, previous studies have placed the accelerometers on the first metatarsal head and/or the ankle (Harazin & Grzesik, 1998; Wee & Voloshin, 2003; Kiiski et al., 2008; Singh et al., 2011; Singh et al., 2016; Goggins et al., 2016).

1.1. FTV Measurement Limitations

Although several researchers have reported worker exposure to FTV (Leduc et al., 2011; Eger et al., 2014; Goggins et al., 2016), the reliability of the method used to measure FTV has yet to be studied. Furthermore, international standards for the measurement of occupational vibration exposure (ISO 2631-1; ISO 5349-1) do not provide appropriate guidance for FTV exposure measurement. ISO 2631-1:1997 'Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration' is the standard typically used for WBV measurement, which includes exposure to the vibration when standing, lying down or sitting. However, several researchers have suggested this standard may not be appropriate for the measurement of FTV (Thompson et al, 2010; Leduc et al., 2011) as this method is designed to measure vibration transmitted to the whole body, as opposed to a body segment (ISO 2631-1, 1997). ISO 5349-1 (2001) provides guidelines for the mounting location of accelerometers on the vibrating tools and hands of workers. This of course, does not apply to the measurement of FTV, as the primary source of vibration exposure is the vibrating platform the worker stands on and the primary route of exposure is through the feet. Therefore, neither ISO 2631-1 or ISO 5349-1 provide guidance on where to mount accelerometers on the feet for FTV transmissibility measurement, as such, researchers have placed them on different locations leading to variability in reported exposure values.

If performing a controlled laboratory experiment, the platform accelerometer is usually placed as close as possible to the foot; in field measurements this can be more difficult. When conducting vibration exposure measurements in the field, such as on a drilling platform in an underground mine, the accelerometer is typically placed as close as possible to the foot but in an area where it will not be damaged. Published measures of FTV exposure are limited and there is no standard method used for measurements.

1.2. Measurement Uncertainty

Every practical physical measurement has some uncertainty involved in its result; evaluating the measurement uncertainty is vital in assessing the reliability of technical procedures and to establish the validity limits of theories in research (Fornasini, 2008). Generally, the uncertainty in physical measurements are influenced by factors such as operating characteristics of the instrument, and interactions between instruments, systems, experimenters, measurement methodology, and environmental conditions (Fornasini, 2008). According to Mansfield (2005) even with guidance on accelerometer placement outlined in ISO 5349-2 (2001), uncertainty in measurements of HAV (in the field) can be as high as 40% due to variability of the work environment and the precise locations of the accelerometers. Other factors that may play a role in measurement uncertainty, as per ISO 5349-1 (2001), involve the location and orientation of accelerometers, electrical interference, changes in the method of work, changes in posture of the worker, changes in the condition of the vibrating tool, and others. Furthermore, the investigator mounting the accelerometers during set-up can also influence measurement error and/or uncertainty due to differences in skill and experience handling the equipment (ISO 5349-1, 2001). Hewitt (1998) explains how misalignment of the adaptor for HAV measurement is a major source of variability in measures and will result in transmissibility measurement errors. Experiments have shown that participants can rotate the adaptor off-axis up to 10-40° when mounting it to the palm, donning a glove, and gripping a hand tool; this amount of misalignment can overestimate the true transmissibility by 20% (Hewitt, 1998; Dong et al. 2002). A study by Dong et al. (2002) assessing anti-vibration gloves found that yaw misalignment of the hand-mounted adaptors contributed to the highest measurement error of glove transmissibility. The study suggests that the high inter and intra-subject variability observed was mainly due to adaptor misalignment (Dong et al., 2002).

1.3 Method Development

Developing and validating a method is important to ensure correct measurement and observation (Rogers, 2013). According to Rogers, key elements for method validation include determining the specificity, accuracy, precision, limit of detection, linearity & range, and robustness & ruggedness. Rogers (2013) defines accuracy as the capability of a method to determine the correct measurement, robustness as a method's ability to produce consistent results under various normal conditions such as the use of different laboratories, researchers, and instruments;

ruggedness as a method's ability to produce results consistently when conditions have been intentionally altered; precision as the ability of a method to produce consistent results and is determined by its repeatability, intermediate precision, and reproducibility; repeatability as the consistency of results between trials run by the same researcher under all the same conditions; intermediate precision as the consistency of a second researcher within the same lab under the same conditions and reproducibility is the consistency between different laboratories and researchers (Rogers, 2013).

1.3. Purpose and Rationale

The purpose of this research is to create a reliable protocol for measuring human exposure to FTV (Vance FTV Measurement Protocol, V-FTVMP). A series of preliminary tests were conducted to understand the contribution of several factors leading to variability of FTV measures. The ruggedness of the current method used to measure FTV exposure was determined by investigating the effect that alterations in: location and orientation of accelerometer placement, standing posture of participant, time of day of measurement, and duration of measurement had on FTV transmissibility measurement. The specific objectives of the preliminary tests were to determine the effect that the independent variables (posture, duration, time of day, accelerometer location and orientation) had on the dependent variables (un-weighted r.m.s. accelerations and transmissibility).

Developing a reliable protocol for the measurement of FTV is important in order to determine health risks associated with exposure to FTV, and to determine potential benefits of controls designed to mitigate exposure to FTV. Researchers in this field need to know the reliability and validity of FTV measurement methods to advance and improve techniques to diagnose vibration injury, and to test interventions aimed at reducing vibration exposure in the workplace.

2. Methodology

The Laurentian University Research Ethics Board approved the methodology in this study and all participants gave informed consent prior to vibration measurement.

2.1. Participants

Two participants were recruited from a sample of convenience. These participants were aged 23 and 25 years, with a height of 179 cm and 184 cm, and weight of 78.5 kg and 72.9 kg.

2.2. Vibration Measurement

FTV transmissibility was measured with four ADXL 326, 19g miniature tri-axial accelerometer (Windsor, ON) (Figure 2.1). Accelerometers were mounted to the platform, lateral malleolus of fibula (ankle), metatarsal head of big toe, and the midfoot. The accelerometers were secured to the participant and the platform with the protocol outlined in Appendix A. Measurements were recorded at a sampling frequency of 1000Hz and stored on two portable data loggers (DataLog MWX8; Biometrics Ltd., Newport, UK) (Figure 2.2). The ADXL 326 accelerometers (also known as teardrop accelerometers) were calibrated according to Goggins et al. (2016) prior to recording the measurements.

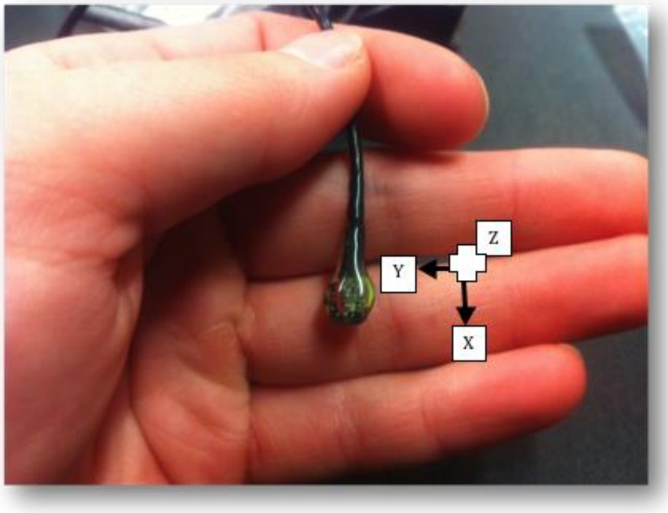


Figure 2.1: ADXL 326 19g accelerometer with orientations

Figure 2.2: DataLog MWX8

2.3. Posture Measurement

A twin-axis goniometer SG150 (Biometrics Ltd, Newport, UK) (Figure 2.3) was used to measure and monitor knee joint angle of the participants in real-time during Test Session 2. The goniometer was attached by having the participant standing straight so that the knee was in full extension (0°). The goniometer was mounted to the lateral side of the left leg with double-sided tape with the two leads above and below the knee joint. Knee flexion angles were monitored and measured at 0°, 5°, 10°, 15° and 20°.

2.4. Vibration Profile

A vibration exercise platform (T-Zone Vibration Technology) (Figure 2.4) was used to generate the vibration exposure profile at a dominant frequency 6.3Hz in the z-axis. The same vibration exposure was chosen for all trials for both participants in all four test sessions. Un-weighted root mean squared acceleration (r.m.s. m/s^2) was measured for each trial at four locations: vibration platform under the heel, lateral malleolus, midfoot, first metatarsal head (Figure 2.8).

FTV transmissibility was calculated at three locations during all trials using the following equations:

Equation 1: $$T_{ankle} = \frac{a_z(ankle)}{a_z(platform)}$$

Where a_z(ankle) is the un-weighted r.m.s. acceleration on the lateral malleolus, and a_z (platform) is the un-weighted r.m.s. average acceleration on the platform under the heel.

Equation 2: $$T_{midfoot} = \frac{a_z(midfoot)}{a_z(platform)}$$

Where a_z (midfoot) is the un-weighted r.m.s. acceleration on top of the midfoot, and a_z (platform) is the un-weighted r.m.s. acceleration on the platform under the heel.

Equation 3: $$T_{toe} = \frac{a_z(toe)}{a_z(platform)}$$

Where a_z (toe) is the un-weighted r.m.s. acceleration on top of the first metatarsal head, and a_z (platform) is the un-weighted r.m.s. acceleration on the platform under the heel.

2.5. Experimental Protocol

Four test sessions were completed over five days in order to evaluate the impact of changes to accelerometer location and orientation, standing posture of participants, time of day of measurement, and trial duration on FTV measures. Figure 2.5 provides a visual representation of how the test sessions were carried out for the entire length of data collection. Figure 2.9 describes the rationale for testing these variables and the considerations that were made for testing.

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Week 1	**Session 1**	**Session 2**	**Session 3&4**		**Session 3&4**		
	Accelerometer Positioning	Posture Alterations	Morning Testing		Morning Testing		
			Afternoon Testing		Afternoon Testing		
Week 2		**Session 3&4**					
		Morning Testing					
		Afternoon Testing					

Figure 2.5: Experimental protocol for pilot testing

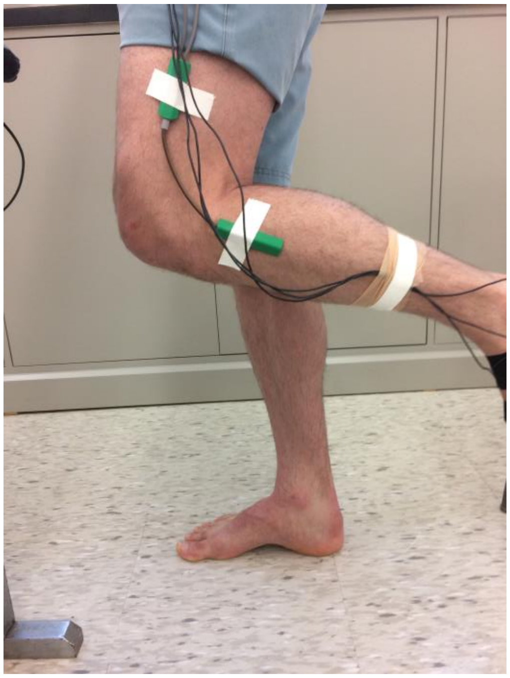


Figure 2.3: Twin-axis goniometer SG150 secured to participant to monitor knee flexion

Figure 2.4: T-Zone vibration exercise platform used to generate the vibration exposure

2.5.1. Test Session 1: Accelerometer positioning

Participants were instructed to stand on the platform so that their left heel was planted directly over the accelerometer on the machine (Figure 2.8) with their feet shoulder-width apart and a slight bend in their knees. Participants were exposed to vibration for 45 seconds for all trials in this session with the following conditions: researcher rotated the accelerometer 5°, 10°, 20°, 30°, and shifted the accelerometers 1cm above, below, left and right of all desired landmarks (Figure 2.6). The desired landmarks were the centre of the lateral malleolus of fibula (ankle), centre of the metatarsal head of big toe, and the midfoot (2cm distal of the ankle joint, slightly lateral of the midline of the foot) (Figure 2.7).

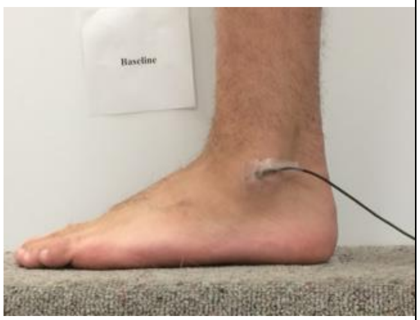
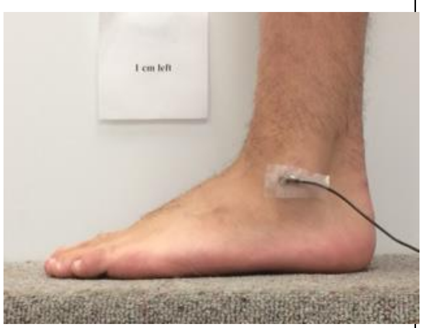
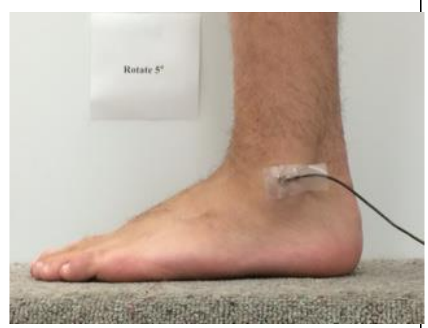
i - Baseline	ii – 1 cm up	iii – 1 cm down
		
iv – 1 cm left	**v – 1 cm right**	**vi – Rotate 5°**
		
vii - Rotate 10°	**viii - Rotate 20°**	**ix - Rotate 30°**
		

Figure 2.6: Test Session 1 procedure: accelerometer manipulations (top left shows baseline condition, ii-v shows shifts in position, and vi-ix show changes in rotation)

2.5.2. Test Session 2: Posture Alterations

Participants were exposed to vibration for 45 seconds for all trials in this session. Participants were instructed to stand on the platform so that their left heel was planted directly over the accelerometer on the machine with their feet shoulder-width apart and with each of the following postures: knee flexion angles at 0°, 5°, 10°, 15° and 20°.

2.5.3. Test Session 3: Time of day

Participants were instructed to stand on the platform so that their left heel was planted directly over the accelerometer on the machine with their feet shoulder-width apart and a slight bend in their knees. FTV measurements were taken twice per day (morning and afternoon) on three different days (day 1, day 3, and day 7). Participants were exposed to vibration for two consecutive minutes in each trial (to meet the objectives for the next test session).

2.5.4. Test Session 4: Trial duration

The participants were exposed to vibration for two consecutive minutes. Each trial was divided and analyzed as 30-second, 45-second, and 60-second trials.

Figure 2.7: Accelerometer locations: first metatarsal head, midfoot, lateral malleolus (left: top view; right: sagittal view)

Figure 2.8: Platform-mounted accelerometer under the heel

Factors influencing foot-transmitted vibration measurement		
	From the literature for whole-body vibration and hand-arm vibration	**Laboratory tested (Chapter 2)**
Accelerometer Location and Position	- For WBV measurement, accelerometer/seat pad alignment should remain within a 15º range - (ISO 2631-1, 1997) - For HAV measurement, off-axis accelerometer rotation of 10-40º can alter transmissibility measures up to 20%. (Hewitt, 1998; Dong et al., 2002; ISO 5349-1, 2004)	- Locations: 1) platform, 2) lateral malleolus, 3) first metatarsal head, 4) midfoot - Accelerometers were rotated 5°, 10°, 20°, 30°, and shifted 1cm above, below, left and right of all desired landmarks
Posture	- Changes to knee angle can change transmissibility measurements up to 50% (Paddan & Griffin, 1993; Matsumoto & Griffin, 1998; Harazin & Grzesik, 1998)	- Knee flexion angles at 0°, 5°, 10°, 15° and 20°.
Time of Day and Trial Duration	- Lower limb volume can vary over the course of the day due to temperature, activity level, hours spent awake, and inactivity (Noddeland & Winkel, 1988; Man et al., 2004) - Muscle fatigue and physical activity significantly decreases ability to attenuate impact (Voloshin et al., 1998; Mercer et al., 2003)	- Measurements were taken twice per day (morning and afternoon) on three different days (day 1, day 3, and day 7) - Two-minute trials were analyzed in 30, 45, and 60-second windows
Inter-Subject Variability	- Biological tissues in the foot differ based on sex and age (Morales-Orcajo et al., 2016) - Differences in foot anthropometrics can lead to vibration transmissibility measurement variation (Laszlo & Griffin, 2011) - Participant mass influences transmissibility (Mansfield, 2005)	

Figure 2.9: Summary of the factors influencing FTV measurement from the literature and laboratory testing

2.6. Data Analysis

Vibration data from each test session were processed using a Vibratools custom MATLab program, (Appendix D) (The Mathworks Inc., MA, USA v 7.1.). Un-weighted root-mean-squared accelerations in the x, y, and z-axes were recorded. Transmissibility from the platform-toe, platform-ankle, and platform-midfoot were calculated according to Equations 1, 2, and 3. Means and standard deviations were calculated for each test session to determine the effect that each independent variable (accelerometer location, posture, time of day, trial duration) had on un-weighted r.m.s. acceleration and FTV transmissibility. Data from the z-axis (vertical direction) were used for analysis since this axis is the most valuable in assessing vibration exposure, as it is found in most studies to be the dominant axis for FTV exposure (Leduc et al., 2011; Eger et al., 2014). The middle 30-seconds of each trial was selected for analysis to reduce signal noise from the beginning and end of each trial in Test Sessions 1-3. Data were analyzed for 30, 45, and 60-seconds for Test Session 4. No inferential testing was conducted for these preliminary tests. The results are descriptions of the range, mean, standard deviation, and coefficient of variation of measures at each location.

3. Results

3.1. Effect of accelerometer positioning

Shifting and rotating the accelerometers away from the baseline condition resulted in varying FTV measures for all locations (Table 2.2). At the ankle location, shifting the accelerometers (up, down, left, right) resulted in changes to calculated transmissibility (vertical axis) ranging from 0.80 to 1.03 for Participant 1 and from 0.96 to 1.36 for Participant 2. Shifting the accelerometer 1cm down from the medial malleolus is the condition that altered transmissibility the most from baseline for both participants. When rotating the accelerometer at the ankle (5°, 10°, 20°, 30°**)**, transmissibility changes from baseline ranged from 1.03 to 1.27 for Participant 1 and from 0.96 to 1.21 for Participant 2. Rotation at 20° and 5° are the conditions that changed transmissibility the most. Mean floor-ankle transmissibility was 1.08 (SD=0.14) for Participant 1 and 1.14 for Participant 2 (SD=0.14). The relative variability of transmissibility measured at the ankle location was approximately 13%.

Floor-midfoot transmissibility ranged from 0.15 to 0.26 when shifting the accelerometer (baseline to shifting up) and from 0.11 to 0.15 when rotating the accelerometer (5° from baseline) for Participant 1. For Participant 2, floor-midfoot transmissibility ranged from 0.18 to 0.52 (shifting right) and from 0.52 to 0.73 (5° rotation). There was a considerable difference observed between the two participants for measurements taken at the midfoot location. The average transmissibility for Participant 1 at the midfoot was 0.15 (SD=0.05) compared to 0.60 (SD=0.19) for Participant 2. The relative variability of measures at this location were similar for both participants at 33% and 32% respectively.

Floor-toe transmissibility for Participant 1 ranged from 0.80 to 0.92 (shift right) and 0.74 to 0.92 (5° rotation). For Participant 2 floor-toe transmissibility ranged from 1.0 to 1.06 (shift left) and 1.0 to 1.16 (20° rotation). The toe location measures were associated with the least relative variability compared to the other locations with a coefficient of variation of 8% for Participant 1 and 7% for Participant 2.

Table 2.1: Test Session 1 data: un-weighted r.m.s. acceleration and transmissibility in the vertical axis

Participant	Trial	Un-weighted r.m.s. acceleration (m/s^2)				Transmissibility		
		Platform	**Ankle**	**Midfoot**	**Toe**	**Floor-Ankle**	**Floor-Midfoot**	**Floor-Toe**
1	Baseline	3.52	3.61	0.55	3.23	1.03	0.15	0.92
	Shift 1cm up	3.45	4.05	0.89	3.22	1.17	0.26	0.93
	Shift 1cm down	3.48	2.78	0.42	2.98	0.80	0.12	0.86
	Shift 1cm left	3.41	3.91	0.66	3.22	1.15	0.19	0.94
	Shift 1cm right	3.48	3.98	0.47	2.79	1.14	0.13	0.80
	Rotate 5°	3.52	3.80	0.39	2.61	1.08	0.11	0.74
	Rotate 10°	3.51	3.56	0.51	3.17	1.01	0.14	0.90
	Rotate 20°	3.58	4.54	0.45	3.12	1.27	0.12	0.87
	mean	**3.50**	**3.78**	**0.54**	**3.04**	**1.08**	**0.15**	**0.87**
	sd	**0.05**	**0.50**	**0.16**	**0.23**	**0.14**	**0.05**	**0.07**
	cv	**1%**	**13%**	**30%**	**8%**	**13%**	**33%**	**8%**
2	Baseline	3.41	3.26	1.79	3.42	0.96	0.52	1.00
	Shift 1cm up	3.42	4.30	1.69	3.53	1.26	0.50	1.03
	Shift 1cm down	3.39	4.60	2.44	3.30	1.36	0.72	0.97
	Shift 1cm left	3.40	4.11	2.80	3.60	1.21	0.82	1.06
	Shift 1cm right	3.41	4.04	0.61	3.35	1.18	0.18	0.98
	Rotate 5°	3.45	4.17	2.51	3.83	1.21	0.73	1.11
	Rotate 10°	3.46	3.73	2.01	3.99	1.08	0.58	1.15
	Rotate 20°	3.42	3.11	2.12	3.96	0.91	0.62	1.16
	Rotate 30°	3.48	3.78	2.41	3.91	1.09	0.69	1.12
	mean	**3.43**	**3.90**	**2.04**	**3.65**	**1.14**	**0.60**	**1.07**
	sd	**0.03**	**0.48**	**0.64**	**0.27**	**0.14**	**0.19**	**0.07**
	cv	**1%**	**12%**	**31%**	**7%**	**12%**	**32%**	**7%**

3.2. Effect of posture alterations

There was very little variability in FTV measures as a result of changing standing posture (Table 2.3) as observed by the small range in transmissibility measures. Transmissibility in the vertical axis ranged from 0.70 – 0.76 at the ankle, 0.68 – 0.71 at the midfoot, and 0.97 – 0.99 at the toe for Participant 1. 20° knee flexion was the condition that altered transmissibility the most for all locations. Transmissibility data from Participant 2 ranged from 1.0 – 1.09 at the ankle, 0.9 – 1.03 at the midfoot, and 0.92 – 0.96 at the toe. 20° knee flexion altered transmissibility the most at the midfoot and toe, but 5° was the condition that changed floor-ankle measures the most.

Table 2.2: Test Session 2 data: un-weighted r.m.s. acceleration and transmissibility in vertical axis for changes in knee angle

Participant	Trial	Un-weighted r.m.s. acceleration (m/s^2)				Transmissibility		
		Platform	Ankle	Midfoot	Toe	Floor-Ankle	Floor-Midfoot	Floor-Toe
1	Normal 0˚ knee flexion	3.43	2.39	2.32	3.32	0.70	0.68	0.97
	5˚ knee flexion	3.55	2.38	2.41	3.49	0.67	0.68	0.98
	10˚ knee flexion	3.58	2.57	2.52	3.51	0.72	0.70	0.98
	15˚ knee flexion	3.61	2.68	2.47	3.56	0.74	0.68	0.99
	20˚ knee flexion	3.67	2.80	2.59	3.64	0.76	0.71	0.99
	mean	**3.57**	**2.56**	**2.46**	**3.51**	**0.72**	**0.69**	**0.98**
	sd	**0.09**	**0.18**	**0.10**	**0.12**	**0.04**	**0.01**	**0.01**
	cv	**3%**	**7%**	**4%**	**3%**	**6%**	**1%**	**1%**
2	Normal 0˚ knee flexion	3.10	3.10	2.81	2.84	1.00	0.90	0.92
	5˚ knee flexion	3.18	3.47	2.99	3.03	1.09	0.94	0.95
	10˚ knee flexion	3.31	3.54	3.30	3.11	1.07	1.00	0.94
	15˚ knee flexion	3.47	3.70	3.55	3.29	1.07	1.02	0.95
	20˚ knee flexion	3.64	3.86	3.75	3.48	1.06	1.03	0.96
	mean	**3.34**	**3.54**	**3.28**	**3.15**	**1.06**	**0.98**	**0.94**
	sd	**0.22**	**0.29**	**0.39**	**0.24**	**0.03**	**0.06**	**0.02**
	cv	**7%**	**8%**	**12%**	**8%**	**3%**	**6%**	**2%**

3.3. Effect of time of day

Floor-ankle transmissibility in the vertical axis for Participant 1 ranged from 0.73 – 0.94, floor-midfoot transmissibility ranged from 0.72 – 1.10, and floor-toe ranged from 0.94 – 1.0. For Participant 2, vertical axis transmissibility ranged from 0.56 – 0.83 at the ankle, 1.02 – 1.12 at the midfoot, and 0.86 – 1.03 at the toe (Table 2.4). At the midfoot location, there is 16% relative variability in measures from Participant 1 and only 4% from Participant 2.

3.4. Effect of trial duration

Changes in trial duration did not have an effect on FTV measures. Average un-weighted r.m.s. accelerations in the vertical axis did not change by more than $0.02 m/s^2$ if the data were analyzed for 30-seconds, 45-seconds, or 60-seconds (Table 2.5).

Table 2.3: Test Session 3 data: Un-weighted r.m.s. acceleration and transmissibility in vertical axis

Participant	Trial	Un-weighted r.m.s. acceleration (m/s^2)				Transmissibility		
		Platform	**Ankle**	**Midfoot**	**Toe**	**Floor-Ankle**	**Floor-Midfoot**	**Floor-Toe**
1	Day 1, morning	3.50	2.78	2.53	3.41	0.79	0.72	0.97
	Day 1, afternoon	3.57	2.61	2.75	3.40	0.73	0.77	0.95
	Day 3, morning	3.38	3.18	3.73	3.39	0.94	1.10	1.00
	Day 3, afternoon	3.55	3.10	3.39	3.36	0.87	0.95	0.95
	Day 7, morning	3.52	3.08	3.07	3.31	0.87	0.87	0.94
	Day 7, afternoon	3.70	2.90	3.89	3.59	0.78	1.05	0.97
	mean	**3.54**	**2.94**	**3.22**	**3.41**	**0.83**	**0.91**	**0.96**
	sd	**0.10**	**0.22**	**0.54**	**0.09**	**0.08**	**0.15**	**0.02**
	cv	**3%**	**7%**	**17%**	**3%**	**10%**	**16%**	**2%**
2	Day 1, morning	3.41	2.09	3.56	3.20	0.61	1.04	0.94
	Day 1, afternoon	3.48	2.88	3.91	3.42	0.83	1.12	0.98
	Day 3, morning	3.40	2.60	3.80	3.49	0.76	1.12	1.03
	Day 3, afternoon	3.59	2.54	3.81	3.45	0.70	1.06	0.96
	Day 7, morning	3.55	1.99	3.70	3.18	0.56	1.04	0.90
	Day 7, afternoon	3.67	2.54	3.74	3.14	0.69	1.02	0.86
	mean	**3.52**	**2.44**	**3.75**	**3.31**	**0.69**	**1.07**	**0.94**
	sd	**0.11**	**0.34**	**0.12**	**0.16**	**0.1**	**0.04**	**0.06**
	cv	**3%**	**14%**	**3%**	**5%**	**15%**	**4%**	**6%**

Table 2.4: Test Session 4 data for Participant 1 and 2

Location	Duration	Participant 1	Participant 2
		Mean r.m.s. m/s^2 (sd)	
Platform	30	3.54 (0.10)	3.52 (0.11)
	45	3.55 (0.10)	3.52 (0.11)
	60	3.56 (0.10)	3.52 (0.11)
Ankle	30	2.94 (0.22)	2.44 (0.34)
	45	2.96 (0.22)	2.44 (0.38)
	60	2.95 (0.22)	2.43 (0.39)
Midfoot	30	3.22 (0.54)	3.75 (0.12)
	45	3.24 (0.53)	3.76 (0.15)
	60	3.26 (0.52)	3.75 (0.16)
Toe	30	3.41(0.09)	3.31 (0.16)
	45	3.42 (0.09)	3.32 (0.17)
	60	3.43 (0.09)	3.32 (0.18)

4. Discussion

This preliminary testing was conducted to improve understanding of variables that might influence FTV measurement in order to develop a protocol for measuring FTV exposure (The Vance FTV Measurement Protocol, V-FTVMP). The first objective of this study was to determine the effect of shifting and rotating accelerometers' attachment locations on FTV measures. ISO 5439-1 (2001) states that accelerometer location is one of the factors that may influence vibration measurement uncertainty. Results from this test show that there is considerable variability in FTV measures at the midfoot location when the accelerometer positioning is slightly rotated or shifted off the baseline measurement location. At the midfoot location in particular, calculated transmissibility from Participant 1 ranged from 0.15 – 0.26 and 0.18 - 0.52 from Participant 2. Shifting the accelerometers 1cm down, up, right, and rotating them 5° and 20° resulted in the greatest measures deviating from baseline (Table 2.2). Furthermore, measures recorded for both participants at the midfoot varied approximately 33%. Mean midfoot transmissibility was found to be 0.15 for Participant 1 with a relative variability of 33% (SD=0.05) and calculated transmissibility varied 32% for Participant 2 (mean=0.60; SD=(0.19). Previous research on HAV exposure shows that carefully carrying out a test under the same repeatable conditions will lead to transmissibility results with a coefficient of variation of 5-6%; however, the repeatability decreases when the accelerometers are misaligned (Hewitt, 1998). According to Hewitt (1998), laboratory HAV measurements have been documented to alter transmissibility measures up to 20% when accelerometers are rotated 10° – 40° off-axis. FTV midfoot transmissibility measurements exceeded this variability limit during testing.

In these preliminary tests, accelerometers were also secured to the midpoint of the lateral malleolus and first metatarsal head. These are round bony landmarks with very little soft tissue, therefore it is logical to see that shifting the accelerometer slightly off-centre would change the measures as it could roll off the small bony protrusion and misalign the axes. Axis misalignment of the accelerometers is a strong contributor to measurement variability (Hewitt, 1998). Furthermore, vibration measurements at the toe location were relatively consistent varying approximately 7% compared to vibration measured at the midfoot (CV = 33%) and ankle (CV = 13%). Vibration measures at the midfoot location were the most inconsistent; however, it is possible that the variability was due to inconsistency of the researcher mounting the accelerometers. Consistently mounting the accelerometer to the midfoot proved to be more difficult as there was not a specific anatomical landmark to reference. The midfoot location was described as being placed 2cm distal of the ankle joint, and slightly lateral of the midline of the foot. Some of the variability seen at the midfoot location may also be attributed to greater movement of the soft tissues on top of the foot, as muscle contraction would occur and potentially cause more movement of the skin tissue the accelerometer was attached to. Due to inconsistency in vibration measures at the midfoot, the midfoot location is not recommended for FTV transmissibility measurement. Also, with respect to recommendations for development of the Vance FTVMP, researchers should mark the precise location and orientation of the accelerometers in order to be as consistent as possible when measuring repeated trials on a participant in a laboratory or field study, especially at the ankle location.

The second objective of this study was to determine the impact of variations in standing posture on measures of FTV. Bending the knees while standing on a vibrating surface is suggested to prevent rigidity in the body, resulting in increased vibration transmitted to the head, which can be very uncomfortable (Paddan & Griffin, 1993). In this test, slight changes in knee flexion angles were investigated to determine the impact on FTV measures. Previous research has shown that posture is a major factor to consider when measuring vibration transmissibility (Paddan & Griffin, 1993; Harazin & Grzesik, 1998), and reducing transmission of vibration can be achieved by compliance of the ankle, knee, and hip joints (Abercromby et al., 2007). Findings suggest that changes in knee angle (up to 20° knee flexion) did not considerably alter measures of acceleration or transmissibility (Table 2.3). Vertical axis transmissibility at the ankle ranged from 0.70 – 0.76 for Participant 1 and 1.0 – 1.09 for Participant 2 with relative variability in measures of approximately 5%. At the midfoot location, relative variability in transmissibility was approximately 4% and ranged from 0.68 – 0.71 for Participant 1 and 0.9 – 1.03 for Participant 2. As for the toe location, relative variability in transmissibility was approximately 2% and measures ranged from 0.97 – 0.99 from Participant 1 and 0.92 – 0.96 from measures on Participant 2. With such little variability in measures resulting from this test session, suggesting variations in knee flexion up to 20° will be acceptable when establishing guidelines for the V-FTVMP.

The objective of the third preliminary test was to determine if FTV exposure measures changed as a function of time-of-day or day-of-week. Measures were conducted in the mornings and afternoons on three different days of the week. Findings suggest that time of day and day of the week did not impact FTV measures (Table 2.4). Although previous research has not investigated the effect of measuring vibration exposure at different times of the day, it is widely documented that lower limb volume changes as a function of time and activity level (Voloshin et al., 1998; Mercer et al., 2003) and muscle fatigue can impact the body’s ability to attenuate vibrations (Noddeland & Winkel, 1988; Man et al., 2004). With this knowledge, time of day was considered with FTV measurement in this test session since changes in activity levels, muscle fatigue, and lower limb volume can be observed throughout the day. In the development of the V-FTVMP, it will be suggested that researchers can measure and record repeated trials on participants at different times of day and on repeated days of the week as there was no evidence found from this experiment to expect a considerable amount of variability in measures of acceleration and transmissibility. Measures varied the most at the midfoot location, with relative variability in transmissibility of 16% for Participant 1 but only varied 4% for measures from Participant 2. It is unlikely for this variability to be caused by the time of day or days of week, as a considerable difference in unweighted r.m.s. acceleration and transmissibility was observed between the two participants at the ankle and midfoot locations.

The final objective of this preliminary testing was to determine if trial duration had an impact on measures of FTV. Data were collected for two continuous minutes, and at three different intervals of time: 30-seconds, 45-seconds, and 60-seconds. FTV measures were calculated for

20-50 seconds, 20-65 seconds, and 20-80 seconds. Results from this test session suggest that there is no difference in r.m.s. accelerations or transmissibility measures when analyzing the data over different intervals of time. It is suggested, if appropriate for a laboratory study, to use a 30-second trial duration to minimize the total vibration exposure time on their participants, as there appears to be no changes in FTV measures at 45 or 60-seconds.

Factors influencing foot-transmitted vibration measurement(s)			
	From the literature for whole-body vibration and hand-arm vibration	**Laboratory tested (Chapter 2)**	**Results concluded for establishing measurement protocol (in Chapter 3)**
Accelerometer Location and Position	- For WBV measurement, accelerometer/seat pad alignment should remain within a 15º range (ISO 2631-1, 1997) - For HAV measurement, off-axis accelerometer rotation of 10-40º can alter transmissibility measures up to 20%. (Hewitt, 1998; Dong et al.,2002; ISO 5349-1, 2004)	- Locations: 1) platform, 2) lateral malleolus, 3) first metatarsal head, 4) midfoot - Accelerometers were rotated 5°, 10°, 20°, 30°, and shifted 1cm above, below, left and right of all desired landmarks	Do not measure at the midfoot location Accelerometers should maintain the same orientation and positioning throughout testing, specifically at the ankle location
Posture	- Changes to knee angle can change transmissibility measurements up to 50% (Paddan & Griffin, 1993; Matsumoto & Griffin, 1998; Harazin & Grzesik, 1998)	- Knee flexion angles at 0°, 5°, 10°, 15° and 20°.	Knee flexion up to 20°is allowable. Researchers should monitor knee flexion and caution participants from exceeding this limit
Time of Day and Trial Duration	- Lower limb volume can vary over the course of the day due to temperature, activity level, hours spent awake, and inactive (Noddeland & Winkel, 1988; Man et al., 2004) - Muscle fatigue and physical activity significantly decreases ability to attenuate impact (Voloshin et al., 1998; Mercer et al., 2003)	- Measurements were taken twice per day (morning and afternoon) on three different days (day 1, day 3, and day 7) - Two-minute trials were analyzed in 30, 45, and 60-second windows	Measurements may be taken at different times of day, and on consecutive days Data recorded in 30-second durations is sufficient. Longer trial durations do not change measures
Inter-Subject Variability	Differences in foot anthropometrics can lead to vibration transmissibility measurement variation (Laszlo & Griffin, 2011) - Participant mass influences transmissibility (Mansfield, 2005)		

Figure 2.10: Findings from laboratory-tested factors that influence FTV measures

There are a number of limitations with these preliminary tests. First, only one vibration profile was evaluated and the selected profile did not cover all the frequency ranges associated with reported FTV exposures in the workplace (Leduc et al., 2011; Eger et al., 2014). The low-frequency vibration input used in these tests was not representative of common exposures in the workplace; however, the vibration input was not a concern for the research team as the primary objective was simply to determine the extent at which FTV measures change by altering some factors. This low frequency was selected as the vibration input, as it was convenient for the researchers due to availability and proximity of equipment. Another limitation is the small range of posture change selected in Test Session 2 (0-20° knee flexion). As previously stated, this posture range was chosen to replicate normal standing posture that is seen in studies when participants are instructed to stand with a slight bend in their knees. However, it may be possible that some participants are more comfortable with a knee bend greater than 20°. Lastly, only two participants were used in this testing period so it is unrealistic to assume that the same results would be observed with a larger sample. Only two participants were selected in this preliminary study to establish a measurement protocol for FTV, the V-FTVMP, as future testing to evaluate the method was planned. These small experiments were done in preparation for the broader focus of determining the reliability of the method used to measure FTV exposure.

To conclude, four test sessions were conducted to identify the conditions under which reliable measurements can be made. On this basis, a protocol for FTV measurement was proposed (the Vance FTVMP: Appendix A, B, C). This was performed by determining the effect that several factors had on FTV measures (accelerometer location and placement, posture, time of day, and trial duration). Main findings of this study included recommendations such as: using the first metatarsal head and lateral malleolus as accelerometer mounting locations, not selecting the midfoot as a location, and monitoring knee flexion angle on standing participants as well as ensuring they remain between 0 and 20°. Other results found minimal variation in FTV measures with respect to changes in time of day or trial duration (Figure 2.10). Future research should evaluate the inter-rater and intra-rater reliability of the V-FTVMP. Knowing the reliability associated with the measurement of FTV will allow for the design of an improved protocol for measuring FTV exposure. Future research should also be conducted to further standardize this method, with emphasis on FTV measurement analysis. To be specific, a frequency-weighting curve for FTV evaluation should be established, as this is available for WBV and HAV evaluation. Researchers in this field need a reliable and valid standardized method of FTV measurement and evaluation to advance and improve the abilities to diagnose vibration injury and test interventions aimed at reducing and preventing vibration exposure.

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Appendix

Appendix A: Accelerometer mounting protocol

To measure FTV transmissibility the technician should mount the accelerometers as follows:

1) Have participant sit comfortably with foot hanging over the edge of a bench (or similar), warn them that the set-up may be uncomfortable if they have sensitive feet.
2) Put on gloves and use an alcohol swab to clean the areas of the foot where the accelerometers will be mounted (first metatarsal head, midfoot and lateral malleolus).
3) Have participant slide the compression sleeve onto their leg, leaving it loose.
4) Feed the wires of the accelerometers through the sleeve, ensuring to be gentle in the handling of the wires. Keep the wires on the lateral side of the thigh.
5) Take one of the accelerometer sensors, placing the flat side of the accelerometer against the foot, positioned with the sensor on the boniest spot of the desired location. Make sure to note which accelerometer number has been placed on which location.
6) Place the accelerometer so that the wire comes across the top of the foot from the medial side to the lateral side where the wire runs up the leg, crossing on top of the ankle bone. Use clear medical tape to secure the sensor to the foot, covering the whole sensor and a small part of the wire so that it will not shift.
7) Take a picture of the accelerometer on the participant’s foot to note the orientation of the accelerometer for each axis (x,y,z).
8) Use elastic therapeutic tape (KT tape) to secure the wire to the foot. Make sure to cover the entire sensor part of the accelerometer and cover the wire all the way to above the ankle bone. Only a small amount of tension is needed in the tape. If the person will be

wearing the accelerometer all day or will be sweating, use the spray to help the tape stick for longer. Rub the tape to activate the adherence.

9) Repeat steps 5-8 for any following accelerometers.
10) Have the participant stand up and pull the tension on the wires so that there is minimal slack, but enough that they can move their leg freely. Pull the compression sleeve up so that it is tight and holding the wires in place. If needed, use the tensor band to hold the wires around the calf area. Use the fanny pack to hold the data logger on the participant.
11) Give the participant a sock to gently put on over accelerometer set-up.

Chapter 3: Evaluation of the Inter-Rater and Intra-Rater Reliability of a Method for the Measurement of Foot-Transmitted Vibration

Abstract

The purpose of this study was to determine the inter-rater and intra-rater reliability of the Vance FTV Measurement Protocol (V-FTVMP), a newly proposed protocol for the measurement of foot-transmitted vibration. Twelve male participants, and three research assistants were recruited for this study. Each research assistant, followed the V-FTVMP to secure two accelerometers to the platform (on the vibration platform next to the ankle; on the vibration platform next to big toe) and two to the right foot (on the medial malleolus of the tibia (ankle), on the first metatarsal head of big toe) of each participant. Each research assistant repeated the process three times, resulting in 9 trials during the experimentation session. After the accelerometers were mounted each participant was asked to stand on a vibration platform, set to vibrate at a dominant frequency of 30Hz, for 45 seconds per trial. Un-weighted root-mean-squared accelerations in the x, y, and z-axes were calculated for each accelerometer, and platform to toe and platform to ankle transmissibility were calculated. ICC tests reveal reliability coefficients in the range of 'good' reliability for 3 of the 4 measurement locations, and moderate reliability at the ankle (r.m.s. acceleration). Vector sum acceleration revealed the highest reliability at all measurement locations (ICC=0.82, 0.80, 0.86, 0.76). Transmissibility calculated at the toe and ankle were found to be moderately reliable. Although the results from this study suggest that the V-FTVMP is reliable, future research should be conducted to quantify the reproducibility and inter-laboratory reliability of the measurement protocol.

1. Introduction

Exposure to vibration that enters the body through the feet has been reported in mining, construction and agriculture (Hedlund, 1989; Thompson et al., 2010; Leduc et al., 2011). Workers that operate equipment while standing on a vibrating surface are at an increased risk of suffering from vibration white-foot, an irreversible disease with vascular, neurological and musculoskeletal symptoms (Thompson et al., 2010). Furthermore, exposure frequencies between 30Hz and 50Hz appear to be associated with the onset of vibration white-foot and discomfort (Leduc et al., 2011; Eger et al., 2014; Goggins et al., 2016).

ISO 2631-1:1997 'Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration' is the standard typically used to evaluate health effects associated with vibration exposure when standing. However, several researchers have suggested this standard may not be sufficient for the measurement of FTV (Thompson et al, 2010; Leduc et al., 2011) as the standard does not provide guidance on how to mount accelerometers to the feet or lower body segments to determine vibration transmissibility. Therefore, some researchers have suggested ISO 5349-1, for measurement of vibration transmitted to the hand-arm segments, might be more appropriate for FTV measurement (Leduc et al., 2011; Eger et al., 2014). However, there are still limitations in using ISO 5349-1 for the assessment and evaluation of FTV. For example, the standard provides guidelines for the mounting location of accelerometers on vibrating tools and hands of workers, but provides no guidelines for the assessment of vibration transmitted to the foot segments. Furthermore neither ISO 2631-1 or ISO 5349-1 provide guidance on where to mount accelerometers on the feet for FTV exposure measurement, as such, investigators are not using a standardized method for measuring FTV (Table 3.1). For example, only two of 15 previous studies that measured vibration exposure while standing, used the same measurement method and the two studies were led by the same author (Singh et al. 2011; Singh, 2012). The only other studies with the same FTV measurement method were field studies led by Eger et al. (2014) and Leduc et al. (2011); however, vibration exposure was only measured at the platform. Therefore, a standardized approach for the measurement of FTV is required.

Preliminary testing by Vance and colleagues (Chapter 2) evaluated changes in measured FTV for different accelerometer mounting locations, accelerometer orientations, participant standing postures, time of day of measurements, and trial duration, in an effort to propose a protocol for the measurement of FTV, the Vance Foot-Transmitted Vibration Measurement Protocol (V-FTVMP). However, the measurement uncertainty associated with the proposed V-FTVMP has yet to be determined.

The ISO 21748:2010 states that measurement uncertainty must be understood in order to accurately interpret results. Furthermore, Fornasini (2008) stated that evaluating measurement uncertainty is vital to assess the reliability of technical procedures and to establish the validity limits of theories in research. Generally, the uncertainty in physical measurements are influenced by factors such as operating characteristics of the instrument, and interactions between instruments, systems, experimenters, measurement methodology, and environmental conditions (Fornasini, 2008). Determining the repeatability and reproducibility of methods may also be considered when evaluating uncertainty. Repeatability is assessed under conditions where the same operator, using the same equipment obtains the measurements with the same method, on identical measurement items, in the same facility. Reproducibility on the other hand, requires measurements to be obtained in different measurement facilities with different operators using different equipment (ISO 3534-2, 2006).

Table 3.1: Review of FTV measurement methods used in previous studies

Author (year)	Title	Locations of FTV measurement	Type of study
Abercromby et al. (2007)	Vibration exposure and biodynamic responses during whole-body vibration training	- Platform - Head	Lab
Byrnell (2016) unpublished Masters thesis	Personal protective equipment as a control strategy to reduce foot-transmitted vibration	- platform - underside of heel	Lab
Caryn (2011) (unpublished Masters thesis)	Transmission of whole-body vibration from exercise platforms	- platform - greater trochanter - 5th lumbar vertebrae - frontal bone of skull	Lab
Eger et al. (2014)	Vibration induced white-feet: overview and field study of vibration exposure and reported symptoms in workers	- platform	Field
Friesenbichler et al. (2014)	Vibration transmission to lower extremity soft tissues during whole-body vibration	- skin at triceps surae of the calf - quadriceps femoris	Lab
Goggins et al. (2016)	Study of the biodynamic response of the foot to vibration exposure	- two locations on the platform - first metatarsal head - lateral malleolus	Lab
Harazin & Grzesik (1998)	The transmission of vertical whole-body vibration to the body segments of standing subjects	- metatarsus (unspecified), - medial malleolus, - knee - hip - shoulder - head.	Lab
Kiiski et al. (2008)	Transmission of vertical whole body vibration to the human body	- medial malleolus - knee - hip - lumbar spine	Lab

Leduc et al. (2011)	Examination of vibration characteristics, and reported musculoskeletal discomfort for workers exposed to vibration via the feet	- platform	Field
Leduc et al. (2011)	Evaluation of transmissibility properties of anti-fatigue mats used by workers exposed to foot-transmitted vibration	- platform - surface of the mat	Lab
Matsumoto & Griffin (1998)	Dynamic response of the standing human body exposed to vertical vibration: influence of posture and vibration magnitude	- T1 - T8 - L4 - left and right iliac crests - knee	Lab
Singh et al. (2011)	Evaluation of gender differences in foot-transmitted vibration	- platform - lateral malleolus	Lab
Singh (2012) (unpublished Masters thesis)	Evaluation of foot-transmitted vibration and transmissibility characteristics of mining boots and insoles	- platform - lateral malleolus	Lab
Singh et al. (2016)	Site-specific transmission of a floor-based, high-frequency, low-magnitude vibration stimulus in children with spastic cerebral palsy	- platform - medial malleolus - lateral condyle of femur	Lab
Wee & Voloshin (2013)	Transmission of vertical vibration to the human foot and ankle	- medial malleolus - tibial tuberosity (while seated)	Lab

According to Mansfield (2005) even with guidance on accelerometer placement outlined in ISO 5349-2 (2001), uncertainty in measurements of HAV can be as high as 40% due to variability of the vibration in the work environment and the precise mounting location for the accelerometers. The researcher mounting the accelerometers during set-up can influence measurement error and/or uncertainty due to differences in skill and experience handling the equipment (ISO 5349-1, 2001). Accelerometer misalignment for HAV measurement is a major source of variability in measures and will result in errors of transmissibility (Hewitt, 1998). Previous research has documented accelerometer alignment errors between 10-40 degrees between participants when mounting accelerometers to the palm, donning a glove, and gripping a hand tool; leading to an overestimate of transmissibility by 20% (Hewitt, 1998; Dong et al. 2002). A study by Dong et al. assessing anti-vibration gloves found that yaw misalignment of the hand-mounted adaptors contributed to the highest measurement error of glove transmissibility and was the greatest contributor to the high inter and intra-subject variability observed (Dong et al., 2002).

When a validated method is not available for a specific measurement, method development and validation must be performed to ensure correct observation (Rogers, 2013). In a paper by Rogers, key elements (determining the specificity, accuracy, precision, limit of detection, linearity & range, and robustness & ruggedness) were set out to provide guidance on how to develop and validate a method. Furthermore, Rogers went on to define accuracy as the capability of a method to determine the correct measurement; robustness as a method's ability to produce consistent results under various normal conditions such as the use of different laboratories, researchers, and instruments; ruggedness as a method's ability to produce results consistently when conditions have been intentionally altered; precision as the ability of a method to produce consistent results and is determined by its repeatability, intermediate precision, and reproducibility; repeatability as the consistency of results between trials run by the same researcher under all the same conditions; intermediate precision as the consistency of a second researcher within the same lab under the same conditions and reproducibility is the consistency between different laboratories and researchers (Rogers, 2013). Previous research on anti-vibration gloves for HAV exposure shows that carefully carrying out a test using the same glove, on the same person, on the same day, and in the same facility will lead to results of a percent standard deviation from the mean transmissibility of 5-6% (Hewitt, 1998); however, the repeatability decreases if misalignment of the accelerometers occurs and is not closely monitored.

Reliability is defined at the degree to which measures are free from error and therefore yield consistent results and this must be assessed for truly scientific research (Peters, 1979). Unreliable methods reduce the correlation between measures so if reliability is not assessed and the correlation between measures is low, the researcher would not be able to conclude whether the difference between measures is real or due to an unreliable method (Peters, 1979). An intraclass correlation statistical test (ICC) can provide a useful estimate of test-retest reliability, intra-rater reliability, and inter-rater reliability for quantitative data (Landers, 2015; Koo & Li, 2016). Inter-rater reliability "reflects the variation between two or more raters who measure the same group of subjects" and intra-rater reliability "reflects the variation of data measured by one rater across two or more trials" (Koo & Li, 2016). ICC provides a measure that represents the degree of correlation as well as the agreement between measures (Koo & Li, 2016). According to Koo and Li (2016), a research study should always involve at least three raters when evaluating the reliability of a method.

A study by Al-Masri & Amin (2005) provides an example of how a developed method was validated using similar processes as previously described. Researchers compared three techniques for the determination of uranium in environmental samples by using the Eurachem guide on method validation. This was determined by identifying each method's detection limits, reproducibility, repeatability and uncertainty. The repeatability limit was identified by analyzing ten duplicates of a soil sample under repeatable conditions, with a known uranium concentration. The reproducibility limit was estimated by analyzing ten duplicates of a soil sample (with a known uranium concentration) but with at least one condition changed in the process such as the researcher, instrument, or time of day (Al-Masri & Amin, 2005). Another study by Tiryaki (2006) used a similar approach by determining limits of detection, accuracy, precision, ruggedness, and robustness to validate a method used for pesticide residue analysis.

In relation to measures of FTV, a validated method has not been developed or tested. Elements such as the robustness, ruggedness, and precision (or reliability) of the developed method should be captured in the process of validation. It is important to know how reliable the method is in order to determine the effectiveness of interventions aimed at reducing vibration exposure. In order to have confidence in field studies that document vibration exposure characteristics associated with the development of vibration-induced white-foot, a reliable standard method for FTV exposure measurement is required. Furthermore, a reliable method is required in order to determine if control strategies aimed at mitigating risks associated with FTV exposure are effective. Therefore, the purpose of this study is to determine the inter-rater and intra-rater reliability of the V-FTVMP.

2. Methodology

The Laurentian University Research Ethics Board approved the methodology in this study and all participants gave informed consent prior to commencing the study.

2.1. Participants

Twelve male participants (Table 3.2) were recruited from a sample of convenience with an average age of 24 years (±4.4), height of 180 cm (±6.9), mass of 87.2 kg (±12.37), and shoe size of 10.5 (±1.28). All participants had no previous history of head injury, foot pain, lower leg pain, back pain, discolouration in the toes, or pain and numbness in the feet in the previous 6 months.

Table 3.2: Participant demographic information

Participant	Age	Height (cm)	Mass (kg)	Shoe size
1	22	182.90	76.36	10.0
2	20	170.20	63.64	8.5
3	20	193.00	102.27	13.0
4	27	170.20	75.00	10.0
5	21	180.30	95.45	12.0
6	35	177.80	102.27	10.5
7	23	176.50	90.91	11.0
8	24	185.50	100.00	11.5
9	22	182.90	75.91	9.0
10	29	177.80	91.82	9.5
11	22	175.20	88.64	11.0
12	23	188.10	84.09	10.0
Mean	24	180.03	87.20	10.50
SD	4.37	6.87	12.37	1.28

2.2. Vibration and Posture Measurement Equipment

Four ADXL 326, 19g miniature tri-axial accelerometers (Windsor, ON) were used to measure vibration in this study. Accelerometers were firmly secured to the skin using medical adhesive tape and kinesiology tape. Vibration data were recorded at a sampling frequency of 1000Hz and stored on two portable data loggers (DataLog MWX8; Biometrics Ltd., Newport, UK). A twin-axis goniometer SG150 (Biometrics Ltd, Newport, UK) was used to measure and monitor knee joint angle. The goniometer was firmly secured by extending the goniometer to maximum length and mounting the proximal endblock of the goniometer to the participant's lateral thigh, and the distal endblock laterally to the participant's lower leg when standing with the knee fully extended.

2.3. Vibration Exposure Profile

A vibration exercise platform (Power Plate North American, Inc., Irvine, CA) was used in this study to generate the vibration profiles at a dominant frequency of 30 Hz. This dominant frequency was selected as it is in line with the dominant frequency experienced by workers previously diagnosed with vibration white-foot (Hedlund, 1989; Leduc et al., 2011; Eger et al., 2014). Each participant was exposed to nine trials of 45 seconds with rest between trials to remove and re-mount the accelerometers.

2.4. Vance FTVMP

The V-FTVMP (Chapter 2) was followed for the measurement of FTV. The method requires two accelerometers to be secured to the right foot; 1) to the medial malleolus of the tibia (ankle) and 2) to the first metatarsal head (big toe). In the previous study (Vance, Chapter 2), vibration measurements at the ankle were recorded at the lateral malleolus; however, recent research by Goggins et al., (2017) suggested that the medial malleolus exhibited higher transmissibility when exposed to vertical axis vibration at 30 Hz. Therefore, the medial malleolus was selected as the preferred ankle measurement location instead of the lateral malleolus. Furthermore, the sensitivity measures conducted in Chapter 2 for accelerometer mounting on the lateral malleolus are still relevant as the accelerometer is still mounted on the skin over the malleolus. The accelerometers are secured with medical adhesive tape and kinesiology tape (Figures 3.1 and 3.2). The head of the ADXL accelerometers were placed firmly to the centre of the boniest part of each landmark. The orientation with reference to the x, y, and z-axes were carefully noted. Participants were instructed to stand on the platform comfortably with their feet shoulder-width apart and the areas directly adjacent to the accelerometers on their feet were marked on the platform with tape. When the participant stepped down, two additional accelerometers were mounted to the vibration platform (Figure 3.3) at the locations marked with tape to make sure that they were placed as close as possible to the participant's foot. Before each trial, the participants were instructed to stand with a slight bend in their knees. Knee flexion was measured by the twin-axis goniometer and monitored during each trial by a member of the research team. If the participant exceeded 20° knee flexion they were reminded to slightly straighten their legs. For a more detailed description of the Vance FTVMP see Appendix B and C.

2.5. FTV Measurement Protocol

Participants were asked to stand on the vibrating platform for 45-second trial durations. Three research assistants (RA) performed the measurements by following the protocol outlined in the Vance FTVMP. Each research assistant conducted three repeated trials on all participants. The order in which the three research assistants completed the trials was randomized. Between every trial, the accelerometers attached to the participant's right foot were removed and then re-mounted for the next trial. Figure 3.4 outlines the experimental procedure that was followed for each participant.

Figure 3.1: Accelerometer location: first metatarsal head

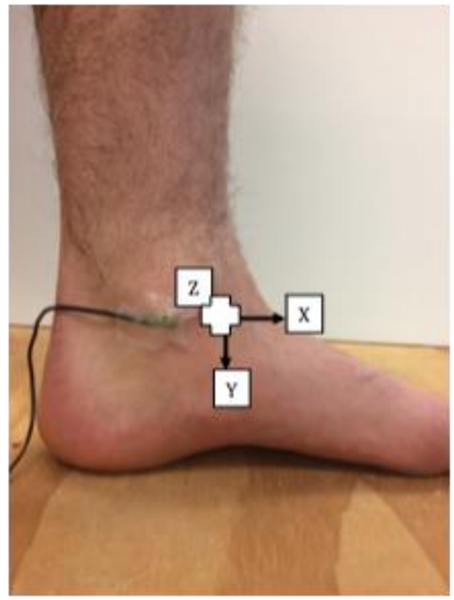

Figure 3.2: Accelerometer location: medial malleolus

Figure 3.3: Platform accelerometer locations

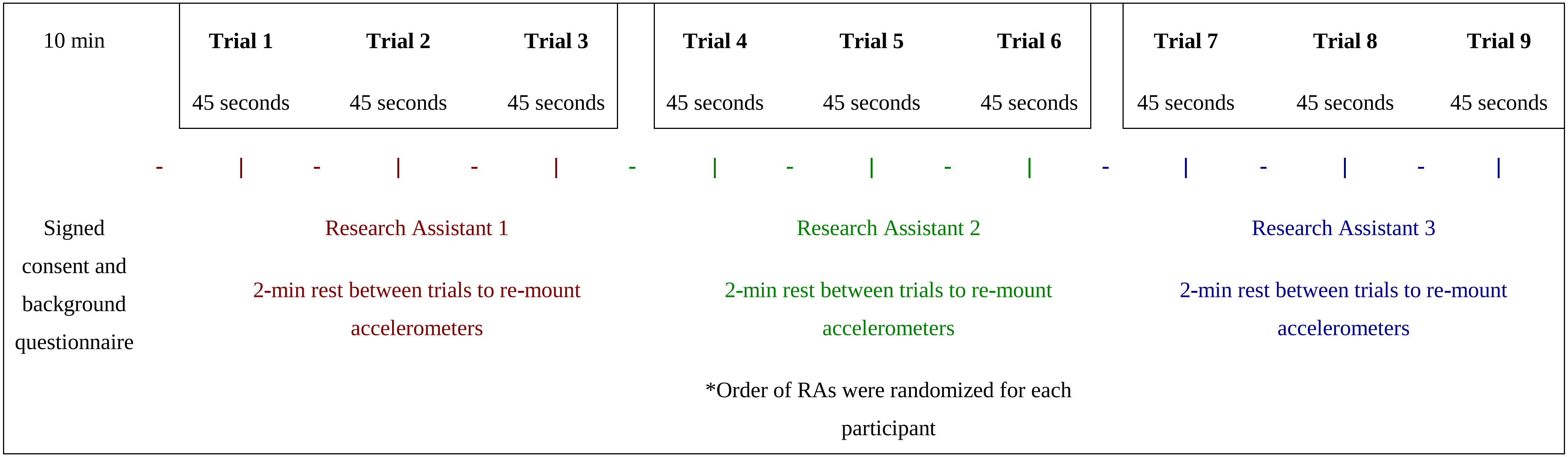

Figure 3.4: Data collection procedure

2.6. Data Analysis

Vibration data from each trial were processed using a Vibratools custom MATLab program (The Mathworks Inc., MA, USA v 7.1.). Un-weighted root-mean-squared accelerations in the x, y, and z-axes were recorded at four locations (vibration platform next to the ankle, vibration platform next to the first metatarsal head of the big toe, the medial malleolus of the tibia (ankle), first metatarsal head of big toe). The vector sum un-weighted acceleration of all axes were also calculated for all locations (platform at the toe, platform at the ankle, first metatarsal head of big toe, medial malleolus of ankle) according to Equation 1.

Equation 1: $a_{x,y,z} = \sqrt{a_{wx}^2 + a_{wy}^2 + a_{wz}^2}$

Where $a_{x,y,z}$ is the un-weighted vector sum, and $a_{wx,}$ $a_{wy,}$ and $a_{wz,}$ are the un-weighted r.m.s. accelerations in the x-axis, y-axis, and z-axis.

FTV transmissibility was calculated at the ankle (Equation 2) and toe (Equation 3) for all trials. Data from the z-axis were used for all transmissibility calculations as this axis is reported in most studies to be the dominant axis for FTV exposure (Leduc et al., 2011; Eger et al., 2014).

Equation 2: $T_{ankle} = \frac{a_z(ankle)}{a_z(platform)}$

Where T_{ankle} is the transmissibility at the medial malleolus: a_z(ankle) is the un-weighted r.m.s. acceleration on the medial malleolus, and a_z (platform) is the un-weighted r.m.s. acceleration on the platform next to the ankle.

Equation 3: $T_{toe} = \frac{a_z(toe)}{a_z(platform)}$

Where T_{toe} is the transmissibility at the first metatarsal head: a_z (toe) is the un-weighted r.m.s. acceleration on top of the first metatarsal head, and a_z (platform) is the un-weighted r.m.s. acceleration on the platform next to the big toe.

2.6.1. Statistical analysis

Intra-class correlation (ICC) estimates and their 95% confidence intervals were conducted using STATA 14.2, based on a single-rating (n=3), absolute agreement, one-way random model. This test was conducted to determine the reliability of un-weighted z-axis acceleration measures, vector sum acceleration measures, and transmissibility measures (platform to toe, platform to ankle).

3. Results

3.1. Measured vibration data

Un-weighted r.m.s. accelerations measured by each accelerometer for all 12 participants were calculated (Table 3.3; Table 3.4). Mean un-weighted r.m.s. acceleration in the vertical direction measured on the vibration platform at the toe, vibration platform at the ankle, on the toe (first metatarsal head), and on the ankle (medial malleolus) were 13.01 m/s^2 (±0.87), 12.68 m/s^2 (±1.19), 8.23 m/s^2 (±2.24), 16.05 m/s^2 (±3.81), respectively (Table 3.3). The mean vector sum un-weighted r.m.s. acceleration at the two platform locations were 13.24 m/s^2 (±0.85) and 12.92 m/s^2 (±1.15), verifying that the vibration platform primarily generated vibration in the vertical axis (Table 3.4). Vector sum acceleration measured on the foot segment at the toe was 21.90 m/s^2 (±3.28) and at the ankle 31.11 m/s^2 (±5.92).

Table 3.3: Un-weighted r.m.s. acceleration in z-axis for all locations

Un-weighted r.m.s. acceleration (m/s^2)					
Participant	**Rater**	**Platform (toe)**	**Platform (ankle)**	**Toe**	**Ankle**
1	3	13.08	12.74	5.24	22.17
		13.32	13.26	6.13	20.44
		13.82	13.84	8.58	17.30
	2	13.65	13.49	7.91	20.73
		13.29	13.25	6.06	20.76
		13.45	13.30	6.71	22.36
	1	13.35	13.29	5.59	19.33
		13.57	13.55	6.01	20.61
		13.34	13.07	6.81	21.62
2	3	14.40	14.32	8.54	16.34
		14.31	14.15	6.57	18.43
		14.11	13.96	5.43	17.77
	1	14.61	14.49	8.26	21.16
		14.61	14.52	6.60	19.13
		13.79	13.67	8.85	23.90
	2	13.43	13.36	7.32	23.34
		14.35	14.30	8.45	21.00
		13.43	13.32	7.84	26.38
3	1	14.16	14.89	8.18	17.83
		13.22	13.39	6.12	15.63
		13.04	13.21	7.99	13.80
	3	12.85	13.16	6.36	23.62
		13.03	13.46	7.24	21.51
		13.24	13.55	7.46	20.43
	2	13.40	13.63	9.44	11.27
		13.10	13.37	7.70	12.60
		13.64	13.93	9.78	18.28
4	1	14.01	14.37	12.22	15.60
		13.47	13.42	11.46	14.31
		13.61	14.20	11.31	13.27
	3	13.41	13.29	10.93	13.64
		14.25	14.97	13.02	14.36
		14.18	14.76	12.79	9.46
	2	13.16	13.36	10.74	19.38
		12.86	12.96	10.57	14.42
		12.98	12.68	11.95	9.14
5	3	12.79	11.53	6.87	17.35
		12.68	11.61	6.62	13.27
		12.45	11.69	5.29	12.37

	1	13.12	12.72	7.71	13.96
		13.74	13.36	10.96	10.02
		13.20	12.66	7.60	12.56
	2	12.38	11.67	7.48	10.84
		12.62	11.99	6.16	9.88
		12.19	11.18	3.84	15.25
6	1	11.50	10.89	6.91	14.55
		11.49	10.84	5.55	17.57
		11.30	10.44	4.94	9.24
	2	11.63	11.12	5.54	11.84
		11.38	10.54	5.16	13.84
		11.54	10.84	4.93	15.09
	3	11.21	10.28	5.86	17.88
		11.45	10.62	6.34	18.50
		11.49	10.61	6.19	15.35
7	2	11.35	9.68	11.04	12.59
		12.80	11.88	9.52	13.81
		12.61	10.80	10.30	13.11
	3	12.83	11.48	10.08	13.57
		13.38	11.73	9.83	15.21
		12.78	11.12	10.17	13.05
	1	12.92	11.47	6.28	15.89
		13.16	12.04	7.65	15.45
		12.99	11.76	7.01	12.90
8	2	12.64	12.46	7.49	17.30
		11.43	10.17	9.62	13.46
		12.59	12.50	7.66	17.86
	3	12.31	12.23	7.02	17.12
		12.12	11.96	8.02	15.71
		11.44	11.09	7.58	16.29
	1	11.46	10.74	7.56	16.02
		12.00	11.39	6.40	14.45
		11.28	10.58	7.10	16.44
9	1	13.90	13.64	8.45	10.66
		13.60	13.16	7.29	13.02
		13.63	13.17	8.78	10.19
	3	13.58	13.16	6.95	15.13
		13.52	13.08	8.00	17.26
		13.63	13.21	8.18	14.41
	2	13.38	12.94	6.25	14.48
		13.61	13.17	7.06	13.50
		13.37	12.99	6.67	11.89
10	1	11.77	11.41	7.92	20.04
		12.18	11.93	7.36	19.60

		13.00	12.77	7.56	16.60
	3	12.31	12.02	7.90	18.75
		12.22	11.92	4.82	21.33
		12.33	11.97	6.71	18.10
	2	12.96	12.74	7.28	17.91
		12.04	11.68	4.41	18.71
		12.18	11.80	5.23	16.13
11	3	14.04	13.56	11.42	13.87
		14.60	14.32	12.50	15.33
		13.68	13.14	10.98	21.71
	2	14.09	13.83	12.07	15.64
		13.84	13.36	11.44	16.49
		14.19	13.97	11.85	16.87
	1	13.60	12.99	9.38	19.83
		13.47	12.93	9.27	18.30
		14.09	13.37	9.43	16.64
12	1	12.89	13.23	6.08	14.47
		12.61	12.62	10.98	24.53
		13.11	13.58	11.03	13.52
	3	13.17	13.47	10.85	12.04
		12.71	12.88	11.16	14.09
		12.53	12.74	10.22	12.93
	2	13.31	13.65	12.30	8.79
		13.26	13.67	12.33	9.00
		12.84	13.04	12.15	10.37
mean		**13.01**	**12.68**	**8.23**	**16.05**
sd		**0.87**	**1.19**	**2.24**	**3.81**

Table 3.4: Vector sum r.m.s. un-weighted acceleration for all locations

		Vector sum un-weighted r.m.s. acceleration (m/s^2)			
Participant	**Rater**	**Platform (toe)**	**Platform (ankle)**	**Toe**	**Ankle**
1	3	13.14	12.76	24.19	37.62
		13.41	13.33	22.42	32.70
		13.86	13.93	21.82	30.08
	2	13.72	13.54	20.12	33.48
		13.36	13.29	22.88	36.46
		13.50	13.35	23.22	37.30
	1	13.40	13.33	21.61	36.65
		13.63	13.60	21.70	35.90
		13.39	13.12	23.99	36.08
2	3	14.58	14.52	24.67	34.75
		14.56	14.47	23.35	38.85
		14.29	14.19	25.05	35.27
	1	14.83	14.78	24.49	37.69
		14.88	14.84	25.81	42.76
		13.92	13.83	25.44	44.76
	2	13.57	13.52	26.26	40.00
		14.51	14.50	24.82	38.43
		13.56	13.43	24.99	44.32
3	1	14.19	14.99	23.17	34.38
		13.26	13.50	23.35	38.02
		13.06	13.31	23.88	37.41
	3	12.92	13.29	21.78	33.77
		13.08	13.57	22.17	35.10
		13.28	13.65	19.93	29.00
	2	13.42	13.73	21.64	31.85
		13.15	13.48	21.40	34.87
		13.67	14.05	23.54	34.60
4	1	14.01	14.39	19.76	23.83
		13.49	13.47	25.30	36.67
		13.64	14.24	21.85	32.27
	3	13.45	13.35	22.50	29.33
		14.30	15.03	20.88	20.47
		14.22	14.83	21.47	22.20
	2	13.22	13.43	23.05	34.21
		12.94	13.04	23.52	35.77
		13.12	12.83	24.12	27.72
5	3	12.89	11.76	22.45	26.57
		12.74	11.77	22.68	26.95
		12.49	11.85	24.69	29.13

	1	13.16	12.90	23.19	29.43
		13.77	13.46	21.80	25.35
		13.23	12.82	22.36	26.46
	2	12.42	11.84	23.75	31.42
		12.68	12.20	25.77	29.80
		12.25	11.33	23.00	29.09
6	1	11.68	11.11	22.12	32.69
		11.68	11.05	21.54	31.90
		11.44	10.57	20.58	27.42
	2	11.75	11.22	20.96	32.94
		11.50	10.64	21.30	33.40
		11.64	10.93	24.19	34.38
	3	11.35	10.40	21.38	31.56
		11.57	10.73	23.26	37.10
		11.59	10.68	22.45	34.76
7	2	11.50	10.36	12.44	14.47
		12.92	12.46	16.16	22.24
		12.76	11.44	13.90	17.09
	3	12.98	12.18	15.02	19.04
		13.50	12.44	16.19	21.66
		12.96	11.86	14.60	18.06
	1	13.06	12.24	15.75	21.51
		13.26	12.77	14.85	19.73
		13.15	12.75	15.91	20.63
8	2	13.12	12.85	19.23	32.22
		11.88	10.58	15.20	22.20
		12.97	12.88	18.63	34.20
	3	12.78	12.57	19.65	31.26
		12.46	12.19	21.57	31.62
		11.82	11.31	19.02	27.18
	1	11.95	11.05	18.69	27.14
		12.30	11.63	18.78	27.13
		11.68	10.83	17.30	25.77
9	1	13.90	13.72	21.33	29.30
		13.60	13.24	22.42	33.22
		13.64	13.25	23.61	32.55
	3	13.59	13.24	23.72	31.44
		13.53	13.16	23.15	32.49
		13.63	13.28	21.56	28.63
	2	13.38	13.05	22.65	30.20
		13.62	13.26	21.39	30.08
		13.38	13.06	20.05	29.87
10	1	13.02	12.24	27.69	34.57
		12.85	12.30	29.15	35.26

		13.63	13.16	27.85	37.43
	3	12.72	12.25	27.94	34.45
		12.62	12.14	27.78	35.48
		12.52	12.04	27.52	33.77
	2	13.30	12.89	25.12	36.41
		12.30	11.78	25.26	34.83
		12.38	11.88	26.29	34.55
11	3	14.18	13.85	19.01	24.44
		14.72	14.64	20.64	25.22
		13.74	13.36	22.28	30.33
	2	14.11	13.94	22.68	32.68
		13.86	13.46	23.90	37.19
		14.20	14.08	22.65	33.59
	1	13.63	13.17	22.36	31.85
		13.49	13.07	25.26	37.37
		14.14	13.59	25.61	31.98
12	1	14.33	14.10	20.82	32.99
		13.74	13.22	21.79	35.84
		14.41	14.30	22.92	34.18
	3	14.32	14.07	17.98	23.75
		13.96	13.56	19.59	27.39
		13.71	13.37	19.19	29.08
	2	14.49	14.27	16.87	20.07
		14.39	14.23	17.47	22.37
		13.86	13.52	18.84	27.06
mean		**13.24**	**12.92**	**21.90**	**31.11**
sd		**0.85**	**1.15**	**3.28**	**5.92**

The mean platform-to-toe and platform-to-ankle transmissibility in the vertical direction (z-axis) was found to be 0.63 (±0.16), and 1.27 (±0.30) respectively (Table 3.5).

Table 3.5: Calculated z-axis platform-to-toe and platform-to-ankle transmissibility for all trials

Participant	Rater	Platform-to-Toe Transmissibility	Platform-to-Ankle Transmissibility
1	3	0.40	1.74
		0.44	1.54
		0.62	1.24
	2	0.58	1.53
		0.45	1.57
		0.50	1.68
	1	0.41	1.45
		0.44	1.52
		0.51	1.65
2	3	0.59	1.14
		0.46	1.30
		0.38	1.27
	1	0.57	1.46
		0.45	1.32
		0.64	1.75
	2	0.54	1.75
		0.59	1.47
		0.58	1.98
3	1	0.57	1.19
		0.45	1.17
		0.61	1.04
	3	0.49	1.79
		0.56	1.60
		0.56	1.50
	2	0.70	0.82
		0.59	0.94
		0.70	1.28
4	1	0.87	1.06
		0.84	1.05
		0.82	0.92
	3	0.81	1.03
		0.91	0.95
		0.90	0.62
	2	0.81	1.45
		0.82	1.11
		0.92	0.71
5	3	0.54	1.51

		0.52	1.14
		0.42	1.06
	1	0.59	1.10
		0.80	0.75
		0.57	0.99
	2	0.60	0.93
		0.49	0.82
		0.32	1.36
6	1	0.60	1.34
		0.48	1.62
		0.44	0.88
	2	0.48	1.06
		0.45	1.31
		0.43	1.39
	3	0.52	1.74
		0.55	1.74
		0.54	1.45
7	2	0.97	1.30
		0.74	1.16
		0.82	1.21
	3	0.79	1.18
		0.74	1.30
		0.80	1.17
	1	0.49	1.38
		0.58	1.28
		0.54	1.10
8	2	0.59	1.39
		0.84	1.32
		0.61	1.43
	3	0.57	1.40
		0.66	1.31
		0.66	1.47
	1	0.66	1.49
		0.53	1.27
		0.63	1.55
9	1	0.61	0.78
		0.53	0.99
		0.64	0.77
	3	0.51	1.15
		0.59	1.32
		0.60	1.09
	2	0.47	1.12
		0.52	1.02
		0.50	0.92

10	1	0.67	1.76
		0.60	1.64
		0.58	1.30
	3	0.64	1.56
		0.39	1.79
		0.54	1.51
	2	0.56	1.40
		0.37	1.60
		0.43	1.37
11	3	0.81	1.02
		0.86	1.07
		0.80	1.64
	2	0.86	1.12
		0.83	1.23
		0.83	1.20
	1	0.69	1.53
		0.68	1.41
		0.67	1.24
12	1	0.47	1.09
		0.87	1.95
		0.84	0.99
	3	0.82	0.89
		0.88	1.09
		0.82	1.01
	2	0.92	0.64
		0.93	0.65
		0.94	0.79
mean		**0.63**	**1.27**
sd		**0.16**	**0.30**

3.2. ICC test results for un-weighted r.m.s. acceleration measures in z-axis

The intraclass correlation tests showed good or acceptable reliability for measures of un-weighted r.m.s. acceleration at all four measurement locations (Table 3.6): platform location at the toe ICC(1,1) =.83 (CI =.67 -.92), platform at ankle ICC(1,1) =.82 (CI=.65-.92), toe ICC(1,1) =.77 (CI =.37 -.81), ankle ICC(1,1) =.60 (CI =.18 -.68).

When comparing vibration measurements obtained by the three research assistants (RA1; RA2; RA3), the agreeableness between their measurements can be observed (Figure 3.5). For the first accelerometer location (platform at the toe), mean un-weighted r.m.s. accelerations were found to be 13.08 m/s^2 (±0.91) by RA1, 12.92 m/s^2 (±0.80) by RA2, and 13.04 m/s^2 (±0.90) by RA3. At the second accelerometer location (platform at ankle), mean accelerations for all participants were reported to be 12.77 m/s^2 (±1.20) by RA1, 12.57 m/s^2 (±1.19) by RA2, and 12.69 m/s^2 (±1.22) by RA3. Measurements reported for the third location (toe) were 8.02 m/s^2 (±1.86) by RA1, 8.40 m/s^2 (±2.53) by RA2, and 8.27 m/s^2 (±2.33) by RA3. At the fourth location (ankle), mean accelerations for all participants were found to be 16.18 m/s^2 (±3.77) by RA1, 15.40 m/s^2 (±4.32) by RA2, and 16.56 m/s^2 (±3.28) by RA3.

Furthermore, the intraclass correlation tests revealed good reliability for un-weighted vector sum measurements at all four accelerometer locations (Table 3.6): platform at toe ICC(1,1) =.82 (CI =.66 -.92), platform at ankle ICC(1,1) =..80 (CI =.63 -.91), toe ICC(1,1) =.86 (CI =.72 -.93), and ankle ICC(1,1) =.76 (CI =.59 -.88).

3.3. ICC test results for transmissibility measures

The agreeableness between transmissibility measurements obtained by the three research assistants (RA1; RA2; RA3) was fair (Figure 3.6). Mean platform-to-toe transmissibility was measured at 0.61 (±0.13) by RA1, 0.65(±0.19) by RA2, and 0.63(±0.16) by RA3 and mean platform-to-ankle transmissibility was found to be 1.27(±0.30) by RA1, 1.22(±0.32) by RA2, and 1.31(±0.29) by RA3 (Figure 3.6). The intraclass correlation tests revealed barely acceptable reliability at the toe location (ICC(1,1) =.57, CI =.32 -.79) and the ankle location (ICC(1,1) =.55, CI =.12 -.62) (Table 3.6).

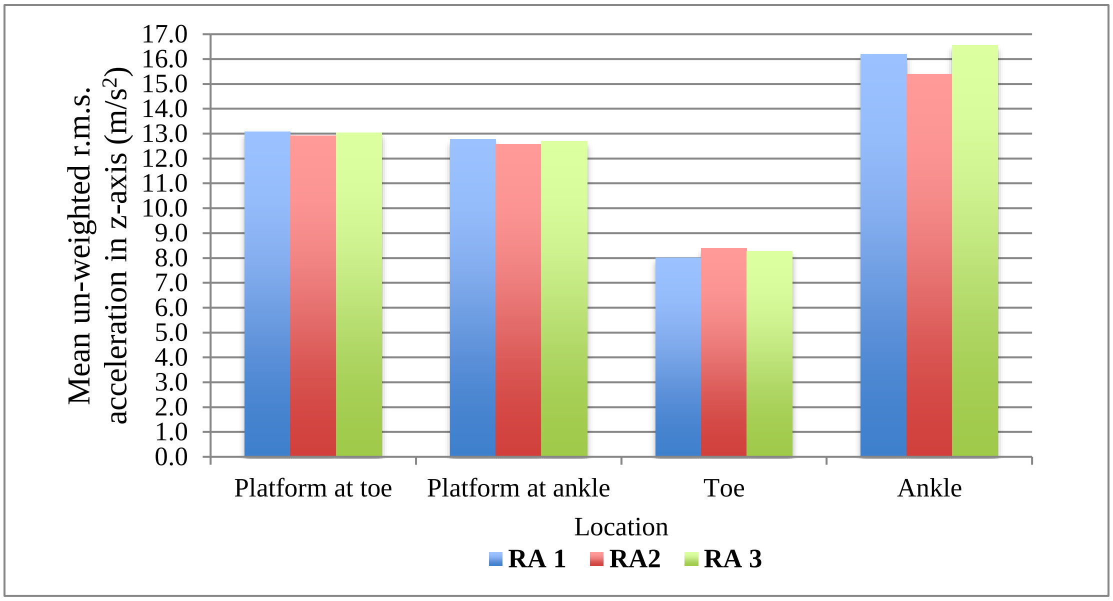

Figure 3.5: Comparison of measurements obtained by the three research assistants - mean un-weighted r.m.s. acceleration

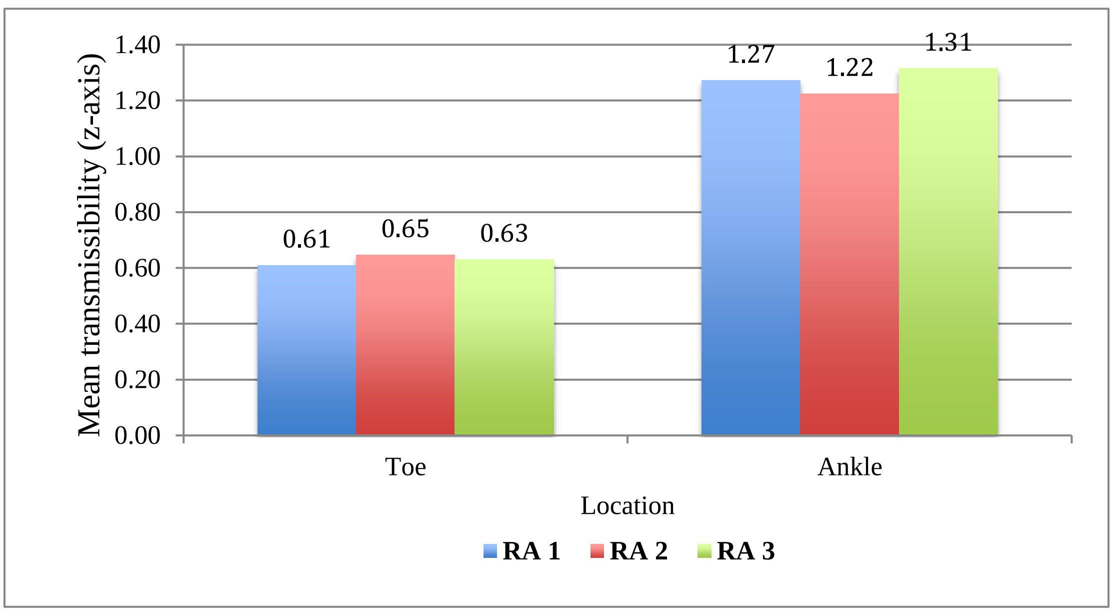

Figure 3.6: Comparison of transmissibility measures obtained by the three research assistants

Table 3.6: ICC test results

Calculated Variable	Measurement	ICC	95% Confidence interval (lower bound)	95% Confidence interval (lower bound)
r.m.s. un-weighted acceleration (z-axis)	Platform at the toe	.83	.67	.92
	Platform at the ankle	.82	.65	.92
	On the toe	.77	.37	.81
	On the ankle	.60	.18	.68
Transmissibility	Platform-to-toe	.57	.32	.79
	Platform-to-ankle	.55	.12	.62
Vector sum acceleration	Platform at the toe	.82	.66	.92
	Platform at the ankle	.80	.63	.91
	On the toe	.86	.72	.93
	On the ankle	.76	.59	.88

4. Discussion

The purpose of this study was to determine the reliability of the Vance FTV Measurement Protocol. Participants were exposed to the same FTV profile throughout the study while three research assistants donned and doffed the accelerometers for vibration measurement. Vibration was measured at four locations: (on the vibration platform at the toe, on the vibration platform at the ankle, on the first metatarsal head, and on the medial malleolus of the tibia (ankle). Un-weighted r.m.s. accelerations were measured at all four locations and reported in the vertical axis and sum. Platform to toe and platform to ankle transmissibility was also calculated. Results of this study indicate that the V-FTVMP appears to be a reliable method for the measurement of FTV.

According to Koo and Li (2016) ICC coefficients of 0.5-0.75 should be interpreted as moderate reliability, values of 0.75-0.9 represent good reliability, and values higher than 0.9 represents excellent reliability. In this study, ICC tests reveal reliability coefficients in the range of ‘good’ reliability for 3 of the 4 measurement locations, and moderate reliability at the ankle for measures of r.m.s. acceleration. The vector sum acceleration measures were found to be ‘good’ at all four locations and transmissibility calculated at the toe and ankle were found to be moderately reliable. The lower reliability in acceleration measures at the ankle location (ICC=0.60), and the variability in measures recorded at this location may be due to the difficulty in reproducing the placement of accelerometers on the centre of the malleolus as shifting may occur. Un-weighted r.m.s. acceleration at the ankle was found to be 16.05m/s^2, with a standard deviation covering 24% of the mean (SD=3.81). In addition, the standard deviation of measures at the toe covered 27% of the mean r.m.s. un-weighted acceleration for all participants (8.23m/s^2 ±2.24). On bony and protruding surfaces such as the malleolus and the first metatarsal head the accelerometer may be shifting and resulting in misalignment of the axes; however, the reliability score for these measures is still acceptable. Variability associated with mass of the participants was not controlled in this study and varied considerably with a range from 63.64kg to 102.27kg. Furthermore, research by Mansfield (2005) has shown transmissibility measures are influenced by mass; therefore, the reliability observed in this study should not be understated.

Low reliability was seen for calculated transmissibility at the ankle and toe location (ICC=0.57, 0.55) and axis misalignment may also be involved with this. Misalignment of axes during vibration measurement is one of the main factors leading to error and uncertainty and can significantly over or underestimate transmissibility measures (Hewitt, 1998; Dong et al., 2002). Mean toe transmissibility was calculated at 0.63 across all participants, with a standard deviation covering 25% (SD=0.16). Also, transmissibility at the ankle showed measures varying up to 24% with a mean measure of 1.27 (SD=0.30). Previous research on anti-vibration gloves for HAV exposure shows that carefully carrying out a test using the same glove, on the same person, on the same day, and in the same facility will lead to results of a percent standard deviation from the mean transmissibility of 5-6%; however, if misalignment of the accelerometers occurs the repeatability decreases (Hewitt, 1998). Variability in measures up to 27% may seem excessive, as observed here, when considering that all trials were recorded with the same input conditions; however, it is reported for instance, that uncertainty in measures of HAV can be as high as 40% (Mansfield, 2005) although uncertainty associated with FTV has not yet been investigated.

The transmissibility calculated at the toe location (0.63) is in line with a previous study (0.70) measuring exposure to FTV at the toe and ankle at 30Hz (Goggins et al., 2016). Transmissibility calculated at the ankle in the current study (1.27) was higher than in the Goggins et al., study (0.86); however, the current study measured vibration at the medial malleolus whereas Goggins et al., (2016) measured at the lateral malleolus (Figure 3.7). Furthermore, a comparison of published transmissibility values at the ankle, when exposed to FTV at 30Hz, suggests there are differences in transmissibility when measured at the medial and lateral malleolus (Figure 3.8). For example, in the study conducted by Harazin & Grzesik (1998) measured vibration transmissibility at the medial malleolus at an exposure frequency of 31.5 Hz was reported to be 1.26 which is very close to the data observed in this current study (1.27). The study by Wee & Voloshin (2003) reported higher transmissibility at the medial malleous (1.74) with the same exposure frequency (30 Hz); however, the participants in the study were seated with their feet on a vibrating platform.

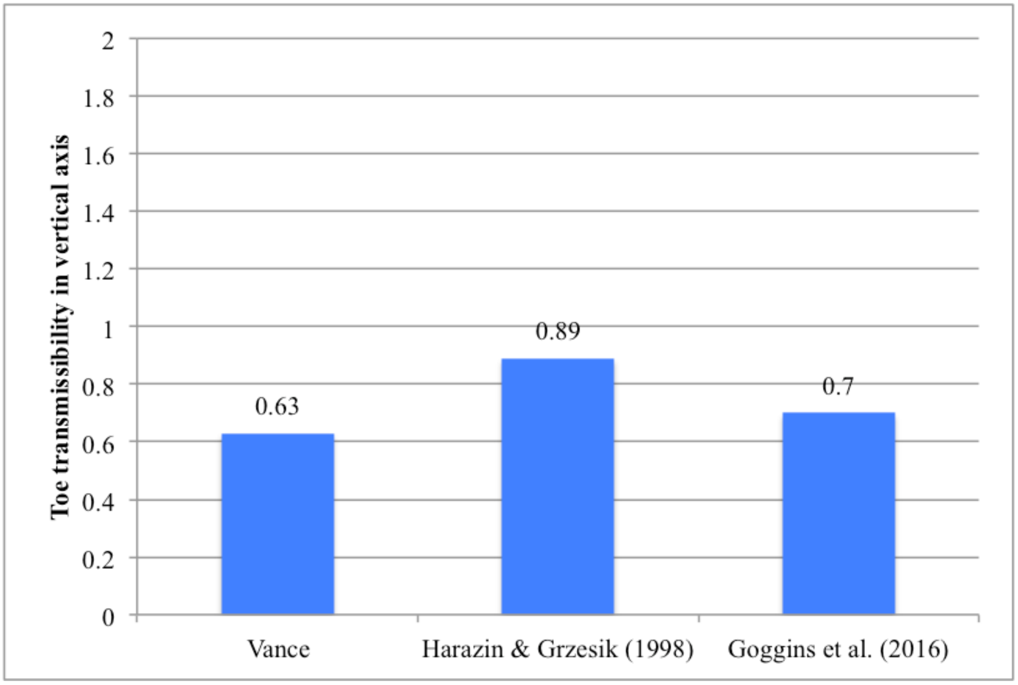

Figure 3.7: FTV studies measuring platform-to-toe transmissibility at 30 Hz

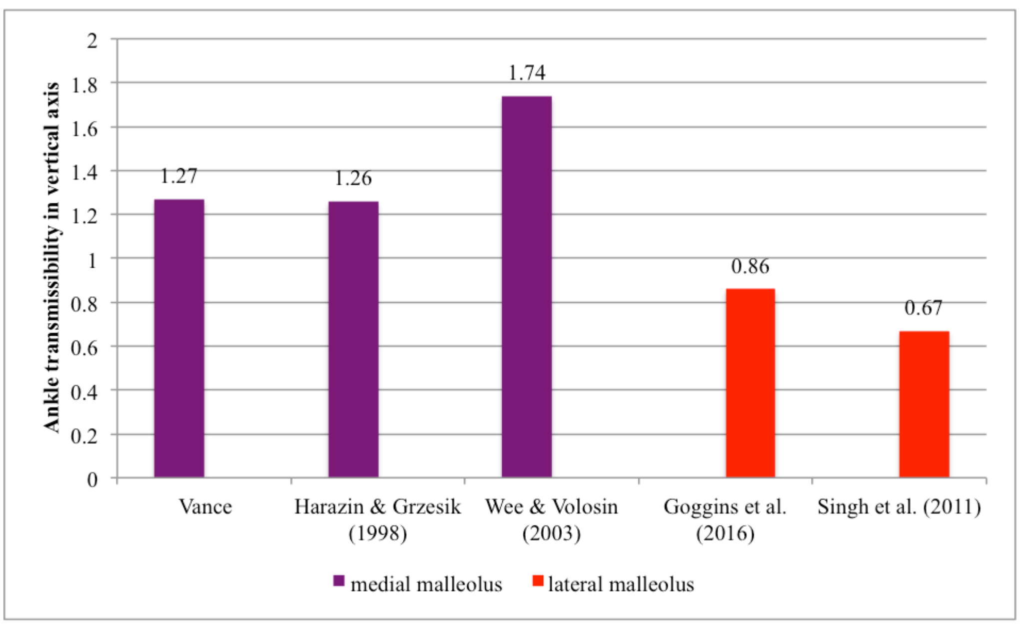

Figure 3.8: FTV studies measuring platform-to-ankle transmissibility at 30 Hz

Although the results from this study suggest that the V-FTVMP is reliable, more research is needed to complete validation of the method. For example, the measurement uncertainty needs to be quantified as the ISO 21748:2010 states that knowing the measurement uncertainty is essential to the interpretation of results and evaluating the measurement uncertainty is vital in assessing the reliability of technical procedures (Fornasini, 2008). An inter-laboratory validation should also be carried out as this will test the reproducibility of the method. Reproducibility requires measurements to be obtained with the same method on identical measurement items, in different laboratories, with different analysts using different equipment (ISO 3534-2:2006; Rogers, 2013). Many studies, particularly in the chemistry field have used this approach of validating methods and establishing inter-laboratory reliability by testing for its repeatability, reproducibility, and uncertainty (Al-Masri & Amin, 2005; Tiryaki, 2006; Yoneyama et al., 2014). In addition to quantifying the reproducibility and inter-laboratory reliability of the V-FTVMP, this validated protocol should then be considered in the development of a new standardized method for the measurement of FTV. As previously mentioned, measurement locations vary between studies, as there is currently no standard for FTV measurement. A standardized protocol would address this problem, as all researchers would have to measure, record, and evaluate exposures in accordance with this standard. Future research should also examine analysis procedures and develop appropriate frequency-weighting curves as ISO 2631-1 standards are not appropriate for FTV exposure (Thompson et al., 2010; Leduc et al., 2011; Eger et al., 2014).

There are a few limitations to this study; firstly, the sample size of 12 participants limits the results of the study and may have been the reason for such a wide confidence interval in ICC scores. More participants may have produced more reliable and less varied measures of FTV.

Furthermore, some of the variability in measures that are observed in this study may also relate to the inconsistent vibration signal from the platform itself. The platform used in this study is a commercially-used vibration ‘exercise’ platform that does not have the capability of producing a consistent vibration signal over time. Another limitation of the study is that knee angles were monitored and maintained below 20° flexion. This was chosen since it was found in a previous study (Vance, Chapter 2) that FTV measures did not change between 0-20°; however, knee flexion angles above 20° should potentially be investigated since more joint flexion and less rigidity of the body will reduce transmissibility to the head which could result in discomfort or injury (Paddan & Griffin, 1993; Harazin & Grzesik, 1998; Abercromby et al., 2007).

In conclusion, the Vance FTVMP appears to be a reliable method for the measurement of FTV exposure and further progress should be made to complete validation. Although un-weighted r.m.s. accelerations in the z-axis were deemed reliable from intraclass correlation tests, vector sum acceleration revealed the highest reliability at all measurement locations (ICC=0.82, 0.80, 0.86, 0.76). With this finding, researchers in future studies assessing FTV exposure should consider calculating and reporting vector sum acceleration, as it is in ISO 5349-1 (2001) for HAV assessment, in addition to the z-axis, when interpreting their data. Once fully validated, future research should be conducted to incorporate this measurement protocol into a standardized method for FTV measurement and evaluation. A standardized method for FTV is needed to effectively evaluate health risk, test interventions aimed at reducing exposure, and diagnosing vibration injury.

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Chapter 4: General Discussion

1. General Discussion

Workers exposed to FTV are at risk of suffering from vibration white-foot, a permanent and debilitating condition involving damage to the circulatory, neurological, and musculoskeletal systems of the feet and lower limbs. Researchers have been measuring and reporting worker exposure to FTV for years; however the reliability of the method used to measure FTV has yet to be studied. The purpose of this study was to examine how factors such as location of accelerometer placement on the foot, changes in standing posture, time of day that measurements are taken, and duration of measurement, influence measures of FTV exposure in order to propose a protocol for the measurement of FTV exposure. Primary considerations for the development of the Vance FTV Measurement Protocol included measuring vibration at the first metatarsal head and medial malleolus, and maintaining standing postures below 20° flexion. Inter-rater and intra-rater reliability associated with the proposed method for the measurement of FTV transmissibility was determined. Findings from this study have determined that the V-FTVMP should be used in future studies as it yields reliable measures of vertical axis acceleration, vector sum acceleration and transmissibility from floor-toe and floor-ankle. Additional research should be conducted with this method in order to finalize validation and standard development.

1.1. Relevance to Workers

FTV exposure can lead to permanent and debilitating health outcomes (Thompson et al., 2010); therefore, it is important to understand the risks of FTV exposure and monitor exposure.A reliable and validated method for FTV measurement will allow for accurate and precise measurements when evaluating worker exposures. Monitoring exposure to FTV for workers in mining, construction, forestry, and other sectors is required to understand risk of vibration injury and to test interventions aimed at reducing exposure such as personal protective equipment..

1.2. Relevance to Researchers

Researchers interested in FTV exposure can adopt the V-FTVMP as it has been deemed reliable; however, more research needs to be done to complete validation of the method. Researchers in different laboratories from other institutions are needed for an inter-laboratory validation study to test the reproducibility and measurement uncertainty of the measurement method. Researchers investigating FTV exposure may also want to consider reporting vector sum acceleration in their findings (in addition to vertical axis) as these measures revealed highest reliability in this study.

1.3. Relevance to Industry

A reliable and valid method will allow for proper and effective measurement of FTV exposure for workers in industries where FTV is prevalent such as mining, construction, and forestry. This research could eventually lead to safer work outcomes and identification of hazardous working conditions, such as ineffective PPE, machine operation, and exposure times. Development of this method into an internationally-recognized standard could eventually involve enforcement of guidelines from the employer over how much vibration workers can safely manage in a working day, as it is for WBV and HAV exposure.

1.4. Relevance to Standards Committees

Once further research is conducted using the V-FTVMP, it should be developed and implemented into a new standard for the assessent and evaluation of human exposure to FTV. FTV should be internationally recognized as a potential hazardous work exposure as it is for

WBV and HAV exposure. The protocol for FTV measurement such as the one outlined in this study should be incorporated in the standard, as well as the identification of exposure limits and harmful exposure frequencies, magnitudes and durations. Development of resonant frequencies of the human body in response to FTV should be tested and new frequency-weighting curves should be developed for the assessment of health risk as the curves used in ISO 5349 and ISO 2631 are not entirely suitable for FTV (Eger 2014 et al., Goggins 2016 et al.).

1.5. Conclusions

The Vance FTVMP was developed by identifying appropriate measurement locations, standing postures, and a suitable trial duration for laboratory testing. This method was tested for its inter and intra-rater reliability and was found to be acceptable. Researchers and health professionals measuring vibration exposure can use this method to investigate human responses to FTV and to improve the knowledge of health risk to workers. Standards committees can use this measurement protocol as a starting point to implement an international standard to guide the measurement and evaluation of FTV exposure. With proper and reliable measurement, exposure can be effectively monitored in efforts aimed at reducing exposure and assessing health risk.

Appendices

Appendix A: Accelerometer mounting protocol for Chapter 2

To measure FTV transmissibility the technician should mount the accelerometers as follows:

1. Have participant sit comfortably with foot hanging over the edge of a bench (or similar), warn them that the set-up may be uncomfortable if they have sensitive feet.
2. Put on gloves and use an alcohol swab to clean the areas of the foot where the accelerometers will be placed (first metatarsal head, midfoot and lateral malleolus).
3. Have participant slide the compression sleeve onto their leg, leaving it loose.
4. Feed the wires of the accelerometers through the sleeve, ensuring to be gentle in the handling of the wires. Keep the wires on the lateral side of the thigh.
5. Take one of the accelerometer sensors, placing the flat side of the accelerometer against the foot, positioned with the sensor on the boniest spot of the desired location. Make sure to note which accelerometer number has been placed on which location.
6. Place the accelerometer so that the wire comes across the top of the foot from the medial side to the lateral side where the wire runs up the leg, crossing on top of the ankle bone. Use clear medical tape to secure the sensor to the foot, covering the whole sensor and a small part of the wire so that it will not shift.
7. Take a picture of the accelerometer on the participant's foot to note the orientation of the accelerometer for each axis (x,y,z).
8. Use elastic therapeutic tape (KT tape) to secure the wire to the foot. Make sure to cover the entire sensor part of the accelerometer and cover the wire all the way to above the ankle bone. Only a small amount of tension is needed in the tape. If the person will be

wearing the accelerometer all day or will be sweating, use the spray to help the tape stick for longer. Rub the tape to activate the adherence.

9. Repeat steps 5-8 for any following accelerometers.
10. Have the participant stand up and pull the tension on the wires so that there is minimal slack, but enough that they can move their leg freely. Pull the compression sleeve up so that it is tight and holding the wires in place. If needed, use the tensor band to hold the wires around the calf area. Use the fanny pack to hold the data logger on the participant.
11. Give the participant a sock to gently put on over accelerometer set-up.

Appendix B: Vance FTV Measurement Protocol

Vance FTV Measurement Protocol

Supplies:

- Teardrop accelerometers (4) Datalogger (3)
- Rubber gloves
- Alcohol swabs
- Medical tape
- Elastic therapeutic tape
- Scissors
- Compression sleeve
- Tensor band
- Goniometer
- Socks

Participant set-up

1. Have participant sit comfortably with foot hanging over edge of bench, or standing with their foot raised and rested flat on a bench. Warn them that the set-up may be uncomfortable if they have sensitive feet.
2. Put on gloves and use an alcohol swab to clean areas of foot where the accelerometers will be placed (medial malleolus and first metatarsal head).
3. Have participant slide the compression sleeve onto their leg, leaving it loose.
4. Feed the wires of the accelerometers through the sleeve, ensuring to be gentle in the handling of the wires. Keep the wires on the lateral side of the thigh.
5. Take one of the accelerometer sensors, mounting the flat, microchip side against the foot, positioned with the sensor on the boniest spot of the desired location (i.e. medial malleolus, first metatarsal head). Make sure to note which accelerometer number has been placed on which location. On the toe location, position the microchip so that the wire runs proximally up the foot. For the ankle location, position the microchip so that the wire runs posteriorly. (Figures 1 and 2).
6. Mount the accelerometer so that the wire comes across the top of the foot to the lateral side so that the wire runs up the leg. Use clear medical tape to firmly secure the sensor to the foot, covering the whole sensor and a small part of the wire so that it will not shift.
7. Be sure to take a picture of the accelerometer on the participant’s foot to note the orientation of the accelerometer for each axis (x,y,z).
8. Use elastic therapeutic tape to secure the wire to the foot. Make sure to cover the entire sensor part of the accelerometer and cover at least 3 cm of the wire. Only a small amount of tension is needed in the tape. If the person will be wearing the accelerometer all day or will

be sweating, use the spray to help the tape stick for longer. Rub the tape to activate the adherence (Figure 3).

9. Repeat steps 5-8 for the second accelerometer.
10. Have the participant stand up and pull the tension on the wires so that there is minimal slack, but enough that they can move their leg freely. Pull the compression sleeve up so that it is tight and holding the wires in place. If needed, use the tensor band to hold the wires around the calf area. Use the fanny pack to hold the data logger on the participant, or rest the data-loggers safely on a table beside the participant.
11. Give the participant a sock to gently put on over the accelerometer set-up.
12. Set up the goniometer at the knee joint, to measure the participant's knee flexion angle. Use double-sided tape to mount the two leads on the lateral shin and lateral thigh (Figure 4).

Figure 1: Accelerometer positioning on the first metatarsal head

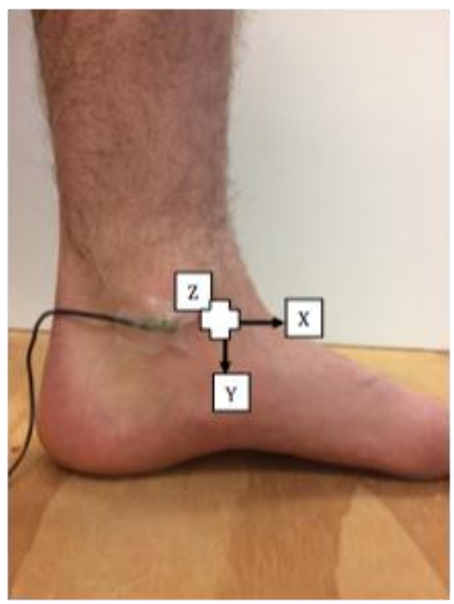
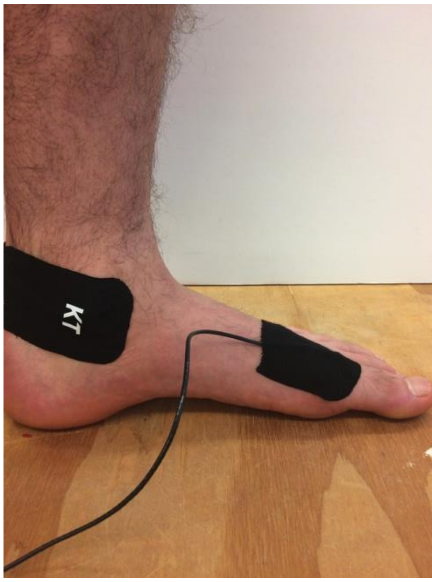


Figure 2: Accelerometer positioning on the medial malleolus



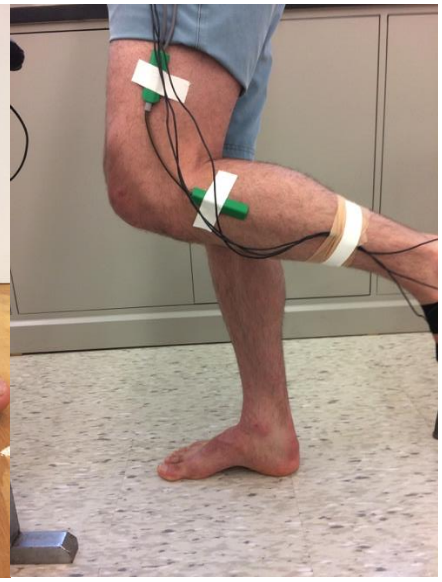


Figure 3: Kinesiology tape applied to secure the accelerometers to the foot

Figure 4: Goniometer attachment at the knee joint

Platform set-up

1) Have the participant stand on the vibration platform and mark the foot placement at the toe and ankle with a piece of tape.
2) Mount the two accelerometers to the vibrating platform at the locations marked with the piece of tape. One should be mounted directly beside the ankle of the participant's foot and one should be mounted beside their toe. The accelerometer should be mounted close enough to the foot so that it lines up with the other accelerometer but is in a location to avoid damage. Secure the accelerometers firmly to the platform using the same method mentioned above (Figure 5).

Figure 5: Platform accelerometer locations

- Be very cautious and consistent with the precise placement of each accelerometer.
- The accelerometers are sensitive to slight deviations in positioning across repeated trials. Be sure that the location is marked to avoid shifting and/or rotating the accelerometer for repeated trials
- If recording repeated trials on a sample of participants for a study, be sure to use the same accelerometer on the same location and that they are connected to the same port in the data logger.

Using the vibration platform

1) Select desired frequency or speed on the platform (PowerPlate or other)

2) Select 45-second trials. The middle 30-seconds should be extracted for further analysis. This excludes some of the noise that may be recorded in FTV measures in the beginning and middle of trials. Longer trial durations are not necessary; 30-second trial durations are found to be consistent and repeatable with minimal variability in measures.
3) Have participant stand with their legs shoulder-width apart with a slight bend in their knees. Ensure that the participant is not exceeding a standing posture of 20° knee flexion. If available, attach a goniometer to the subject to measure knee flexion angle.
4) If you are planning on recording repeated trials for the same subject, it is not imperative that they do them all at once. If the participant were to return on a different day and be available for a different time of the day, FTV measures should not be affected

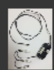
Appendix C: Vance FTV Measurement Protocol Sheet

VANCE FTV MEASUREMENT METHOD

Follow these steps to accurately measure an individuals exposure to foot-transmitted vibration

YOU WILL NEED:

- clear medical tape
- kinesiology tape
- scissors
- alcohol wipes
- medical gloves
- compression sleeve
- tensor band
- 2 data loggers
- 4 accelerometers



TIPS AND THINGS TO REMEMBER

- Be very cautious and consistent with the precise placement of the accelerometer. They are sensitive to slight deviations in positioning across repeated trials
- Be sure that you use the same accelerometer on the same location for repeated trials and that they are connected to the same port in the data logger each time
- Just prior to recording the trial, be sure to zero all channels on the data logger

PLATFORM SET-UP

1. Have the participant stand on the vibration exercise platform and mark the foot placement at the toe and ankle with a piece of tape

2. Firmly mount the two accelerometers to the vibrating platform with medical and kinesiology tape, at the previously marked locations

3. One accelerometer should be mounted directly beside the ankle of the participant, and the other beside the toe. They should be placed as close as possible to the foot in a safe enough location to avoid damage (Figure 1)

4. Connect the accelerometers to the data loggers using the lemo connectors in the corresponding x, y, and z-axis ports. Line up the red dots and lightly push until it clicks in

5. Instruct the participant to stand comfortably with their feet shoulder-width apart, and a slight bend in their knees. Be sure that knee flexion does not exceed 20°

6. Record vibration exposure for 45-second trials

Figure 1: Platform accelerometer placement

45-second trials

SEE REVERSE FOR PARTICIPANT SET-UP

PARTICIPANT SET-UP

1. Have the participant elevate their foot and place it on a flat surface (Note: if planning on repeating trials, ensure to use the same foot)

2. Don your gloves and clean the participant's foot with an alcohol wipe

3. Slide a compression sleeve up their leg and feed the wires from the two accelerometers up the lateral side of the leg

4. Take one accelerometer, with the microchip side against the foot and secure it to the boniest part of the first metatarsal head below the big toe with clear medical tape. Position it so that the wire runs proximally up the foot (Fig. 2)

5. Mount the 2nd accelerometer to the centre part of the medial malleolus of the ankle, positioned so that the wire runs posteriorly (Fig. 3)

6. Position the wires in a way that they run across the foot and up the lateral side of the leg

7. Take a picture of the set-up to document the orientation of each accelerometer for each axis (x,y,z)

8. Firmly secure the accelerometer by covering the entire head of the accelerometer with kinesiology tape. Apply light tension on the tape and cover at least 3cm of the wire. Rub the tape to activate the adhesion (Fig. 4)

9. Pull the compression sleeve carefully up the thigh, ensuring the wires do not restrict any range of motion of the leg

10. If necessary, use an additional tensor band around the calf to further secure the wires to the lateral side of the leg

11. Connect the accelerometers to the data loggers using the lemo connectors in the corresponding x, y, and z-axis ports. Line up the red dots and lightly push until it clicks in

Figure 2

Figure 3

Figure 4

Appendix D: Sample Matlab code

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% bv_ftv_analysis
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Always plug lemo connectors in X=1 Y=2 Z=3, X=5 Y=6 Z=7

%

% Loads files with XYZXYZ column assignments

%

% This code will asses transmissibility using four teardrop accelerometers

%

% Datalogger 1

%   td01=platform at toe (Channel 1=X, 2=Y, 3=Z)

%   td02=platform at ankle (Channel 5=X, 6=Y, 7=Z)

%

% Datalogger 2

%   td03=toe (Channel 1=X, 2=Y, 3=Z)

%   td04=ankle (Channel 4=X, 5=Y, 6=Z)

%

% 1 frequency: 30Hz

%

%

%

%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%

close all

clear all

load subject12_30Hz_trial9_dl1.txt

load subject12_30Hz_trial9_dl2.txt

datalogger1=subject12_30Hz_trial9_dl1;

datalogger2=subject12_30Hz_trial9_dl2;

clear subject12_30Hz_trial9_dl1

clear subject12_30Hz_trial9_dl2

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

sf=1000;

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

clear datalogger1
```

```
clear datalogger2

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

% find and remove low frequency biases

aligned_data_means=mean(aligned_data);

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

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

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

aligned_data_bias_removed_filtered=filtfilt(b,a,aligned_data_bias_removed)
;

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

aligned_data_bias_removed_filtered=filtfilt(b,a,aligned_data_bias_removed_
filtered);

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

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

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

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


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

window_start=round(X(1,1));


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


clear aligned_data_bias_removed_filtered


% Plot 30 second window of aligned data


figure(2)

plot(aligned_data_window(:,:));


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


% Creating teardrop variables


td01=aligned_data_window(:,1:3);
```

```
td02=aligned_data_window(:,4:6);

td03=aligned_data_window(:,7:9);

td04=aligned_data_window(:,10:12);


clear aligned_data_window


% Load scaling factor document


load static_scaling_factors.txt


td01_X_sf=static_scaling_factors(1,1);

td01_Y_sf=static_scaling_factors(1,2);

td01_Z_sf=static_scaling_factors(1,3);


td02_X_sf=static_scaling_factors(2,1);

td02_Y_sf=static_scaling_factors(2,2);

td02_Z_sf=static_scaling_factors(2,3);


td03_X_sf=static_scaling_factors(3,1);

td03_Y_sf=static_scaling_factors(3,2);

td03_Z_sf=static_scaling_factors(3,3);
```

```
td04_X_sf=static_scaling_factors(4,1);

td04_Y_sf=static_scaling_factors(4,2);

td04_Z_sf=static_scaling_factors(4,3);


% Scale data with all four teardrop scaling factors


td01_scaled(:,1)=td01(:,1)*td01_X_sf;

td01_scaled(:,2)=td01(:,2)*td01_Y_sf;

td01_scaled(:,3)=td01(:,3)*-td01_Z_sf;


td02_scaled(:,1)=td02(:,2)*td01_X_sf;

td02_scaled(:,2)=td02(:,1)*td01_Y_sf;

td02_scaled(:,3)=td02(:,3)*-td01_Z_sf;


td03_scaled(:,1)=td03(:,1)*td01_X_sf;

td03_scaled(:,2)=td03(:,2)*td01_Y_sf;

td03_scaled(:,3)=td03(:,3)*-td01_Z_sf;


td04_scaled(:,1)=td04(:,1)*td01_X_sf;

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

td04_scaled(:,3)=td04(:,2)*td01_Y_sf;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%

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

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


%%%%%%%%%%%%%%%%%%%%%%% WBV Processing for td01
%%%%%%%%%%%%%%%%%%%%%%%%%%%
data=[time,td01_scaled,td01_scaled];
```

```
[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNweighted,C
F_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,running_R
MS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,MTVV_aw_r
atio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave_UNweight
ed,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave_UNweight
ed,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave_UNweight
ed,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_octave_UNwei
ghted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_third_octav
e_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw_third
_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectraldata
_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_DFTs
pectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weight
ed,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFT
spectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata
_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UNweighted,
VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RM
S_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_U
Nweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sf,bpfclow,bp
fcup,octbfclow,octbfcup,AT,overlap);

%function[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNw
eighted,CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,
running_RMS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,
MTVV_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave
_UNweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave
_UNweighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave
_UNweighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_oct
ave_UNweighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_th
ird_octave_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_
Yaw_third_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspe
ctraldata_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweight
ed,Y_DFTspectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectralda
ta_weighted,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,
```

```
Pitch_DFTspectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspe
ctraldata_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UN
weighted,VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RM
S_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_U
Nweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sampling_freq
uency,band_pass_lower_freq,band_pass_upper_freq,octave_band_pass_lower_fre
q,octave_band_pass_upper_freq,averageing_time,moving_window_overlap)


td01_unweighted_data(1,1:3)=peak_UNweighted(1,1:3);

td01_unweighted_data(1,4:6)=RMS_UNweighted(1,1:3);

td01_unweighted_data(1,7:9)=CF_UNweighted(1,1:3);

td01_unweighted_data(1,10:12)=running_RMS_UNweighted(1,1:3);

td01_unweighted_data(1,13:15)=MTVV_UNweighted(1,1:3);

td01_unweighted_data(1,16:18)=MTVV_aw_ratio_UNweighted(1,1:3);

td01_unweighted_data(1,19)=VTV_translational_RMS_UNweighted(1,1);


td01_unweighted_3rdoctave_spectra(:,1:2)=running_RMS_X_third_octave_UNweig
hted(:,1:2);

td01_unweighted_3rdoctave_spectra(:,3)=running_RMS_Y_third_octave_UNweight
ed(:,2);

td01_unweighted_3rdoctave_spectra(:,4)=running_RMS_Z_third_octave_UNweight
ed(:,2);


td01_unweighted_DFT_spectra(1:101,1:2)=X_DFTspectraldata_UNweighted(1:101,
1:2);
```

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

td01_unweighted_DFT_spectra(1:101,4)=Z_DFTspectraldata_UNweighted(1:101,2)
;




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

data=[time,td02_scaled,td02_scaled];



[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNweighted,C
F_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,running_R
MS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,MTVV_aw_r
atio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave_UNweight
ed,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave_UNweight
ed,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave_UNweight
ed,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_octave_UNwei
ghted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_third_octav
e_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw_third
_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectraldata
_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_DFTs
pectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weight
ed,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFT
spectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata
_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UNweighted,
VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RM
S_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_U
Nweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sf,bpfclow,bp
fcup,octbfclow,octbfcup,AT,overlap);
```

```
%function[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNw
eighted,CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,
running_RMS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,
MTVV_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave
_UNweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave
_UNweighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave
_UNweighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_oct
ave_UNweighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_th
ird_octave_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_
Yaw_third_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspe
ctraldata_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweight
ed,Y_DFTspectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectralda
ta_weighted,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,
Pitch_DFTspectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspe
ctraldata_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UN
weighted,VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RM
S_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_U
Nweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sampling_freq
uency,band_pass_lower_freq,band_pass_upper_freq,octave_band_pass_lower_fre
q,octave_band_pass_upper_freq,averageing_time,moving_window_overlap)


td02_unweighted_data(1,1:3)=peak_UNweighted(1,1:3);

td02_unweighted_data(1,4:6)=RMS_UNweighted(1,1:3);

td02_unweighted_data(1,7:9)=CF_UNweighted(1,1:3);

td02_unweighted_data(1,10:12)=running_RMS_UNweighted(1,1:3);

td02_unweighted_data(1,13:15)=MTVV_UNweighted(1,1:3);

td02_unweighted_data(1,16:18)=MTVV_aw_ratio_UNweighted(1,1:3);

td02_unweighted_data(1,19)=VTV_translational_RMS_UNweighted(1,1);
```

```
td02_unweighted_3rdoctave_spectra(:,1:2)=running_RMS_X_third_octave_UNweig
hted(:,1:2);

td02_unweighted_3rdoctave_spectra(:,3)=running_RMS_Y_third_octave_UNweight
ed(:,2);

td02_unweighted_3rdoctave_spectra(:,4)=running_RMS_Z_third_octave_UNweight
ed(:,2);



td02_unweighted_DFT_spectra(1:101,1:2)=X_DFTspectraldata_UNweighted(1:101,
1:2);

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

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




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

data=[time,td03_scaled,td03_scaled];



[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNweighted,C
F_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,running_R
MS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,MTVV_aw_r
atio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave_UNweight
ed,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave_UNweight
ed,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave_UNweight
ed,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_octave_UNwei
ghted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_third_octav
e_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw_third
```

```
_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectraldata
_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_DFTs
pectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weight
ed,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFT
spectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata
_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UNweighted,
VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RM
S_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_U
Nweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sf,bpfclow,bp
fcup,octbfclow,octbfcup,AT,overlap);

%function[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNw
eighted,CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,
running_RMS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,
MTVV_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave
_UNweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave
_UNweighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave
_UNweighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_oct
ave_UNweighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_th
ird_octave_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_
Yaw_third_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspe
ctraldata_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweight
ed,Y_DFTspectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectralda
ta_weighted,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,
Pitch_DFTspectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspe
ctraldata_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UN
weighted,VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RM
S_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_U
Nweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sampling_freq
uency,band_pass_lower_freq,band_pass_upper_freq,octave_band_pass_lower_fre
q,octave_band_pass_upper_freq,averageing_time,moving_window_overlap)


td03_unweighted_data(1,1:3)=peak_UNweighted(1,1:3);
```

```
td03_unweighted_data(1,4:6)=RMS_UNweighted(1,1:3);

td03_unweighted_data(1,7:9)=CF_UNweighted(1,1:3);

td03_unweighted_data(1,10:12)=running_RMS_UNweighted(1,1:3);

td03_unweighted_data(1,13:15)=MTVV_UNweighted(1,1:3);

td03_unweighted_data(1,16:18)=MTVV_aw_ratio_UNweighted(1,1:3);

td03_unweighted_data(1,19)=VTV_translational_RMS_UNweighted(1,1);


td03_unweighted_3rdoctave_spectra(:,1:2)=running_RMS_X_third_octave_UNweig
hted(:,1:2);

td03_unweighted_3rdoctave_spectra(:,3)=running_RMS_Y_third_octave_UNweight
ed(:,2);

td03_unweighted_3rdoctave_spectra(:,4)=running_RMS_Z_third_octave_UNweight
ed(:,2);


td03_unweighted_DFT_spectra(1:101,1:2)=X_DFTspectraldata_UNweighted(1:101,
1:2);

td03_unweighted_DFT_spectra(1:101,3)=Y_DFTspectraldata_UNweighted(1:101,2)
;

td03_unweighted_DFT_spectra(1:101,4)=Z_DFTspectraldata_UNweighted(1:101,2)
;


%%%%%%%%%%%%%%%%%%%%%%% WBV Processing for td04
%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
data=[time,td04_scaled,td04_scaled];


[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNweighted,C
F_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,running_R
MS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,MTVV_aw_r
atio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave_UNweight
ed,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave_UNweight
ed,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave_UNweight
ed,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_octave_UNwei
ghted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_third_octav
e_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_Yaw_third
_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspectraldata
_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweighted,Y_DFTs
pectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectraldata_weight
ed,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,Pitch_DFT
spectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspectraldata
_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UNweighted,
VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RM
S_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_U
Nweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sf,bpfclow,bp
fcup,octbfclow,octbfcup,AT,overlap);

%function[peak_UNweighted,peak_weighted,RMS_UNweighted,RMS_weighted,CF_UNw
eighted,CF_weighted,third_octave_RMS_UNweighted,third_octave_RMS_weighted,
running_RMS_UNweighted,running_RMS_weighted,MTVV_UNweighted,MTVV_weighted,
MTVV_aw_ratio_UNweighted,MTVV_aw_ratio_weighted,running_RMS_X_third_octave
_UNweighted,running_RMS_X_third_octave_weighted,running_RMS_Y_third_octave
_UNweighted,running_RMS_Y_third_octave_weighted,running_RMS_Z_third_octave
_UNweighted,running_RMS_Z_third_octave_weighted,running_RMS_Roll_third_oct
ave_UNweighted,running_RMS_Roll_third_octave_weighted,running_RMS_Pitch_th
ird_octave_UNweighted,running_RMS_Pitch_third_octave_weighted,running_RMS_
Yaw_third_octave_UNweighted,running_RMS_Yaw_third_octave_weighted,X_DFTspe
ctraldata_UNweighted,X_DFTspectraldata_weighted,Y_DFTspectraldata_UNweight
ed,Y_DFTspectraldata_weighted,Z_DFTspectraldata_UNweighted,Z_DFTspectralda
```

```
ta_weighted,Roll_DFTspectraldata_UNweighted,Roll_DFTspectraldata_weighted,
Pitch_DFTspectraldata_UNweighted,Pitch_DFTspectraldata_weighted,Yaw_DFTspe
ctraldata_UNweighted,Yaw_DFTspectraldata_weighted,VTV_translational_RMS_UN
weighted,VTV_translational_RMS_weighted,
VTV_6DOF_RMS_UNweighted,VTV_6DOF_RMS_weighted,VTV_translational_running_RM
S_UNweighted,VTV_translational_running_RMS_weighted,VTV_6DOF_running_RMS_U
Nweighted,VTV_6DOF_running_RMS_weighted]=wbv_processing(data,sampling_freq
uency,band_pass_lower_freq,band_pass_upper_freq,octave_band_pass_lower_fre
q,octave_band_pass_upper_freq,averageing_time,moving_window_overlap)


td04_unweighted_data(1,1:3)=peak_UNweighted(1,1:3);

td04_unweighted_data(1,4:6)=RMS_UNweighted(1,1:3);

td04_unweighted_data(1,7:9)=CF_UNweighted(1,1:3);

td04_unweighted_data(1,10:12)=running_RMS_UNweighted(1,1:3);

td04_unweighted_data(1,13:15)=MTVV_UNweighted(1,1:3);

td04_unweighted_data(1,16:18)=MTVV_aw_ratio_UNweighted(1,1:3);

td04_unweighted_data(1,19)=VTV_translational_RMS_UNweighted(1,1);


td04_unweighted_3rdoctave_spectra(:,1:2)=running_RMS_X_third_octave_UNweig
hted(:,1:2);

td04_unweighted_3rdoctave_spectra(:,3)=running_RMS_Y_third_octave_UNweight
ed(:,2);

td04_unweighted_3rdoctave_spectra(:,4)=running_RMS_Z_third_octave_UNweight
ed(:,2);
```

```
td04_unweighted_DFT_spectra(1:101,1:2)=X_DFTspectraldata_UNweighted(1:101,
1:2);

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

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




% The output variables of the code are as follows

%

% peak_Unweighted

%

% col 1 = X

% col 2 = Y

% col 3 = Z

%

% RMS_Unweighted --> continous band or frequency sum or vector sum

%

% col 4 = X

% col 5 = Y

% col 6 = Z

%

% CF_UNweighted
```

```
%
% col 7 = X
% col 8 = Y
% col 9 = Z
%
% running_RMS_UNweighted --> continous band or frequency sum or vector sum
%
% row 1 = mean
%
% col 10 = X
% col 11 = Y
% col 12 = Z
%
% MTVV_UNweighted
%
% row 1 = mean
%
% col 13 = X
% col 14 = Y
% col 15 = Z
%
% MTVV_aw_ratio_UNweighted
```

```
%
% row 1 = mean
%
% col 16 = X
% col 17 = Y
% col 18 = Z
%
% VTV_translational_RMS_UNweighted --> summed across axes
%
% col 19
%
% running_RMS_AXIS?_third_octave_UNweighted & weighted
%
% col 1 = 1/3 octave bin center frequency
% col 2 = X-axis mean RMS acceleration
% col 3 = Y-axis mean RMS acceleration
% col 4 = Z-axis mean RMS acceleration
%
% AXIS?_DFTspectraldata_UNweighted & weighted
%
% col 1 = DFT frequency bin
% col 2 = X-axis mean signal power
```

```
% col 3 = Y-axis mean signal power

% col 4 = Z-axis mean signal power

%

%

% NOTE: that some of the lower overlap percentages will result in some
data

% at the end of the trials not being used for averaging (occurs with

% percentages less than 50%).

%

% NOTE: In the future the rotational data collected should be used to
remove

% g*sin theta error will be removed from the accelerometer data



subject_unweighted_data=[td01_unweighted_data;td02_unweighted_data;td03_un
weighted_data;td04_unweighted_data];



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


% Ratio of running RMS acceleration (output to input)
```

```
toe_transmissibility=(td03_unweighted_data(1,10:12))./(td01_unweighted_dat
a(1,10:12));


ankle_transmissibility=(td04_unweighted_data(1,10:12))./(td02_unweighted_d
ata(1,10:12));


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


%x-axis_toe

outputdata=td03_scaled(:,1);

inputdata=td01_scaled(:,1);

%sf

%bpfclow

%bpfcup

%AT

%overlap


[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,pha
se_deg_unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfc
low,bpfcup,AT,overlap);


toe_modulus_size=size(modulus);

columns=toe_modulus_size(1,2);
```

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


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


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


%y-axis_toe
outputdata=td03_scaled(:,2);
inputdata=td01_scaled(:,2);
%sf
%bpfclow
%bpfcup
%AT
%overlap
```

```
[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,pha
se_deg_unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfc
low,bpfcup,AT,overlap);


toe_modulus_size=size(modulus);

columns=toe_modulus_size(1,2);

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


toe_coherence_size=size(modulus);

columns=toe_coherence_size(1,2);

toe_coherence(1:101,3)=(coherence(1:101,columns-1));


peak_modulus=max(modulus(1:101,columns-1));

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

toe_dom_freq(1,2)=toe_modulus(peak_rows,1);


%z-axis_toe

outputdata=td03_scaled(:,3);

inputdata=td01_scaled(:,3);

%sf

%bpfclow

%bpfcup
```

```
%AT
%overlap

[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,pha
se_deg_unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfc
low,bpfcup,AT,overlap);

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

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

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


%x-axis_ankle
outputdata=td04_scaled(:,1);
```

```
inputdata=td02_scaled(:,1);

%sf

%bpfclow

%bpfcup

%AT

%overlap


[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,pha
se_deg_unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfc
low,bpfcup,AT,overlap);


ankle_modulus_size=size(modulus);

columns=ankle_modulus_size(1,2);

ankle_modulus(1:101,1)=(modulus(1:101,1));

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


ankle_coherence_size=size(modulus);

columns=ankle_coherence_size(1,2);

ankle_coherence(1:101,1)=(coherence(1:101,1));

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


peak_modulus=max(modulus(1:101,columns-1));
```

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

ankle_dom_freq(1,1)=ankle_modulus(peak_rows,1);


%y-axis_ankle

outputdata=td04_scaled(:,2);

inputdata=td02_scaled(:,2);

%sf

%bpfclow

%bpfcup

%AT

%overlap


[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,pha
se_deg_unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfc
low,bpfcup,AT,overlap);


ankle_modulus_size=size(modulus);

columns=ankle_modulus_size(1,2);

ankle_modulus(1:101,3)=(modulus(1:101,columns-1));


ankle_coherence_size=size(modulus);

columns=ankle_coherence_size(1,2);
```

```
ankle_coherence(1:101,3)=(coherence(1:101,columns-1));


peak_modulus=max(modulus(1:101,columns-1));

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

ankle_dom_freq(1,2)=ankle_modulus(peak_rows,1);


%z-axis_ankle

outputdata=td04_scaled(:,3);

inputdata=td02_scaled(:,3);

%sf

%bpfclow

%bpfcup

%AT

%overlap


[XDFTspectraldata,DFTspectraldata_input,DFTspectraldata_output,modulus,pha
se_deg_unwrapped,coherence]=transfer_function(outputdata,inputdata,sf,bpfc
low,bpfcup,AT,overlap);


ankle_modulus_size=size(modulus);

columns=ankle_modulus_size(1,2);

ankle_modulus(1:101,4)=(modulus(1:101,columns-1));
```

```
ankle_coherence_size=size(modulus);

columns=ankle_coherence_size(1,2);

ankle_coherence(1:101,4)=(coherence(1:101,columns-1));


peak_modulus=max(modulus(1:101,columns-1));

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

ankle_dom_freq(1,3)=ankle_modulus(peak_rows,1);


save subject12_30Hz_trial9_unweighted_data.txt subject_unweighted_data -
ASCII -TABS


save subject12_30Hz_trial9_td01_unweighted_3rdoctave_spectra.txt
td01_unweighted_3rdoctave_spectra -ASCII -TABS

save subject12_30Hz_trial9_td02_unweighted_3rdoctave_spectra.txt
td02_unweighted_3rdoctave_spectra -ASCII -TABS

save subject12_30Hz_trial9_td03_unweighted_3rdoctave_spectra.txt
td03_unweighted_3rdoctave_spectra -ASCII -TABS

save subject12_30Hz_trial9_td04_unweighted_3rdoctave_spectra.txt
td04_unweighted_3rdoctave_spectra -ASCII -TABS


save subject12_30Hz_trial9_td01_unweighted_DFT_spectra.txt
td01_unweighted_DFT_spectra -ASCII -TABS
```

```
save subject12_30Hz_trial9_td02_unweighted_DFT_spectra.txt
td02_unweighted_DFT_spectra -ASCII -TABS

save subject12_30Hz_trial9_td03_unweighted_DFT_spectra.txt
td03_unweighted_DFT_spectra -ASCII -TABS

save subject12_30Hz_trial9_td04_unweighted_DFT_spectra.txt
td04_unweighted_DFT_spectra -ASCII -TABS


save subject12_30Hz_trial9_toe_modulus.txt toe_modulus -ASCII -TABS

save subject12_30Hz_trial9_toe_coherence.txt toe_coherence -ASCII -TABS

save subject12_30Hz_trial9_ankle_modulus.txt ankle_modulus -ASCII -TABS

save subject12_30Hz_trial9_ankle_coherence.txt ankle_coherence -ASCII -
TABS

save subject12_30Hz_trial9_toe_dom_freq.txt toe_dom_freq -ASCII -TABS

save subject12_30Hz_trial9_ankle_dom_freq.txt ankle_dom_freq -ASCII -TABS


save subject12_30Hz_trial9_toe_transmissibility.txt toe_transmissibility -
ASCII -TABS

save subject12_30Hz_trial9_ankle_transmissibility.txt
ankle_transmissibility -ASCII -TABS
```

Appendix E: Background questionnaire

Questionnaire

Background Information

1. Have you ever sustained a head injury? ________________________

2. Have you had foot pain, lower leg pain or back pain within the last 6 months?_______

3. Do you get pain and discoloration of toes with change in temperature? ________

4. Do you get numbness or reduced sensations in the feet?____________

If you have answered **NO** to **the questions above**, 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.

5. What is your current age? ______________

6. What is your current weight? (Lbs) ______________

7. What is your current height? (Feet/inches) ____________

8. What is your shoe size? ___________

Appendix F: Consent form

Consent Form

"Establishing a standardized protocol for the measurement of human exposure to foot-transmitted vibration"

I, **_______________________**, am interested in participating in the study on the **"Establishing a standardized protocol for the measurement of human exposure to foot-transmitted vibration"** lead by Brandon Vance, Masters in Human Kinetics student (MHK), under the supervision of Prof. Tammy Eger, Research Chair in Occupational Health and Safety at Laurentian University. The purpose of the study is to determine the reliability of the method used to measure foot-transmitted vibration.

I understand that I am not eligible to participate if I have been previously diagnosed by a physician to have diabetes, vibration-induced white-foot, or a concussion. I am also ineligible if I suffer from motion sickness, have had a lower body musculoskeletal injury in the previous 6-months, am pregnant, or allergic to medical adhesive tape.

If I agree to participate, I will be asked to complete a short questionnaire (**5-10 minutes**) about my height, weight, age, and any health symptoms. I understand that I will be given a clean pair of socks and I will be asked to stand on a vibration exercise platform.

Two small accelerometers will be taped to my foot and ankle. Two additional accelerometers will be attached to the vibrating surface I stand on. During the study I will be asked to stand on a platform that vibrates at a level of 30 Hz (similar to operating a whipper snipper). I will be asked to stand on this platform for 45 seconds, with 20 seconds of rest between trials. In total I will be exposed to 6 minutes and 45 seconds of total vibration over 9 trials. Testing time will be under 2 hours. Three research assistants will be performing the measurements in this experiment. I know that the vibration exposure I will be exposed to is less than the daily allowance suggested by international standards.

If I choose to participate in this study, I understand that medical adhesive tape will be used to secure the accelerometers to my foot. I have been informed that in very rare cases a participant might develop a rash from the adhesive tape. The rash will likely fade within 24hours. However, if I am itchy I can withdraw from the study. If the itch or rash persists I am advised to seek medical attention.

I have been informed that only members of the research team will have access to the data collected. **My participation is strictly voluntary** and I am free to withdraw from the study at any moment or refuse to participate without any penalty. I have received assurance from the researcher that all data collected will remain strictly confidential. My individual results will not be reported. All collected data will be coded with a subject number and stored in a locked filing cabinet (in Professor Eger's Office) or on a password secured laptop that only members of the research team will have access to.

I understand that I will receive no immediate benefit from my participation.

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

If I have any questions or concerns about the study or about being a participant, I may contact the lead researcher, Professor Tammy Eger:

email teger@laurentian.ca

Phone: 705-675-1151 ext. 1005

If I have any questions or concerns surrounding the ethical conduct of the study, I may contact the Research Ethics Officer, Laurentian University Research Office, telephone: 705-675-1151 ext 3213, 2436 or toll free at 1-800-461-4030 or email: ethics@laurentian.ca.

I would like to obtain a short summary of the findings from this study upon completion of the project

☐ Yes ☐ No (if yes, please provide email address): ________________________________

I agree to participate in this study.

Participant's Signature: __________________________ Date: __________________________

Thank you for your participation.

Appendix G: Recruitment Script

Recruitment Script

Research study – Brandon Vance, MHK Candidate

My name is Brandon Vance and I am a Masters student, with the Centre for Research in Occupational Safety and Health (CROSH) at Laurentian University and studying in the Masters in Human Kinetics program. I am currently working on my thesis project entitled “Establishing a standardized protocol for measurement of human exposure to foot-transmitted vibration”. My thesis supervisor is Professor Tammy Eger, Research Chair of CROSH.

Long-term exposure to foot-transmitted vibration can cause tingling and numbness in the toes, and impair circulation which can lead to vibration induced white-foot. To decrease this risk, researchers are working to develop a standardized protocol to measure vibration that is transmitted from a vibrating surface into the feet. The purpose of this research is to determine the reliability of this protocol to yield consistent measures of vibration transmissibility for participants exposed to foot-transmitted vibration.

We are interested in recruiting male participants between 18-65 years of age to participate in this study. Participants will be asked to come to the laboratory in the Centre for Research in Occupational Safety and Health to go over the study objectives and provide consent. They will be asked to sign a short questionnaire about their current height, weight, age, and health status. Participants will then be asked to stand on the vibration exercise platform in the gym at a frequency of 30 Hz (similar to a whipper snipper) for 45-seconds at a time. They will complete 9 trials, totaling 6 minutes and 45-seconds of vibration exposure time. Total testing time should take less than 1.5 hours and they will be scheduled in a two-hour block.

In each experiment, vibration measurements will be performed by attaching two small accelerometers (smaller than a thumb nail) to the top of the foot and ankle of each participant. They will be attached using medical tape and kinesiology tape.

Participants will be exposed to vibration levels below international standards for daily exposure; therefore, injury risks are minimal. The exposure associated with participation in this study is highly unlikely to cause any lasting discomfort or lead to any other health problems associated with long-term vibration exposure; However, some participants might find exposure to vibration uncomfortable for a short period of time.

The study is restricted to male participants between the ages of 18-65 years of age with no previous history of blood vessel problems, motion sickness, diabetes or any previous diagnosis of a concussion. Participants with a lower body musculoskeletal injury in the past 6-months, or an allergy to adhesive tape will also be excluded.

There is no immediate benefit to you for participating in this study. If you volunteer to take part in the study, you have the right to withdraw at any point without any penalty.

If you are interested in participating in this study, or if you have any questions you can contact **Brandon Vance** at **bj_vance@laurentian.ca** or by signing up with the Research Technologist in the CROSH office.

Thank you for your attention and consideration.