Published in final edited form as:
Work. 2014 ; 47(1): 101–110. doi:10.3233/WOR-131692.

Vibration induced white-feet: Overview and field study of vibration exposure and reported symptoms in workers

Tammy Eger[a,b,*], **Aaron Thompson**[c,d], **Mallorie Leduc**[a], **Kristine Krajnak**[e], **Katie Goggins**[a], **Alison Godwin**[a,b], and **Ron House**[c,d]

[a]School of Human Kinetics, Laurentian University, Sudbury, ON, Canada

[b]Centre for Research in Occupational Safety and Health, Laurentian University, Sudbury, ON, Canada

[c]Department of Medicine, Division of Occupational Medicine, University of Toronto, Toronto, ON, Canada

[d]Department of Occupational and Environmental Health, St. Michael's Hospital, Toronto, ON, Canada

[e]Engineering and Controls Technology Branch, National Institute for Occupational Safety and Health, Morgantown, WV, USA

Abstract

BACKGROUND—Workers who stand on platforms or equipment that vibrate are exposed to foot-transmitted vibration (FTV). Exposure to FTV can lead to vibration white feet/toes resulting in blanching of the toes, and tingling and numbness in the feet and toes.

OBJECTIVES—The objectives are 1) to review the current state of knowledge of the health risks associated with foot-transmitted vibration (FTV), and 2) to identify the characteristics of FTV and discuss the associated risk of vibration-induced injury.

PARTICIPANTS—Workers who operated locomotives (n = 3), bolting platforms (n = 10), jumbo drills (n = 7), raise drilling platforms (n = 4), and crushers (n = 3), participated.

METHODS—A tri-axial accelerometer was used to measure FTV in accordance with ISO 2631-1 guidelines. Frequency-weighted root-mean-square acceleration and the dominant frequency are reported. Participants were also asked to report pain/ache/discomfort in the hands and/or feet.

RESULTS—Reports of pain/discomfort/ache were highest in raise platform workers and jumbo drill operators who were exposed to FTV in the 40 Hz and 28 Hz range respectively. Reports of discomfort/ache/pain were lowest in the locomotive and crusher operators who were exposed to FTV below 10 Hz. These findings are consistent with animal studies that have shown vascular and neural damage in exposed appendages occurs at frequencies above 40 Hz.

---

[*]Corresponding author: Tammy Eger, School of Human Kinetics, Laurentian University, 935 Ramsey Lake Road, Sudbury, ON, P3E 2S2, Canada. Tel.: +1 705 675 1151 x. 1005; Fax: +1 705 675 4845; teger@laurentian.ca.

CONCLUSIONS—Operators exposed to FTV at 40 Hz appear to be at greater risk of experiencing vibration induced injury. Future research is required to document the characteristics of FTV and epidemiological evidence is required to link exposure with injury.

Keywords

Occupational vibration; Raynaud's; white-foot; standing; vibration white-toes

1. Introduction

Vibration, an oscillatory motion about a fixed point, can enter the body at any point that is in contact with a vibrating surface including the hands (hand-arm vibration), feet (foot-transmitted vibration), or buttock and back (whole-body vibration). Adverse health effects, associated with vibration exposure are partially dependent on the primary point of entry to the body; therefore, it is important to document the source of the occupational exposure and the transmission route. For example, when driving a motorized vehicle a worker is exposed to hand-arm vibration (HAV) through contact with the steering wheel, whole-body-vibration (WBV) through the seat, and foot-transmitted vibration (FTV) through contact with the floor. In another scenario, a worker using a pneumatic power-tool may be solely exposed to HAV from the tool; however, if the tool is attached to a platform then the worker may also have concurrent FTV exposure. Similarly, some workers may only have FTV exposure, for example those who work on platforms that vibrate (i.e. crusher platform; drilling platform, bolting platform, etc.).

Several researchers have estimated occupational exposure to WBV including Bovenzi [1] who suggested 4–7% of the workforce in North America and Europe were exposed annually to harmful levels of WBV, and Wasserman [2] who reported 7 million workers in the United States had annual exposure to WBV. More recently Palmer and colleagues [3], estimated that 7.2 million men and 1.8 million women in Great Britain are exposed to occupational WBV. To date, published epidemiological data has not classified FTV independent from general WBV. Therefore, we do not know how many people from the estimated WBV exposure groups are primarily exposed to FTV. Epidemiological data are available for HAV exposure, suggesting 1.7–5.8% of workers in the United States, Canada and European countries are exposed to occupational HAV [4]. Furthermore, the prevalence of vibration white finger is estimated at 0–5% amongst workers using vibrating tools in warm climates and jumps up to 80–100% amongst workers exposed in countries at higher latitudes with colder climates [4,5].

Health effects associated with WBV have been well documented and include low-back pain, spinal degeneration, neck problems, headaches, nausea, gastrointestinal tract problems, disturbed sleep, and autonomic nervous system dysfunction [6–8]. HAV exposure causes a condition referred to as hand-arm-vibration syndrome (HAVS). HAVS is associated with vascular, neurological, and musculoskeletal problems of the hand-arm system [9]. Exposure to FTV may cause an analogous syndrome in the lower extremities; however, little is known about the characteristics of occupational FTV or clinical implications with prolonged exposure. The extent of disability caused by vibration exposure is variable and may depend on the magnitude, frequency, and duration of exposure; however, a clear dose response relationship has yet to be proven [4]. Low-back pain is the most common complaint amongst workers exposed to WBV, which can lead to lost work time depending on the severity of the disorder [10,11]. The severity of HAVS is generally classified using the Stockholm Workshop Scales (SWS) [12]. The SWSs are based on symptomatic history and generally require additional objective testing to establish a diagnosis of HAVS and provide accurate staging. The highest vascular component score on the SWS describes frequent blanching attacks affecting most fingers accompanied by trophic skin changes. The highest SWS score for the sensorineural component describes persistent numbness with tingling accompanied by reduced tactile discrimination and manual dexterity impairment. FTV can result in vascular and sensorineural changes in the feet; however, the SWS does not lend itself to staging of vibration white foot (VWFt) and no similar staging system has been developed to date to classify severity of FTV related disease.

The objective of this paper is to review the current state of knowledge of health risks associated with FTV, including evidence from animal studies, clinical studies and field studies. Case data from a field study in mining are presented to document the characteristics of FTV and discuss the associated risk of VWFt.

2. Effects of segmental vibration on physiology: Evidence from animal studies

Foot- and hand-transmitted vibration can be referred to as segmental vibration because the transmission of energy from the vibrating source to the body is limited to a single region or segment of the body. In workers, most studies examining the effects of segmental vibration have focused on vibration transmission to the hands. Skin biopsy samples collected from the fingers of workers have demonstrated that repeated, long-term exposure to vibration can result in damage to the arteries of the fingers and hands. This damage is characterized by thickening of the vascular smooth muscle, and fibrosis of the internal lining of blood vessels (i.e., the intima [13]). There is also nerve damage in these samples that is characterized by fibrosis in the region around peripheral nerves, a thinning or loss of the myelin sheath, and a reduction in peripheral nerves [14]. Although these studies demonstrate the morphological changes associated with vascular and sensorineural dysfunction in workers, additional data are needed to understand the mechanisms underlying these changes.

Animal models have been used to study the damage and mechanisms underlying vibration-induced injuries to the vascular, sensorineural and skeletal muscle systems. The models have included both single and repeated exposures of the fore and hind limbs of rats, mice or rabbits, or tails of rats to vibration using frequencies ranging from 30–1000 Hz with accelerations of approximately 2–7 g [15–18]. These studies have demonstrated that the morphological and physiological effects of both acute and repetitive vibration on these systems are similar to the effects seen in humans [13–20]. Furthermore, the effects are in part dependent upon the frequency of the vibration exposure [15,18, 21,22].

A single session of exposure to vibration (4 h in duration) using a broad range of frequencies has shown that blood flow is reduced in exposed appendages of animals [21]. These acute changes in blood flow may be the result of an increased responsiveness to α2C adrenoreceptor-mediated vaso-constriction [23] and/or a reduced responsiveness to acetylcholine (ACh)-mediated vasodilation [24]. These functional effects appear to be mediated in part by vibration-induced increases in oxidative stress within vessels [24]. Morphological changes after a single vibration exposure include the presence of vacuoles in the smooth muscle and endothelial layers of peripheral arteries [22].

Exposure to repeated bouts of vibration results in fibrosis of the intima (internal lining of arteries comprised of endothelial cells), and obstruction of the lumen in peripheral vessels [16,17], as well as remodeling of arteries characterized by a thickening of the vascular smooth muscle wall and reduction in the diameter of the lumen [20]. Repeated exposures also result in a reduced responsiveness of arteries to ACh-mediated vasodilatation and increases in oxidative activity and the expression of remodeling factors [17,20].

Vibration also induces morphological and physiological changes in peripheral nerve function in animal models. Single exposures to vibration of a single frequency (i.e., in the 30–1000 Hz range), have been associated with a reduction in nerve conduction velocity [21], edema and myelin disruption in nerves [18, 25,26], and a transient increase in the sensitivity of peripheral nerves to transcutaneous electrical stimulation at 2000 Hz [27]. Exposure to a single bout of impact vibration (i.e. acceleration shock pulse applied to one point) resulted in swelling in nerve terminals and an increased sensitivity to heat on the day of the exposure in rats exposed to tail vibration. By day 4 post-exposure, there was a reduction in PGP9.5 (a marker of nerve fibers) in nerve terminals, myelin disruption, and a reduced sensitivity to a heat stimulus in tails exposed to impact vibration [28]. In animal models, repetitive exposure results in damage to the myelin sheath around axons [29], reductions in axoplasmic transport [30], a reduced ability of nerves to regenerate after dissection [31], and a permanent reduction in nerve conduction velocity [32]. Similar morphological and functional changes in humans [14] are most likely responsible for the long-term changes in sensorineural function seen in workers exposed to segmental vibration [33–35].

Fewer studies have examined the effects of segmental vibration on skeletal muscle. Single exposures to vibration do not appear to have any effects on skeletal muscle morphology [36]. However, repeated exposure to vibration results in muscle fiber degeneration and regeneration, the presence of central nuclei [36,37] and increases in the cross-sectional areas of slow twitch muscle fibers [38]. Skeletal muscle atrophy also occurs and is accompanied by limb weakness leading to walking difficulty in rats [39]. If similar changes in skeletal muscle and peripheral nerves occur in humans, it is reasonable to assume that they could lead to longer-term changes in motor function and muscle weakness.

Vibration-induced injuries appear to be associated with the amount of tissue stress and strain experienced during exposure to vibration [40]. A research team at the National Institute for Occupational Safety and Health (Morgantown, USA) recently characterized the physical (i.e., biodynamic) response of the rat tail to vibration. This was done by securing the tail to a vibrating platform, exposing the tail to different vibration frequencies, and comparing the displacement of the tail with the displacement of the platform at the various exposure frequencies [41]. The ratio of the tail displacement to the platform displacement, which is referred to as vibration transmissibility, is one measure that can be used to describe the biodynamic response. In an additional study, the frequency-dependent biodynamic response of the tail was correlated with changes in vascular physiology [15]. The results of these studies demonstrated that indices of vascular remodeling and function occurred more rapidly at vibration frequencies that generated the greatest biodynamic response [15]. The results of modeling studies investigating vibration power absorption in the tail suggest this is because tissue stress and strain is greatest at the frequencies that generate the greatest response [41]. These findings are consistent with the results of human studies on the hand-arm system [40], and suggest that characterizing the biodynamic response of a body segment to vibration may be critical for determining the risk of developing a vibration-induced injury.

3. Clinical evidence for vibration white foot/vibration white toes

Vibration white finger (VWF), the vascular component of hand-arm vibration syndrome (HAVS), is a well documented occupational form of secondary Raynaud’s phenomenon first reported by Loriga in 1911 [42]. More recently, a condition descriptively termed “vibration white foot” (VWFt) or “vibration-induced white toes” (VWT) has been recognized. VWT is analogous to vascular HAVS but manifests as Raynaud’s phenomenon in the toes arising after sufficient exposure to foot-transmitted vibration. To date, the published literature addressing cases of VWT in workers without hand-arm vibration syndrome is limited to two case reports [43,44], though a greater number of studies have reported VWT in workers with HAVS after mixed exposure to both hand and foot-transmitted vibration [45–47]. That Raynaud’s phenomenon in the toes could occur in workers with direct foot-transmitted vibration is supported from a pathophysiological standpoint, given that both systemic and *local* mechanisms have been implicated in the hand-arm vibration syndrome [48].

In 1994, Tingsgard et al. [43] reported a case of a 46-year-old mink farmer presenting with cold-induced blanching in the toes of the left foot. The farmer had a twelve-year history of vibration exposure to his left foot from resting the foot on a vibrating pedal while driving a small wagon. In addition to the unilateral Raynaud’s phenomenon observed in the toes, further work-up additionally showed a subtle neuropathy in the affected foot. Other causes were excluded, and the worker was diagnosed with VWT. A second case of VWT has more recently been reported. Thompson et al. described the case of an underground miner with 18 years of experience who presented with isolated symptoms of blanching and pain in the toes after at least four years of FTV exposure from the operation of vehicle-mounted underground bolting machines [44]. Neurological and musculoskeletal examinations of both the upper and lower extremities were normal. Vascular flow in the digits was measured using photocell plethysmography. This technique involves placement of photocell devices around the digits, which detect systolic and diastolic volumetric changes in the blood vessels. Low or absent systolic variations in pulse waveforms post cold stress demonstrates decreased blood flow secondary to vasospasm. Using a standardized protocol, digital photocell plethysmography of the hands and feet of the worker after a 2-minute 10°C cold immersion bath was conducted to determine if the worker had evidence of vascular impairment in the feet and/or hands. Results from the cold provocation digital photocell plethysmography showed significant cold induced vasospasm in the toes with normal findings in the fingers. After excluding other potential causes for vascular abnormalities in the feet, the worker's condition was attributed to past segmental vibration exposure to the feet [44].

Reports have also documented vasospastic disease in the feet of workers exposed to both hand and foot-transmitted vibration, though interpretation of the aetiology of the foot symptoms in these workers is complicated by concurrent vascular HAVS [45–47]. This is due to the fact that workers with documented vascular HAVS in the hands often present with concurrent vasospasm in the toes, even in the absence of FTV exposure [49,50]. In these cases, the underlying mechanism seems to primarily be a centrally mediated increase in sympathetic tone [51], though it is possible that other systemic effects including altered circulating vasoactive mediators such as endothelin may also contribute [52]. Interestingly, there is some evidence that workers with mixed hand and foot-transmitted vibration exposure show more severe foot symptoms than workers with hand vibration exposure alone [46]. Hedlund et al. studied 27 miners exposed to hand-transmitted vibration, with a subset of these workers also having concurrent exposure to FTV secondary to drilling on raised platforms with a dominant frequency of 40 Hz [46]. Six of the 27 miners experienced white toes and all six with white toes were in the FTV group. This study demonstrated a statistically significant association between Raynaud's phenomenon in the toes and a history of FTV [46]. The two published case-reports of VWT [45,47] also support this association, with both reports describing workers with a history of mixed hand and foot vibration exposure having prominent foot symptoms.

4. Literature review summary

Research from animal, clinical and field studies indicate exposure to segmental vibration can cause damage to peripheral nerves and blood vessels. Furthermore, results from animal model studies suggest the negative health effects are frequency dependent and associated with tissue stress and strain experienced when exposed to vibration. Results from field and clinical studies suggest exposure to FTV can result in vibration white feet/toes which is analogous to hand-arm vibration syndrome. To date there have been only two published case reports of VWT independent of a diagnosis of HAVS. Furthermore, workers who are exposed to both HAV and FTV appear to have more severe foot symptoms. However, further research is required to understand the link between occupational exposure to FTV and the development of VWT and/or VWFt. In particular, more research is required to determine the magnitude, frequency, and duration of FTV exposure associated with a clinical diagnosis of VWFt.

5. Field study of FTV exposure and reported symptoms

5.1. Objectives

Many job tasks and responsibilities within the mining industry expose workers to FTV. Limited research has investigated and documented the exposure of FTV and the associated potential health effects. The objectives of this case study are to document the characteristics of FTV associated with the operation of underground mining equipment and to determine the risk of developing VWT.

5.2. Methods

The methods in this study were approved by the Laurentian University Research Ethics Board (Sudbury, Ontario, Canada) and all participating workers provided informed consent prior to data collection.

5.2.1. Participants and equipment—Twenty-seven workers with a mean age of 46 ± 13 years, height of 175 ± 6 cm, mass of 88 ± 16 kg, and experience of 22 ± 13 years participated in this study. Data were collected over the course of one year at six underground mine sites (hard-rock nickel or gold mines) in northern Ontario; however, working conditions underground were not altered by changes in weather above ground. Each worker only operated one piece of equipment resulting in 27 individual measures of FTV from five types of equipment including; locomotives ($n = 3$), bolting platforms ($n = 10$), jumbo drills ($n = 7$), raise drilling platforms ($n = 4$), and crushers ($n = 3$). A locomotive is a small train used to move ore in an underground mine. Workers are exposed to FTV when they stand to drive the locomotive. Workers use specialized drills and bolting booms that are attached to platforms that they stand on in order to install bolts used to stabilize mine openings. Vibration from the hydraulic bolter is transmitted to the floor of the platform, which exposes the worker to FTV. Jumbo drills have one or two boom arms that are used to drill holes into a rock face. The worker stands away from the boom to operate hand controls that are used to control the drill boom. Jumbo drill operators are exposed to HAV through the hand controls and to FTV through the floor. Raise platforms are used to lift workers off the ground to drill rock typically with a jackleg drill. One or two workers simultaneously operate a drill (or drills) while standing on the raise platform. The drill leg is attached to the platform transmitting the vibration generated by the drill to the platform, exposing the worker to FTV. Raise drill workers are also exposed to HAV from contact with the drill controls. Crusher operators are exposed to FTV when they monitor conveyor belts transporting rock/ore to crusher jaws and they can also be exposed to some HTV when operating controls used to break-up larger rock/ore pieces before entering the crusher jaws. Although it was not possible to control for daily exposure to FTV, most participants worked an 8-hour shift underground (note: one participating minesite had a 10 hour shift schedule) with an average estimated daily exposure to FTV of 5.72 (± 0.66) hours.

5.2.2. Data collection—Prior to all vibration measurements each participating worker was asked to verbally report if they had any history of pain, ache or discomfort in their hands or feet in the last 6-months of work. Workers were shown a body map to clearly illustrate the region of the body represented as “feet” and “hands” and asked to report their pain/ache/discomfort on a 4-point scale with 1 equivalent to a *mild* ache/pain/discomfort and 4 equal to a *very, very severe* ache/pain/discomfort. For the purpose of this paper, individual discomfort severity scores are not reported. Alternatively, for each vehicle type evaluated, the percentage of workers who reported the presence of an ache/pain or discomfort (anywhere between a severity level of 1–4) in the hands and/or feet is presented (Table 1).

A 10g series two tri-axial accelerometer (NexGen Ergonomics, Montreal QC) was secured to the vibrating surface the worker stood on, allowing the worker to perform his regular duties. Vibration was measured in the x (fore-aft), y (lateral), and z (vertical) direction, at a sampling frequency of 500 Hz in accordance with ISO 2631-1 guidelines [53]. One of two methods was used to secure the accelerometer to the surface the worker stood on. If the surface was solid metal the accelerometer was secured to a magnet, which was subsequently placed on the metal surface where the worker stood to perform his duties the majority of the time. If a magnet could not be used, the accelerometer was placed in a rubber pad (i.e. designed according to ISO 2631-1 specifications) and securely attached to the equipment of interest using tie wraps, or heavy-duty tape. The accelerometer was monitored throughout the testing period to ensure it remaining firmly in contact with the vibrating surface.

Measurement duration was dependent on the type of equipment being tested and ranged from 30 minutes (raise platforms) to just over 80 minutes (locomotives). In all cases a minimum of three cycles were collected resulting in loaded and unloaded travel for locomotives; several drill and bolt holes for the bolters, several drill holes for the jumbo drill and several drill holes at different angles for the raise. Crusher measures included different sizes of rock/ore at different crusher speeds in order to gain a representative sample.

5.2.3. Data analysis—Data were stored on a P3X8-2C DataLOG II datalogger (Biometrics, Gwent, UK) and processed with VATS 3.4.3 (NexGen Ergonomics, Montreal, Qc). Frequency weighted root-mean-square accelerations (a_{wx}; a_{wy}; a_{wz}) were calculated using the appropriate weighting factors (x-axis = Wd; y-axis = Wd; z-axis = Wk) as described in ISO 2631-1 [53]. The mean a_{wx}, a_{wy}, a_{wz} values were subsequently calculated and are reported along with the dominant frequency (DF). The probability of adverse health effects were determined based on the eight-hour ISO 2631-1 Health Guidance Caution Zone guidelines where frequency-weighted r.m.s. acceleration below 0.45 m/s^2 is associated with a low probability of adverse health effects and exposure above 0.9 m/s^2 is associated with a high probability of adverse health effects [53].

5.3. Findings

5.3.1. Vibration measurements—Frequency-weighted root-mean-square acceleration values and dominant frequency measured at the feet are reported in Table 1. The weighted root-mean-square acceleration was greatest in the z-axis for all equipment tested; meaning workers were exposed to higher levels of vertical vibration than lateral or fore-aft vibration. FTV magnitude was greatest when drilling off the raise platforms ($a_{wz} = 0.84$ m/s^2) and the lowest when operating the crusher ($a_{wz} = 0.22$ m/s^2). The dominant frequency in the vertical axis (z-axis) ranged from a low of 4.2 Hz (driving the locomotive) to a high of 40 Hz (drilling off the raise platform).

According to the ISO 2631-1 eight-hour health guidance caution zone, none of the workers were exposed to vibration levels above the zone of caution. Furthermore, only the raise workers were exposed to vibration placing them in the zone of caution, suggesting an increased probability of adverse health effects.

5.3.2. Pain, ache, discomfort reports—Reports of pain/ache/discomfort in the hands and feet were the lowest amongst workers operating the crusher and highest amongst workers drilling off the raise platforms (Table 1). For example, 100% of the raise workers (*n* = 4) reported pain/ache/discomfort in the hands and 75% (*n* = 3) reported pain/ache/

discomfort in the feet. Whilst, none of the crusher operators reported a pain/ache/discomfort with the hands and only 33% (*n* = 3) reported a pain/ache/discomfort at the feet (within the last 6-months). Recall, vibration exposure magnitude was lowest for the crusher operators and highest for the raise workers, suggesting a correlation between vibration magnitude and discomfort reports.

5.4. Relevance and discussion

The primary objective of this case study was to document the characteristics of FTV exposure with a secondary objective to determine prevalence of pain/ache/discomfort in the feet of workers exposed to FTV. Reports of pain/ache/discomfort (within the last 6-months), at the hands (100%) and feet (75%), were the greatest amongst raise workers. Moreover, the raise workers were exposed to the greatest magnitude of FTV in the vertical direction at a 40 Hz dominant frequency. Although not specifically asked, two of the three raise workers with pain/ache/discomfort in the feet volunteered that they had also been recently diagnosed by their treating physicians to have VWFt and HAVS. Due to the cross-sectional nature of the exposure data we are not able to confirm that exposure to FTV on the raise platform was the primary cause of VWFt; however, it seems plausible given that the raise workers in this study were exposed to the highest levels of FTV and the dominant frequency was 40 Hz, which has been associated with segmental damage. For example, animal studies have shown the finger-hand-arm system is more susceptible to vibration at higher frequencies (40–100 Hz for the hand-arm system, and > 100 Hz for the fingers) [40], and in a field study of miners exposed to local and WBV, 6 of the 27 miners exposed to FTV with a dominant frequency of 40 Hz, were diagnosed with vibration white toes [46].

Reports of pain/ache/discomfort in the feet (*n* = 4) were second highest (57%) amongst Jumbo Drill operators (Table 1). These workers were exposed to a dominant frequency just below 30 Hz. One of the Jumbo Drill operators also reported that he had been diagnosed with VWFt, and four indicated they had a diagnosis of HAVS from their treating physicians.

Locomotive operators reported the fewest problems with the feet. This study found the locomotive operators were exposed to FTV with a dominant frequency of 4.2 Hz. This frequency is associated with resonance in the spine and pelvis [54], suggesting that locomotive operators are likely at a greater risk of experiencing low back problems following prolonged vibration exposure. The FTV exposure generated while operating a locomotive is a result of the locomotive moving along a track, rather than vibration transmitted from a hydraulic drill or bolter attached to a platform. Thus, the dominant frequency for the underground locomotive is more in-line with surface locomotive vehicles [55], and other equipment that is driven such as load-haul dump vehicles [56], and harvesters [57]. This is in contrast to the dominant FTV observed for raise workers, which is in line with the dominant frequency associated with the operation of jackleg and stopper drills [58].

The findings of this study are in keeping with those of animal studies, and suggest that the frequency of vibration exposure should be taken into consideration when determining possible health effects [15,21]. This is particularly important since the suggested standard to evaluate health risks associated with exposure to vibration when sitting, standing, or lying down, ISO 2631-1, incorporates frequency weighting curves that give less importance to vibration levels that occur in frequency ranges above 20 Hz [53]. Alternatively, the standard used to determine health risks associated with exposure to segmental HAV, ISO 5349-1, which places greater weight on frequencies above 20 Hz [59], might be better suited to evaluate exposure to FTV (when the health effect of interest is VWT).

Additional research is required to understand the biodynamic response of the foot to FTV. Animal model studies have shown tissue stress and strain levels are highest at resonance [41], resulting in greater injury. Determining the resonant frequency of the foot is important for prevention because equipment and tools (i.e. anti-vibration drills; isolated platforms) and personal protective equipment (i.e. anti-vibration insoles, boots or mats) could be designed with the focus being to reduce vibration at frequencies where tissue resonance in the foot/toes occurs. Determining the resonant frequencies of the foot and toes could also inform future ISO standards, particularly with respect to the development of appropriate weighting curves that are based on resonance frequencies for the toes, foot, and lower leg. Improved standards would offer more informed guidance with respect to FTV exposure magnitude, and frequency that should be limited in order to prevent health risks associated with exposure to FTV.

Additional studies are also required to determine the influence of other risk factors such as cold exposure, when combined with FTV, on the development of vascular hypertrophy leading to VWFt. For example, epidemiological data suggests workers in cold climates have a higher prevalence of HAVS [11]; however, additional studies are required to determine if vibration exposure when combined with cold increases the risk of developing VWFt. In the meantime, workers exposed to FTV should dress appropriately to keep their feet warm and dry.

6. Conclusion

Animal models have demonstrated vibration-induced alterations in peripheral vascular and nerve physiology, which have given clinicians a better understanding of the changes that occur in the human physiological system when it is exposed to vibration. Clinical and epidemiological studies support the contention that workers with significant segmental vibration exposure to the upper and/or lower extremities can develop cold-induced vasospasm in the toes. In general, in workers exposed to HAV, symptoms of cold-induced finger vasospasm usually seem to be most severe in the directly exposed hands as a result of local vibration-induced trauma, while the non-exposed feet tend to have less severe symptoms best attributed to centrally mediated mechanisms (increased sympathetic tone and altered circulating vasospastic mediators). In workers with direct vibration exposure to the feet, risk of developing VWT is increased. Both the magnitude and, perhaps more importantly, the dominant frequency of the FTV seems to be an important determinant of risk, with research to date suggesting higher frequencies (40 Hz) to carry greater risk with respect to VWFt or VWT compared to lower frequency distributions. Further, study is required to delineate the magnitude of the problem and to better characterize and control foot-transmitted vibration as an occupational hazard.

Acknowledgments

Funding for the field study was provided by the Centre for Research Expertise in the Prevention of Musculoskeletal Disorders and the Workplace Safety and Insurance Board of Ontario.

References

1. Bovenzi M. Low-back pain disorders and exposure to whole-body vibration in the workplace. Semin Perinatol. 1996; 20(1):38. [PubMed: 8899913]
2. Wasserman D, Wilder D, Pope M, Magnusson M, Aleksiev A, Wasserman J. Whole-body vibration exposure and occupational work-hardening. J Occup Environ Med. 1997; 39:403. [PubMed: 9172084]
3. Palmer K, Griffin M, Bendall H, Pannett B, Coggon D. Prevalence and pattern of occupational exposure to whole-body vibration in Great Britain: findings from a national survey. Occup Environ Med. 2000; 57:229. [PubMed: 10810108]
4. Bovenzi M. Health effects of mechanical vibration. G Ital Med Lav Erg. 2005; 27(1):58.
5. Griffin, MJ. Handbook of human vibration. London: Academic Press; 1990.
6. Seidel H, Hiede R. Long-term effects of whole-body vibration: A critical survey of the literature. Int Arch Occup Environ Health. 1986; 58:1. [PubMed: 3522434]
7. Pope M, Hansson T. Vibration of the spine and low-back pain. Curr Orthopaed Prac. 1992:49.
8. Lings S, Leboeuf-Yde C. Whole-body vibration and low back pain: A systematic, critical review of the epidemiological literature 1992–1999. Int Arch Occup Environ Health. 2000; 73:290. [PubMed: 10963411]
9. Griffin MJ, Bovenzi M. The diagnosis of disorders caused by hand-transmitted vibration: Southampton Workshop 2000. Int Arch Occup Environ Health. 2002; 75:1. [PubMed: 11898868]
10. Bovenzi M, Betta A. Low-back disorders in agricultural tractor drivers exposed to whole-body vibration and postural stress. Appl Ergon. 1994; 25(4):231. [PubMed: 15676973]
11. Seidel H. (2005) On the relationship between whole-body vibration exposure and spinal health risk. Ind Health. 2005; 43:361. [PubMed: 16100914]
12. Gemne G, Pyykko I, Taylor W, et al. The Stockholm workshop scale for the classification of cold-induced Raynaud’s phenomenon in the hand arm vibration syndrome: Revision of the Taylor-Pelmear scale. Scand J Work Environ Health. 1987; 13:275. [PubMed: 3433028]
13. Takeuchi T, Futatsuka M, Imanishi H, Yamada S. Pathological changes observed in the finger biopsy of patients with vibration-induced white finger. Scand J Work Environ Health. 1986; 12:280. [PubMed: 3775312]
14. Takeuchi T, Takeya M, Imanishi H. Ultrastructural changes in peripheral nerves of the fingers of three vibration-exposed persons with Raynaud’s phenomenon. Scand J Work Environ Health. 1988; 14:31. [PubMed: 3353694]
15. Krajnak K, Miller GR, Waugh S, Johnson C, Li S, Kashon ML. Characterization of frequency-dependent response of the vascular system to reptitive vibration. J Occup Environ Med. 2010; 52:584. [PubMed: 20523237]
16. Inaba R, Furuno T, Okada A. Effects of low- and high-frequency local vibration on the occurrence of intimal thickening of the peripheral arteries of rats. Scand J Work Environ Health. 1988; 14:312. [PubMed: 3201191]
17. Okada A, Inaba R, Furuno T. Occurrence of intimal thickening of the peripheral arteries in response to local vibration. British Journal of Industrial Medicine. 1987; 44:470. [PubMed: 3620370]
18. Govindaraju SR, Curry BD, Bain JLW, Riley DA. Nerve damage occurs at a wide range of vibration frequencies. Ind Ergonomics. 2008; 38:687.
19. Bovenzi M, Lindsell CJ, Griffin MJ. Acute vascular responses to the frequency of vibration transmitted to the hand. Occupational and Environmental Medicine. 2000; 57:422. [PubMed: 10810133]

20. Krajnak K, Waugh S, Johnson C, Miller R, Kiedrowski M. Vibration disrupts vascular function in a model of metabolic syndrome. Ind Health. 2009; 47:533. [PubMed: 19834263]
21. Okada A. Physiological response of the rat to different vibration frequencies. Scandinavian Journal of Work, Environment and Health. 1986; 12:362.
22. Curry BD, Govindaraju SR, Bain JL, Zhang LL, Yan JG, Matloub HS, Riley DA. Evidence for frequency-dependent arterial damage in vibrated rat tails. Anat Rec A Discov Mol Cell Evol Biol. 2005; 284:511. [PubMed: 15791580]
23. Krajnak K, Dong RG, Flavahan S, Welcome DE, Flavahan NA. Acute vibration increases a_{2c}-adrenergic smooth muscle constriction and alters thermosensitivity of cutaneous arteries. Journal of Applied Physiology. 2006; 100:1230. [PubMed: 16339346]
24. Hughes JM, Wirth O, Krajnak K, Miller R, Flavahan S, Berkowitz DE, Welcome D, Flavahan NA. Increased oxidant activity mediates vascular dysfunction in vibration injury. J Pharmacol Exp Ther. 2009; 328:223. [PubMed: 18955588]
25. Krajnak, K.; Waugh, S.; Johnson, C.; Miller, R.; Li, S.; Kashon, ML. Characterization of frequency-dependent responses of sensory nerve function to repetitive vibration. 12th International Conference on Hand-arm Vibration; Ottawa, Canada. 2011.
26. Lundborg G, Dahlin LB, Danielsen N, Hansson HA, Necking LE, Pyykko I. Intraneural edema following exposure to vibration. Scand J Work Environ Health. 1987; 13:326. [PubMed: 3433033]
27. Krajnak K, Waugh S, Wirth O, Kashon ML. Acute vibration reduces Aβ nerve fiber sensitivity and alters gene expression in the ventral tail nerves of rats. Muscle and Nerve. 2007; 36:197. [PubMed: 17541999]
28. Govinda Raju S, Rogness O, Persson M, Bain J, Riley D. Vibration from a riveting hammer causes severe nerve damage in the rat tail model. Muscle and Nerve. 2011; 44(5):795. [PubMed: 22006694]
29. Matloub HS, Yan JG, Kolachalam RB, Zhang LL, Sanger JR, Riley DA. Neuropathological changes in vibration injury: an experimental study. Microsurgery. 2005; 25:71. [PubMed: 15645420]
30. Yan JG, Matloub HS, Sanger JR, Zhang LL, Riley DA. Vibration-induced disruption of retrograde axoplasmic transport in peripheral nerve. Muscle Nerve. 2005; 32:521. [PubMed: 15977204]
31. Stromberg T, Lundborg G, Holmquist B, Dahlin LB. Impaired regeneration in rat sciatic nerves exposed to short-term vibration. J Hand Surg – Brit Eur. 1996; 21:746.
32. Loffredo MA, Yan J-G, Kao D, Zhang LL, Matloub HS, Riley DA. Persistent reduction of conduction velocity and myelinated axon damage in vibrated rat-tail nerves. Muscle and Nerve. 2009; 39(6):770. [PubMed: 19306323]
33. Bovenzi M, Giannini F, Rossi S. Vibration-induced multifocal neuropathy in forestry workers: electrophysiological findings in relation to vibration exposure and finger circulation. Int Arch Occup Environ Health. 2000; 73:519. [PubMed: 11100946]
34. Lundborg G, Dahlin LB, Lundstrom R, Necking LE, Stromberg T. Vibrotactile function of the hand in compression and vibration-induced neuropathy. Sensibility index – a new measure. Scand J Plast Reconstr Surg Hand Surg. 1992; 26:275. [PubMed: 1335164]
35. Stromberg T, Dahlin L, Lundborg G. Structural nerve chnages at wrist level in workers exposed to vibration. Occupational and Environmental Medicine. 1997; 54:307. [PubMed: 9196451]
36. Necking LE, Dahlin LB, Friden J, Lundborg G, Lundstrom R, Thornell LE. Vibration-induced muscle injury. An experimental model and preliminary findings. J Hand Surg [Br]. 1992; 17:270.
37. Necking LE, Lundstrom R, Dahlin LB, Lundborg G, Thornell LE, Friden J. Tissue displacement is a causative factor in vibration-induced muscle injury. J Hand Surg [Br]. 1996; 21:753.
38. Necking LE, Lundstrom R, Lundborg G, Thornell LE, Friden J. Skeletal muscle changes after short term vibration. Scand J Plast Reconstr Surg Hand Surg. 1996; 30:99. [PubMed: 8815978]
39. Yan JG, Matloub HS, Sanger JR, Zhang LL, Riley DA. Vibration-induced disruption of retrograde axoplasmic transport in peripheral nerve. Muscle Nerve. 2005; 32:521. [PubMed: 15977204]
40. Dong RG, Welcome DE, McDowell TW, Wu JZ. Biodynamic response of human fingers in a power grip subjected to a random vibration. J Biomech Eng. 2004; 126:447. [PubMed: 15543862]
41. Welcome DE, Krajnak K, Kashon ML, Dong RG. An investigation on the biodyamic foundation of a rat tail model. Journal of Engineering in Medicine (Proc Instn Mech Engrs, Part H). 222:1127.

42. Loriga G. Il lavoro con i martelli pneumatici. Bolletino dell' Ispettorato del Lavoro. 1911; 2:35.
43. Tingsgard I, Rasmussen K. Vibration-induced white toes. Ugeskr Laeger. 1994; 156:4836. [PubMed: 7992421]
44. Thompson A, House R, Krajnak K, Eger T. Vibration white foot: A case report. Occup Med (Lond). 2010; 60:572. [PubMed: 20682742]
45. Hashiguchi T, Sakakibara H, Furuta M, Yamada S. Raynaud's phenomenon in the lower extremities induced by vibration exposure: report of 3 cases. Jpn J Trauma Occup Med. 1988; 36:651.
46. Hedlund U. Raynaud's Phenomenon of fingers and toes of miners exposed to local and whole-body vibration and cold. Int Arch Occup Environ Health. 1989; 61:457. [PubMed: 2777390]
47. Choy N, Sim CS, Yoon JK, Kim SH, Park HO, Lee JH, Yoo CI. A case of Raynaud's Phenomenon of both feet in a rock drill operator with hand-arm vibration syndrome. Korean J Occup Environ Med. 2008; 20:119.
48. Noel B. Pathophysiology and classification of the vibration white finger. Int Arch Occup Environ Health. 2000; 73:150. [PubMed: 10787129]
49. Schweigert M. The relationship between hand-arm vibration and lower extremity clinical manifestations: A review of the literature. Int Arch Occup Environ Health. 2002; 75:179. [PubMed: 11954985]
50. House R, Jiang D, Thompson A, Eger T, Krajnak K, Sauve J, Schweigert M. Vasospasm in the feet in workers assessed for HAVS. Occup Med (Lond). 2011; 61:115. [PubMed: 21196472]
51. Olsen N, Petring OU. Vibration elicited vasoconstrictor reflex in Raynaud's phenomena. Br J Ind Med. 1988; 45:415. [PubMed: 3395576]
52. Bovenzi M, D'Agostin F, Rui F, Ambrosi L, Zefferino R. Salivary endothelin and vascular disorders in vibration-exposed workers. Scand J Work Environ Health. 2008; 34:133. [PubMed: 18493696]
53. International Organization for Standardization. ISO 2631-1 Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part 1: General Requirements. Geneva, Switzerland: 1997. Reference number ISO 2631-1: 1997(E)
54. Mansfield N, Griffin M. Non-linearities in apparent mass and transmissibility during exposure to whole-body vertical vibration. J Biomech. 2000; 33:933. [PubMed: 10828323]
55. Johanning E. Vibration and shock exposure of maintenance-of-way vehicles in the railroad industry. Appl Ergon. 2011; 42(4):555. [PubMed: 20870218]
56. Eger T, Stevenson J, Boileau PÉ, Salmoni A, Vib RG. Predictions of health risks associated with the operation of load-haul-dump mining vehicles: Part 1- Analysis of whole-body-vibration exposure using ISO 2631-1 and ISO-2631-5 standards. Int J of Ind Ergonom. 2008; 38:726.
57. Sherwin LM, Owende PM, Kanali CL, Lyons J, Ward SM. Influence of tyre inflation pressure on whole-body vibrations transmitted to the operator in a cut-to-length timber harvester. Appl Ergon. 2004; 35:253. [PubMed: 15145288]
58. Oddo R, Layau T, Boileau PE, Champoux Y. Design of a suspended handle to attenuate rockdrill hand-arm vibration: model development and validation. J Sound Vib. 2004; 275:623.
59. International Organization for Standardization. Exposure to Hand-transmitted Vibration e Part 1: General Requirements. Geneva, Switzerland: 2001. ISO-5349 Mechanical Vibration e Measurement and Evaluation of Human.

Table 1

Summary of field-testing to document FTV in underground mining and reported symptoms of pain/ache/discomfort in the hands and feet. Mean frequency weighted RMS acceleration and standard deviations are reported along with the percentage of operators who reported pain/ache/discomfort in the hands or feet

Equipment type	Dominant frequency Z-axis Hz	Frequency weighted RMS acceleration			Reported pain/Ache/Discomfort	
		a_{wx} m/s^2	a_{wy} m/s^2	a_{wz} m/s^2	Hands %	Feet/Toes %
Locomotive (*n* = 3)	4.2 (1.8)	0.18 (0.02)	0.23 (0.03)	0.4 (0.04)	33	33
Bolter Drill (*n* = 10)	5.7 (2.5)	0.11 (0.07)	0.12 (0.08)	0.29 (0.34)	20	40
Jumbo Drill (*n* = 7)	28.2 (16.4)	0.23 (0.20)	0.20 (0.25)	0.32 (0.15)	29	57
Raise Platform (*n* = 4)	40 (0)	0.14 (0.09)	0.12 (0.08)	0.84 (0.36)	100	75
Crusher (*n* = 3)	10.1 (5.2)	0.08 (0.09)	0.12 (0.15)	0.22 (0.18)	0	33