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Effect of the Shoe Sole on the Vibration Transmitted from the Supporting Surface to the Feet

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Abstract: Vibration transmitted through the foot can lead to vibration white feet, resulting in blanching of the toes and the disruption of blood circulation. Controlled studies identifying industrial boot characteristics effective at attenuating vibration exposure are lacking. This work focused on the evaluation of vibration transmissibility of boot midsole materials and insoles across the range 10–200 Hz at different foot locations. Questionnaires were used to evaluate the comfort of each material. The materials were less effective at attenuating vibration transmitted to the toe region of the foot than the heel. Between 10 and 20 Hz, all midsole materials reduced the average vibration transmitted to the foot. The average transmissibility at the toes above 100 Hz was larger than 1, evidencing that none of the tested material protects the worker from vibration-related risks. There was a poor correlation between the vibration transmissibility and the subjective evaluation of comfort. Future research is needed to identify materials effective for protecting both the toe and the heel regions of the foot. Specific standards for shoe testing are required as well.

Keywords: foot-transmitted vibration; whole-body vibration; vibration-white foot; standing; personal protective equipment

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1. Introduction

1.1. Occupational Exposure to Foot Transmitted Vibration

A worker can be exposed to foot-transmitted vibration (FTV) through foot controls when operating mobile equipment or from a vibrating surface they stand on to operate equipment/tools. The percentage of workers exposed to FTV has not been teased out from whole-body vibration exposure rates typically published in epidemiological studies. Therefore, the percentage of workers annually exposed to FTV remains unknown, although up to 7% of European and North American workers are exposed to whole-body vibration [1]. Two studies [2,3] reported FTV exposure in mining operations, while information about other industrial sectors remains missing.

1.2. Health Effects

The first English language case study of a worker confirmed to have impaired blood circulation in the toes without a similar impairment in the fingers was published in 2010 [4]. The worker had an 18-year history working as a miner underground with mixed exposure to vibration at the buttock, hands, and feet with an estimated four hours of daily exposure to FTV from a bolting platform, three days a week, in the four years prior to his diagnosis. The design of the bolter drill resulted in minimal daily exposure to hand-arm vibration but continuous exposure to vibration that travelled from the platform the worker stood on into his feet. Medical tests confirmed the presents of cold-induced vasospastic disease in the feet termed vibration-induced white foot [4]. In an earlier case [5], a mink farmer who had a 12-year history of exposure to FTV from the pedal of a tractor/wagon was found to have cold-induced blanching in his left foot. Data from field studies offer further evidence of impairment from exposure to FTV. In 1989, Hedlund collected vibration exposure data for 27 miners. All the miners had exposure to hand-arm vibration and a subgroup were also exposed to FTV when drilling off a raised platform [2]. All six drillers presented with white feet. Leduc also found raise drillers self-reported problems with their feet that they associated with daily exposure to FTV [3].

The symptoms of vibration-induced white feet (VIWFt) are analogous to the vascular component of hand-arm vibration syndrome (HAVS) and typically manifest as Raynaud's phenomenon in the toes with blanching in one or more toes observed with cold exposure [4]. Some workers have also presented with tingling and numbness in the toes and feet [3,6,7]. Studies on VIWFt are limited as the medical community previously believed symptoms observed in the feet were due to a systemic response to hand-arm vibration exposure and a diagnosis of HAVS [7]. Moreover, recent changes in technology, in some industries such as underground mining that have attempted to reduce worker exposure to HAV have inadvertently resulted in an increase in exposure to FTV [3,6], and the latency period between first exposure and onset of a medical diagnosis of VIWFt is unknown. Therefore, workers exposed to FTV should be aware of the symptoms of VIWFt (blanching of the toes; tingling and numbness in the feet) and seek medical attention early. Furthermore, the development of control strategies to mitigate exposure to FTV are required.

1.3. Foot Response to Vibration

The biomechanical response of the human foot standing in a natural position has been studied by Goggins et al. [8]. Authors studied the resonant frequencies for different anatomical locations on the human foot, while standing in a natural position using a laser Doppler vibrometer at 24 anatomical locations. The stimulus was a sine sweep in the 10–200 Hz range, mainly because the resonant frequencies of the toes were at 50 Hz or higher. The peak vertical velocity was 30 mm/s, in order to grant a constant SNR. The resonance frequencies of the toes varied between 99 and 147 Hz. The midfoot had resonances between 51 and 84 Hz while the ankle resonance varied between 16 and 39 Hz.

Goggins and colleagues [8,9] also studied the effects of posture (leaning forward, neutral or leaning backward) on the foot's biomechanical response. The experimental setup was similar to the one adopted in [8]. Results evidenced that the transmissibility varies when the center of pressure on the foot shifts towards the forefoot or the rearfoot.

Data collected in these experiments were used by Chadefaux et al. [10] to develop a 2D lumped parameter of the foot. The model parameters were determined by fitting the transmissibility and the apparent mass of subjects standing in a neutral position. The effects of modal parameters' variability was studied with Monte Carlo simulations. Results showed the validity of the proposed seven-DOF model.

The existing literature on the foot response to vibration evidences the presence of different shoe resonances in frequency regions completely neglected by the current standards. The resonance frequencies of the toes and of the midfoot are compatible with those causing discomfort on the foot of seated subjects [11].

1.4. Vibration Control Strategies

To mitigate injury risk associated with occupational exposure to vibration the hierarchy of controls should be followed with priority given to elimination, substitution, and engineering control strategies over administrative and personal protective equipment. An investigation of FTV exposure in underground mining [3] reported reduced FTV exposure associated with the operation of a bolter that had an area of the platform engineered with isolation mounts to reduce the transmission of vibration to the operator. The same study reported that workers who drilled off raised platforms with jackleg drills engineered with a retrofitted "anti-vibration" handle transmitted less vibration to the hands and the feet. Although these two examples illustrate positive outcomes associated with the implementation of engineering control strategies, the use of personal protective equipment also needs to be considered as elimination, substitution and engineering control strategies are not available or currently feasible in many situations where workers are exposed to FTV. Therefore, some companies have started to install "anti-vibration" mats on equipment platforms and workers have reported wearing "anti-vibration" insoles in their boots [3].

Currently, there are no international standards for the evaluation of "anti-vibration" personal protective equipment for the feet, unlike ISO 10819 [12] that specifies the characteristics that must be obtained for a glove to get an anti-vibration label. Therefore, companies looking to develop mats to place on equipment platforms or boot and shoes manufacturers aim at developing boots that reduce FTV exposure without clear criteria to meet. However, research has shown the effectiveness of anti-vibration glove varies depending on the glove characteristics. The efficiency of certified anti-vibration gloves in the reduction of vibration transmitted to the hand-arm system is often very high. For instance, in the case of an air-bladder, the vibration at the wrist was reduced of 86% [13]. Another study [14] compared the performance of an air-bladder glove with a gel-filled glove, finding the gel-filled glove to be more effective at attenuating hand-arm vibration at exposure frequencies between 80 and 400 Hz. Using a rat-tail model, Xu and colleagues [15] showed that an air-bladder and gel material adopted in anti-vibration gloves were effective at reducing peak accelerations with the gel material resulting in a significantly greater reduction. Another study [16] confirmed the importance of the glove material and of the interaction of the glove with the tool, of the vibration direction and of the location of evaluation on the fingers and hands. Using a transfer function method to estimate the tool-specific effectiveness of four vibration reduction gloves (gel; air bladder; air bubbles; neoprene), the authors found that glove performance was dependent on tool use and measurement location. For example, when used with tools that produced lower frequency vibration, all the gloves amplified the vibration transmitted to the distal region of the fingers but were found to dampen vibration in the proximal region of the fingers. When tool-specific interactions were considered, the neoprene gloves were found to offer a greater than 10% reduction in un-weighted vibration for the greatest number of tool/glove combinations compared to air bladder, air bubble, and gel gloves.

Based on the findings from anti-vibration glove research as a control strategy for hand–arm vibration exposure, there is reason to believe that midsole materials for industrial footwear and/or insoles could be effective at reducing the transmission of vibration from vibrating platforms to the feet of workers. Similar findings were also documented for sport shoes [17,18]. Therefore, the primary objective of this study was to evaluate vibration transmissibility to the foot when standing on four different midsoles and three different insole materials. The secondary objective is to determine if there is a correlation between subjective reports of discomfort and the transmissibility properties of the midsole/insole materials.

2. Materials and Methods

The methods followed in this study conformed to the ethical guidelines of Politecnico di Milano and Laurentian University's Research Ethics Board. The effect of shoe soles compliance was studied by analyzing the vibration transmissibility from the supporting surface to the upper part of the feet of 20 participants standing on 7 different materials. A questionnaire was also used to determine participant comfort after each test.

2.1. Occupational Exposure to Foot Transmitted Vibration

Tests were performed at the experimental facilities of Politecnico di Milano, Lecco, Italy [19–21]. The vertical vibration was generated by an electrodynamic shaker (LDS V830, maximum stroke ±25 mm) and was controlled in a closed loop by an LMS Test Lab system.

The participants stood on a steel plate directly fixed to the shaker head in order to obtain a rigid plate motion up to 200 Hz. Plate vibration was measured using a piezoelectric accelerometer (Bruel & Kjaer 4508 B) whose actual sensitivity was measured before the tests using a Bruel & Kjaer 4294 calibrator. The vibration of the upper part of the feet was measured using a single point laser Doppler vibrometer (Polytec OFV 500). The vibrometer was fixed over a tripod and its orientation was manually adjusted to observe 10 different points on the feet. Due to the subjects' legs, it was not possible to maintain a vertical laser position; the maximum tilt was limited (lower than 20°) and the bias error deriving from the tilt was compensated by dividing the transmissibility measured during the tests times the transmissibility measured by the tilted laser on the plate during an idle test. The validity of the correction procedure has been discussed in a recently published paper [8]. Vibration was measured only on the right foot, as the dynamic behavior of the two feet is generally compatible.

Tests were performed by imposing a constant vibration velocity (vertical vibration of 30 mm/s, with a sine sweep from 10–200 Hz, lasting 51 s), thus entailing an increasing vibration level in terms of acceleration. This choice was undertaken in order to obtain a constant signal to noise ratio of the measurement output, similarly to what has been done in previous studies performed in the same laboratory [8–10].

2.2. Materials

The different materials interposed between the feet and the vibrating plate are shown in Figure 1 along with a description of their characteristics. The different materials were labeled with letters from A to G: the first four were foams typically used for manufacturing shoe midsole (shore hardness from 20 to 60, density from 0.09 to 0.23 g/cm^3), while two of the insoles were commercially available and one was a proto-type (F). The material was interposed between both feet when the participants were standing on the vibrating platform.

Figure 1. Outsole materials and insoles that were used in the tests described in this paper. Upper row: outsole materials; lower row: insoles.

2.3. Partecipants

Twenty participants completed the experimental protocol. Prior to vibration transmissibility measurements, the height, mass, and foot length of each participant was recorded (175 ± 10 cm, 71 ± 14 kg, 25.4 ± 2.3 cm; mean ± SD).

2.4. Test Protocol

Vibration transmissibility was measured at 10 different positions (m) on the right foot (Table 1). Positions were selected among the ones used in existing literature studies [8,9]. The order of materials was randomized but the transmissibility measures always started with the participant standing in the barefoot condition. Participants were then required to stand on each of the testing materials assuming their natural upright posture. A plum line attached to their hip, with a mark on their foot, was used as a guide to help them maintain the same natural standing position for all test conditions. Laser vibrometer measurement positions can be seen in Figure 2.

Table 1. Naming convention and anatomical description for the 10 marker locations (m) where vibration transmissibility was measured.

Marker Name	Description of Placement
T1P1	Middle of the nail bed of the 1st toe
T1P3	Joint between the metatarsal and the phalange of the 1st toe
T3P1	Middle of the nail bed of the 3rd toe
T3P3	Between the 2nd and 3rd phalange joint of the 3rd toe
T5P3	Between the 2nd and the 3rd phalange joint of the 5th toe
M2	Middle of the foot on the medial side in line with the 2nd toe
L2	middle of the foot on the lateral side in line with the 4th toe
M4	The most protruding portion of the ankle medial malleolus
L4	The most protruding portion of the ankle lateral malleolus
H1	Head of the calcaneus at the insertion point of the Achilles Tendon

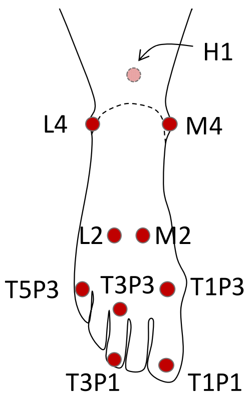

Figure 2. Position where the transmissibility was measured.

2.5. Comfort Questionnaire

After each test, participants were asked to report their discomfort (D) on a 0–9 scale. Decimals were allowed as in existing literature studies [22]. Each participant k reported for each foam F the discomfort $D_{F,k}$. The marks reported by each participant were normalized by subtracting the average discomfort reported by the participant $\overline{D_k}$ and dividing the difference by the standard deviation of data reported by the same participant $\sigma_{D,k}$.

$$\overline{D_k} = \frac{\sum_{F=A}^{G} D_{F,k}}{7} \tag{1}$$

$$\sigma_{D,k} = \sqrt{\frac{\sum_{F=A}^{G} (D_{F,k})^2}{7}} \tag{2}$$

The normalized discomfort $d_{F,k}$ for each participant k and for each foam F is therefore:

$$d_{F,k} = \frac{D_{F,k} - \overline{D_k}}{\sigma_{D,k}} \tag{3}$$

2.6. Data Analysis

Vibration transmissibility between the acceleration imposed on the vibrating plate and each of the 10 measurement locations on the right foot were measured for each midsole/insole material. The procedure for data analysis was similar to that used in the identification of the barefoot response [8]. All vibration data were processed using LabVIEW. The vibration time histories of the stimulus (acceleration, hereinafter x) and of the response (velocity measured by the vibrometer, hereinafter y) were split according to the Bartlett method [23] into 26 buffers of 4096 samples lasting 2 s without overlap. Complex spectra of x and y (S_x and S_y) were computed on each buffer (i) using the rectangular window; the derivative of the velocity was computed in frequency domain by multiplying the signal spectrum times the imaginary unit and angular velocity (j_ω). The auto-spectral averages $\overline{S_{xx}}(f)$ and $\overline{S_{yy}}(f)$ and the cross-spectral average $\overline{S_{xy}}(f)$ are:

$$\overline{S_{xx}}(f) = \frac{\sum_{i=1}^{26} S_{x,i}(f)\cdot S^*_{x,i}(f)}{26} \quad (4)$$

$$\overline{S_{yy}}(f) = \frac{\sum_{i=1}^{26} S_{y,i}(f)\cdot S^*_{y,i}(f)}{26} \quad (5)$$

$$\overline{S_{xy}}(f) = \frac{\sum_{i=1}^{26} S_{x,i}(f)\cdot S^*_{y,i}(f)\cdot j\omega}{26} \quad (6)$$

When k is the number of the participant and m the marker location, the FRF was evaluated across the frequency range (10–200 Hz) using the H_1 estimator:

$$H_{1k,m}(f) = \frac{\overline{S}_{xy,k,m}(f)}{\overline{S}_{xx,k,m}(f)} \quad (7)$$

FRF estimators are commonly used with random stimuli, but in presence of deterministic stimuli, the non-deterministic components from the FRF are removed [24]. The coherence $\gamma^2(f)$ was computed as:

$$\gamma^2_{k,m}(f) = \frac{\left|\overline{S}_{xy}(f)\right|^2}{\overline{S}_{xx}(f)\cdot\overline{S}_{yy}(f)} \quad (8)$$

Coherence is a value between 0 and 1 where a larger number indicates a greater correlation between the two signals being measured [23]. The coherence function drops below unity for a number of reasons, including system non linearities, noise on the input or output signals, leakage not reduced by windowing, or because there are non-measured inputs affecting the output [23,24]. Tests where the average coherence in the range 10–200 Hz dropped below 0.5 were redone, given that the low coherence was due to the poor signal to noise ratio when the laser spot was not inside the reflective adhesive target. At each position m and for each foam F, the average transmissibility $\overline{T}_m(f)$, phase $\overline{\varphi_m}(f)$, and coherence $\overline{\gamma^2}_m(f)$ are as:

$$\overline{T}_{m,F}(f) = \frac{\sum_{k-1}^{20}\left|H_{1k,m,F}(f)\right|}{20} \quad (9)$$

$$\overline{\varphi}_{m,F}(f) = \frac{\sum_{k-1}^{20} arg\left|H_{1k,m,F}(f)\right|}{20} \quad (10)$$

$$\overline{\gamma^2}_{m,F}(f) = \frac{\sum_{k-1}^{20}\gamma^2_{k,m,F}(f)}{20} \quad (11)$$

The effectiveness of the material F in reducing the vibration was quantified by the average transmissibility modulus at each specific position m, $\overline{T}_{m,F}(f)$, that was evaluated both in barefoot conditions $\overline{T}_{m,0}(f)$ and using the foam $\overline{T}_{m,F}(f)$. In order to better visualize the reduction/amplification obtained with the different materials, we analyzed the difference ΔT_m between the transmissibility obtained with a given material $\overline{T}_{m,F}(f)$ and the barefoot transmissibility $\overline{T}_{m,b}(f)$:

$$\Delta \overline{T}_{m,F}(f) = \frac{\overline{T}_{m,F}(f)}{\overline{T}_{m,0}(f)} \tag{12}$$

The quantity, different from what is suggested in the ISO 10819 standard [12] for anti-vibration gloves, has not been frequency-weighted. This was decided because, in the current literature, there is no evidence on the frequency weightings to be adopted for FTV, as discussed later.

The correlation between the reported discomfort and the vibration transmissibility was quantified by the correlation coefficient between the average discomfort reported by 20 users and the average vibration transmissibility. Examples of the test setup can be seen in Figure 3.

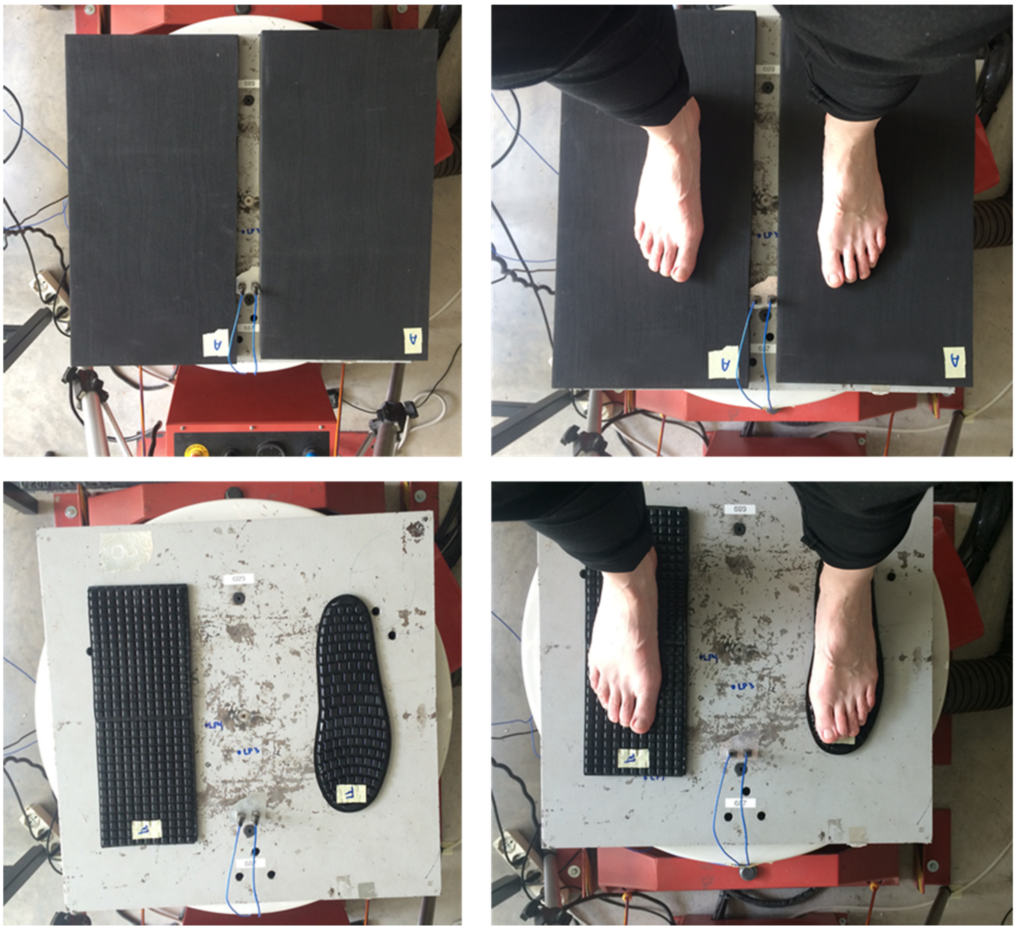

Figure 3. Example midsole material evaluated (**top left**) and participant standing on the shaker and midsole material (**top right**). An example of insole material evaluated (**bottom left**) and participant standing on the insole material (**bottom right**) is also shown.

3. Results

3.1. Vibration Transmissibility

The dependence between the midsole/insole material and the modulus of the vibration transmissibility is shown in Figure 4. Each curve shows $\overline{T}_{m,F}(f)$ at each of the m position indicated in Table 1. Plots show the average transmissibility. An extensive discussion on inter- and intra- subject variability in barefoot conditions on the vibration transmissibility and on the resonant frequencies is presented by Goggins and colleagues [8].

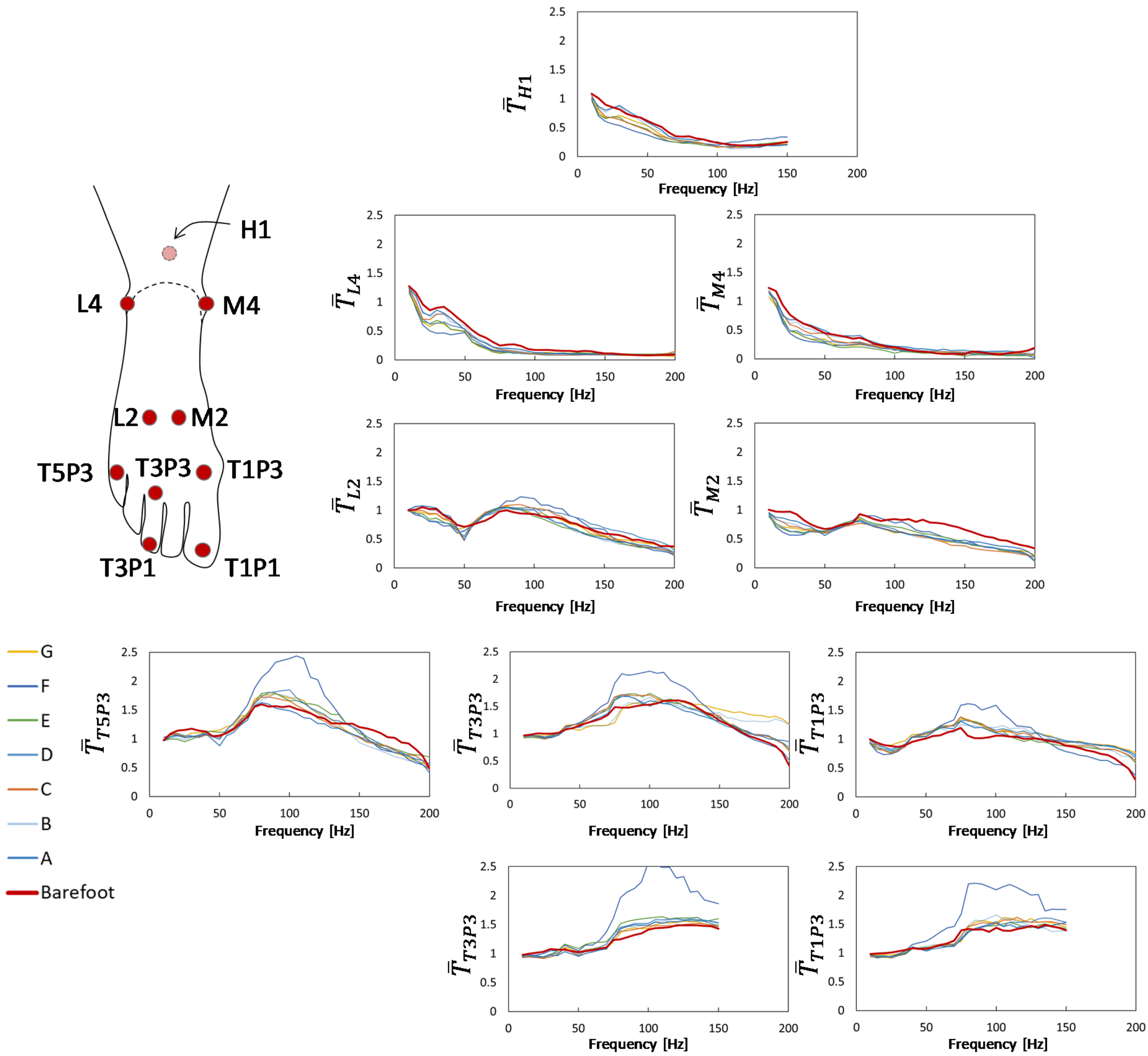

Figure 4. Average transmissibility $\overline{T}_{m,F}(f)$.

Given the poor coherence above 150 Hz at the heel (H1) and at the toes (T1P3 and T3P3), we decided not to report data in the following graphs.

The analysis of Figure 4 shows that the transmissibility at the toes $\overline{T}_{T1P3,F}(f)$ and $\overline{T}_{T3P3,F}(f)$, plotted in the lower part of the figure, are larger than that measured at the rear foot $\overline{T}_{H1,F}(f)$ (first row) independently from the material of the insole/midsole. The average transmissibility at positions T1P1, T1P3, T3P1, T3P3, and T5P3 (rows 4 and 5) is greater than 1 for frequencies smaller than 100 Hz. The transmissibility peaks are due to resonances of the toes, which occur at frequencies between 70 and 120 Hz. The average resonance amplification depends on the insole material, but the average values vary between 1.5 (toes 1 and 3) and 1.8 (toe 5). $\overline{T}_{L2,F}(f)$ and $\overline{T}_{M2,F}(f)$ have two peaks: the first one at frequencies lower than 10 Hz (not always visible in the plots) and the second at approximately 80 Hz with an average resonance amplification close to unity. The transmissibility of vibration at the heel (first row of Figure 4) is always lower than 1 and depends on the mechanical characteristics of the supporting surface, especially in the range between 30 and 50 Hz.

Although the average transmissibility curves are influenced by the characteristics of the supporting material, the hypothesis testing on the equality of means evidenced that the average transmissibility depends on the material only in specific frequency ranges. This is due to the large differences between the 20 transmissibility curves measured with each single material by the 20 tests participants. Nevertheless, also in the presence of large data variability, the average transmissibility curves are fundamental to understand the expected effect of a material at the resonant frequencies of the different foot parts.

Figure 5 shows the comparison between $\overline{T}_{T1P1}(f)$ with materials A and F: the maximum difference between the average transmissibility curves (0.77 at 80 Hz) is small in comparison with the standard deviation of data at the same frequency (1.02 for material F).

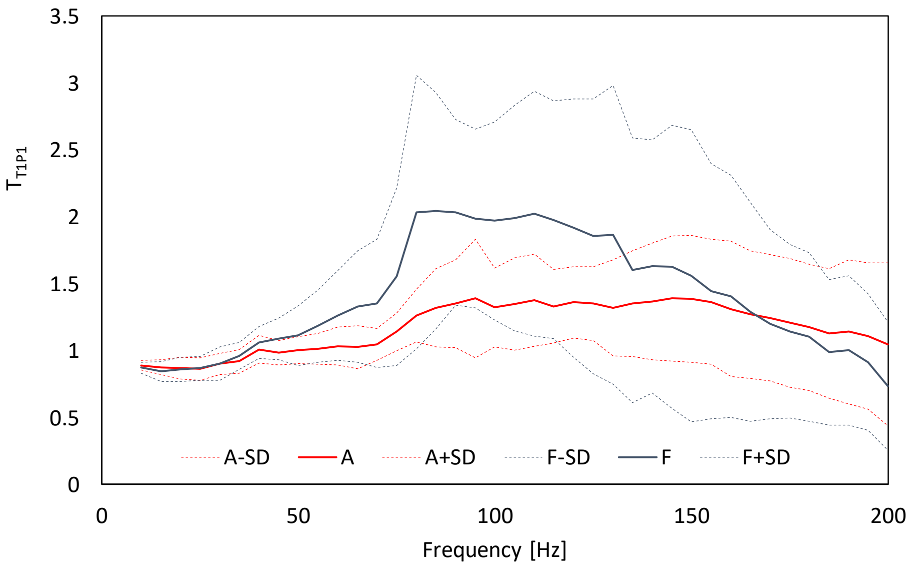

Figure 5. Transmissibility (average transmissibility for the 20 participants ± SD) of materials A and F measured at the position T1P1.

The average reduction obtained with respect to the barefoot conditions is often important: $\Delta T_{m,F}$ (the difference between the transmissibility at the location m measured with the foam F and the one measured barefoot, Figure 6) shows that the effect of the material is often different at the forefoot and at the rearfoot.

In general, the interposition of all the materials reduces the transmissibility at frequencies lower than 50 Hz. $\Delta T_{T1P1,F}$ and $\Delta T_{T3P1,F}$ are larger than 1 between 70 and 150 Hz (apart from the material B that reduced the vibration at T1P1 at 130 Hz). $\Delta T_{M2,F}$ is smaller than 1 above 70 Hz (except for material F). The materials generally reduce the vibration at L4, M4, and H1 (rear foot). Below 50 Hz, the largest reductions are usually obtained with the softer materials.

Data presented in Figure 6 were summarized by analyzing the quantity $100 \times (\Delta T_m - 1)$ in different frequency ranges for each insole. Results are presented in Table 2.

The average of the vibration measured at the forefoot (T1P1, T3P1) in the frequency range between 10 and 200 Hz with all the tested materials is always larger than that measured with barefoot. At the forefoot, the different materials usually attenuate the vibration between 1 and 50 Hz, although the vibration reduction is marginal (1% to 7%). The tested materials always increase the vibration at the forefoot at frequencies above 50 Hz, that are the most critical for the VWF. The worst results are obtained with the material F (air pocket) while the best results are obtained with the hardest material (A).

All the materials averagely reduce the vibration in the frequency range between 10 and 200 Hz at the midfoot (L2, M2) and at the rearfoot (L4, M4, H1). The best material for the attenuation of the vibration at the midfoot is the material E (memory foam insole) while the worst one is material F (although performances of different materials are very similar). The vibration attenuation obtained with the materials A, B, and C at the midfoot is usually larger at high frequencies (100–200 Hz). Conversely, the vibration attenuation obtained with the insoles.

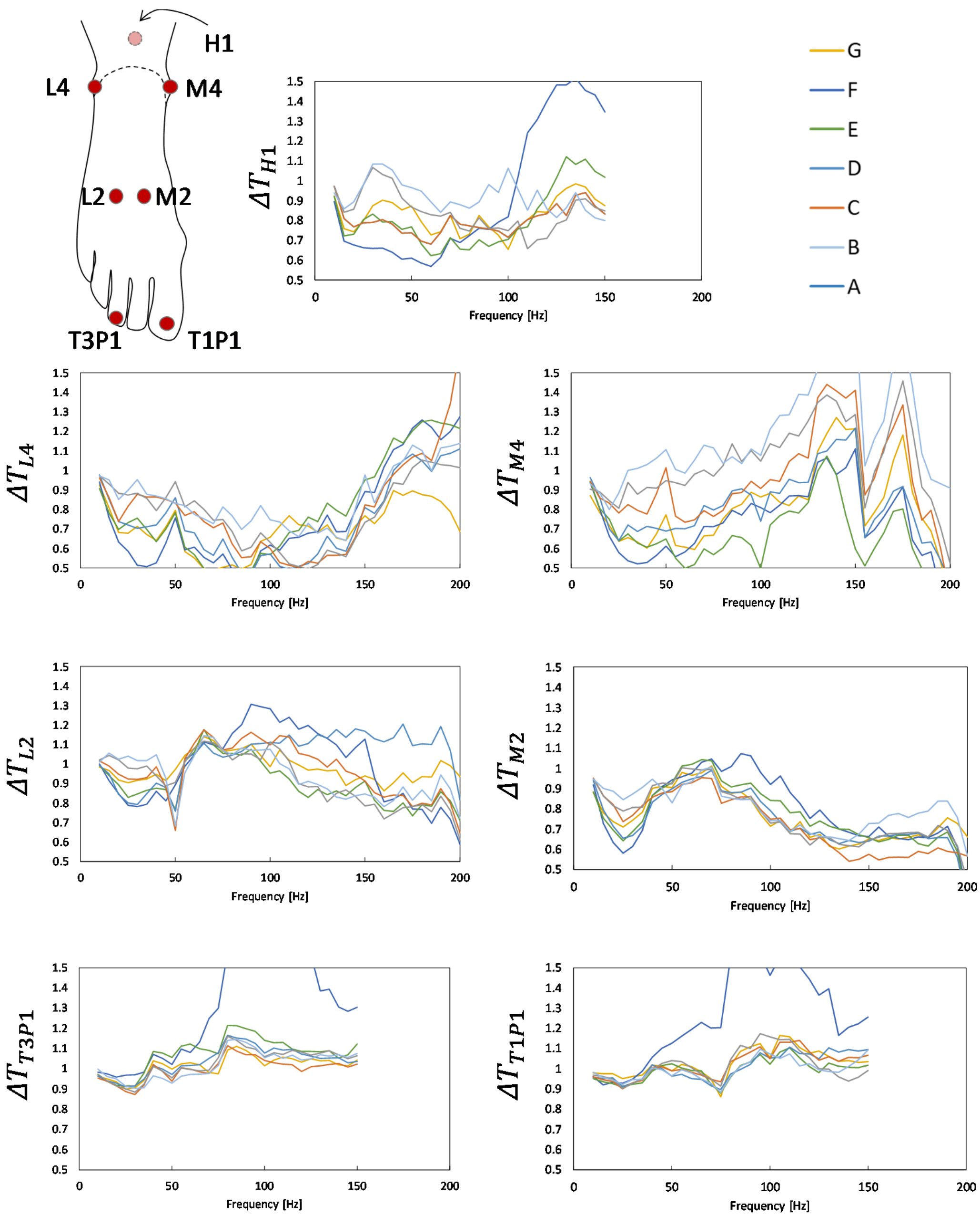

Figure 6. Comparison between the transmissibility measured with different materials with respect to that measured in barefoot.

The best material for reducing the vibration at the rearfoot is material F, while the worst one is again the hardest foam A. In general, at the rearfoot, the foams show performances that are almost independent from the frequency, while performances of the insole usually worsen at high frequencies.

3.2. Questionnaires

Results of the questionnaires are summarized in Table 3. The table shows the normalized discomfort $d_{F,k}$ reported by each participant k for each material F. Results show that the foams used for midsoles (materials A to D) are generally judged less comfortable than the insoles (E to G), although the vibration transmissibility of the different materials evidenced in the previous section did not show a uniform trend.

Table 2. Difference (%) between the average vibration transmissibility measured with the different insoles and that measured in barefoot at the toes, at the midfoot and at the rearfoot.

Forefoot (T1P1, T3P3)							
Frequency Range [Hz]	**A**	**B**	**C**	**D**	**E**	**F**	**G**
10–200	1	3	2	4	4	21	5
10–20	−3	−5	−5	−5	−7	−5	−3
20–50	−5	−4	−4	−3	−3	−1	0
50–100	3	5	7	7	9	33	5
100–150	0	4	3	5	4	32	5
150–200	6	6	3	5	5	10	10
10–20	1	3	2	4	4	21	5
Midfoot (L2, M2)							
Frequency range [Hz]	**A**	**B**	**C**	**D**	**E**	**F**	**G**
10–200	−11	−13	−13	−10	−15	−9	−12
10–20	−3	−5	−7	−13	−14	−16	−12
20–50	−7	−9	−14	−21	−19	−22	−13
50–100	−4	−2	−2	−2	−1	7	−2
100–150	−20	−21	−16	−9	−18	−2	−18
150–200	−21	−29	−30	−13	−29	−27	−20
10–20	−11	−13	−13	−10	−15	−9	−12
Rearfoot (L4, M4, H1)							
Frequency range [Hz]	**A**	**B**	**C**	**D**	**E**	**F**	**G**
10–200	−6	−12	−18	−22	−26	−27	−24
10–20	−10	−10	−13	−14	−19	−21	−19
20–50	−6	−10	−19	−26	−28	−40	−26
50–100	−8	−14	−24	−28	−39	−35	−31
100–150	−4	−17	−17	−21	−16	1	−16
150–200	−6	−11	−11	−17	−8	11	−17
10–20	−6	−12	−18	−22	−26	−27	−24

Table 3. Normalized discomfort reported by all the participants.

Normalized Discomfort ($d_{F,k}$)							
Participant	**Midsoles**				**Insoles**		
k	**A**	**B**	**C**	**D**	**E**	**F**	**G**
1	0.7	1.4	−0.5	−1.2	0.1	0.7	−1.2
2	1.2	1.2	0.6	−0.5	−0.2	−1.1	−1.1
3	1.1	0.7	1.1	−0.5	−0.1	−1.4	−0.9
4	0.9	0.2	0.9	−0.5	−1.8	−0.5	0.9
5	1.3	0.6	−0.2	−0.9	0.9	−0.2	−1.6
6	1.2	−0.2	0.7	0.3	−1.1	0.7	−1.5
7	1.2	1.2	0.6	−1.2	−1.2	0.0	−0.6
8	1.6	0.8	−0.4	−0.4	0.4	−1.2	−0.8
9	1.4	0.9	0.5	0.0	−0.9	−0.5	−1.4
10	1.9	0.3	−0.4	−0.1	−1.2	−0.8	0.3
11	1.3	0.9	0.3	0.5	−0.6	−1.6	−0.8
12	0.3	−0.2	1.9	0.3	−0.8	−1.3	−0.2
13	1.6	0.9	0.1	0.1	−0.7	−1.0	−1.0
14	1.5	1.0	0.5	−0.9	−0.4	−0.9	−0.9
15	1.6	1.1	0.2	−0.3	−0.8	−1.0	−0.8
16	0.1	0.6	1.2	0.6	−1.6	0.1	−1.0
17	1.1	1.1	0.2	0.6	−0.6	−1.0	−1.4
18	1.5	1.0	−0.1	0.4	−1.1	−0.6	−1.1
19	1.3	0.2	0.2	−1.0	−1.0	1.3	−1.0
20	1.0	1.2	−0.1	0.4	−0.1	−1.4	−1.2
$\overline{d_F}$	1.2	0.7	0.4	−0.2	−0.6	−0.6	−0.9
$\sigma_{F,k}$	0.4	0.5	0.6	0.6	0.7	0.8	0.6

The discomfort is related with the shape of the supporting surface (flat materials reported lower values with respect to the anatomic supports) and with the hardness of the surface itself (softer materials are always judged as more comfortable). The normalized averaged discomfort $\overline{d_F}$ of the midsoles is larger than $\overline{d_F}$ of the insoles. $\sigma_{D,F}$, on average, is lower for the midsoles (values between 0.4 and 0.6) than for the insoles (values between 0.6 and 0.8).

3.3. Correlation Analysis

T The last analysis was performed to investigate the correlation between the average discomfort $\overline{d_F}$ and the average transmissibility $\overline{T_F}(f)$. Results are presented in the plot of Figure 7. Each point on the graph symbolizes the average transmissibility measured by 20 subjects with a single material (A to F).

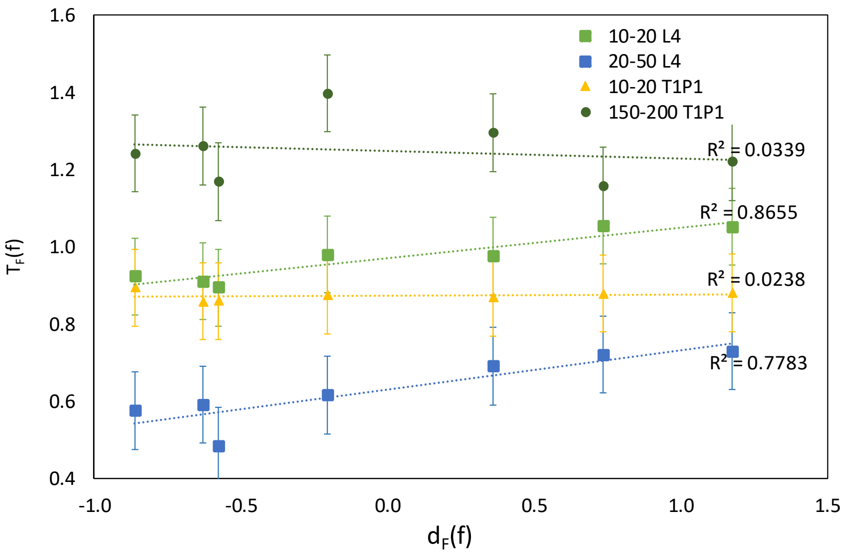

Figure 7. Correlation between the average discomfort and the average transmissibility. Points summarize the transmissibility of a material F; different colors identify different frequencies and positions.

The correlation between the transmissibility at high frequencies and the discomfort is very poor. Conversely, there is a larger correlation between the transmissibility at low frequencies (10–20 and 20–50 Hz) and the reported discomfort.

4. Discussion

4.1. FTV Associated with the Midsole/Insole Materials

The primary objective of this study was to evaluate vibration transmissibility to the foot when standing on four different midsole and three different insole materials. Vibration transmissibility magnitude was dependent on measurement location with significantly greater magnitudes of vibration measured at the toe locations compared to the ankle and heel irrespective of midsole or insole material the participants stood on (Figure 6). This finding is consistent with barefoot tests, where the magnitude of vibration transmitted to the toe region of the foot was greater than that transmitted at the ankle for participants standing in a natural upright position [8].

The materials evaluated in this study were less effective at attenuating vibration transmissibility to the toe region of the foot than the heel. Similarly, a study of glove effectiveness for attenuating hand-arm vibration transmissibility indicated that gloves tend to be less effective at protecting the toes than the palm of the hands [16]. The authors suggest the lower individual effective mass of the toes resulting in less natural cushioning and damping, compared to the palm of the hand, are the likely contributing factors to the differences in measured transmissibility.

Materials capable of attenuating FTV to the toes in the 30–40 Hz range are needed. Findings from the current study and from the extended barefoot analysis [8] suggest that the frequency range between 90 and 150 Hz should be attenuated as this was identified as the resonance frequency range for the toes.

Vibration transmissibility to the 10 measurement locations on the foot also varied across the vibration exposure frequencies for the seven materials tested (Figure 4). The transmissibility at the toes, independently from the material, was very close to the one measured in barefoot, apart from the prototype F that increased the transmissibility at high frequencies. The transmissibility at the heel was lower than 0.3 above 100 Hz and the differences between the foams was always lower than 20%. This indicates the marginal effect of the tested materials in reducing the vibration transmitted to the upper body. The result confirms that a different shoes compliance does not modify the apparent mass measured at the driving point [25]. Goggins and colleagues [26] also observed a difference in vibration transmissibility over a 25–50 Hz exposure frequency with the greatest magnitude of transmissibility occurring at 25–30 Hz for the ankle and 50 Hz for the first toe.

4.2. Comfort Associated with the Midsole/Insole Materials

The secondary objective was to determine if subjective reports of discomfort, associated with exposure to FTV, are correlated with the transmissibility properties of the midsole/insole materials. As a matter of fact, the discomfort reported by the subjects is related to the material compliance, since no correlation was found between the transmissibility at high frequency and the reported discomfort. The higher correlation (0.86) was found between the normalized discomfort and the averaged transmissibility in the frequency range between 10 and 20 Hz. This evidences that the subjective evaluation of comfort is probably related to the amount of vibration that reaches the upper body and not to the attenuation of high-frequency vibration that is of paramount importance for the control of vibration-induced white feet.

Since the resonance frequencies of the toes are similar to those of the fingers (100 to 250 Hz according to Xu and colleagues [27]), it seems reasonable to adopt a procedure similar to that of the ISO 10819 standard [12] to test the usefulness of shoes in the reduction of high frequency vibration. The ISO 10819 [12] standard specifies the tests and the conditions that should be applied to a glove before it can be marketed as an anti-vibration glove. The test consists in the application of specific signals to a vibrating handle and then measuring the vibration transmissibility through the glove.

The differences between the biodynamic response of the foot and of the hand, as well as the effects of posture and contact force, prevent the application of the measurement procedure of the ISO 10819 [12] "as is" on footwear.

In particular, the frequency weighting to be adopted in order to evaluate the mean corrected transmissibility is still unclear, given that the FTV has both musculoskeletal effects (that would require the ISO 2631 [28] frequency weighting curves) and cardiovascular effects (that could be better described using the ISO 5349 weighting curve [29]). Furthermore, the current standard limitations, well evidenced by Dong and col-leagues [30], should be accounted also in the case of anti-vibration shoes.

4.3. Limitations and Future Directions

There are different limitations that should be considered when drawing conclusions from the study findings. First, the number of tested materials is relatively small, and our findings must be confirmed by experiments focused on the study of the combination of outsole (not considered in this paper), midsole, and insole over a broader range of exposure frequencies.

Second, the standing posture of the participants was not strictly controlled. The participants were asked to maintain their natural upright standing posture with the feet approximately shoulder width apart with a slight bend at the knees. Although the participants were asked to maintain this posture for the full 51 s of the vibration exposure, we did not strictly monitor their posture, so it is possible that minor changes in posture occurred. Changes in knee angle or standing center of pressure distribution could influence the magnitude of vibration transmitted through the body [26,31]. However, participants were observed during vibration exposure and no visual deviations from their natural upright standing posture were observed. Although we are confident that any posture deviations were minor during our experimental protocol, we expect large transmissibility variations in the presence of postures that involve leaning forward or backwards. This topic, however, requires more investigation and will be the subject of future studies.

Third, given that the vibration transmissibility was measured with a single vibration level (constant velocity), we might expect different results in the presence of different stimulus amplitudes. Literature studies [24] evidenced that the variation of the frequency response function of standing subjects due to the nonlinear effects is generally smaller than that due to the inter- or intra-subject variability. Consequently, this limitation also does not prevent extending the validity of the data presented in this paper to similar exposure conditions.

Future work is also needed to identify a material and to design an intervention to enhance protection of the toe region of the foot. Evidence from the workplace and clinical findings [4,6] suggest that FTV exposure in the 30–40 Hz range is linked with an increased risk of developing vibration-induced white foot.

Finally, forthcoming standards should include an evaluation of the effectiveness of the anti-vibration materials also used in the workplace, in order to account for the shoes' ageing [32] and for the specific experimental conditions occurring during daily usage. The main differences from laboratory conditions, in this case, could reasonably derive from the worker's posture, from the environmental conditions, and from the effects of uneven supporting surfaces. However, in this case, further studies are also required to confirm our hypotheses.

5. Conclusions

Results of experiments performed on a limited set of materials evidenced that the subjective evaluation of comfort is not adequate to assess the efficiency of midsoles and insoles in reducing the vibration at the toes. Since most of the tested materials worsen the vibration exposure of toes with respect to the barefoot conditions in the frequency region (90–150 Hz) where the toe resonance occurs, it is necessary to introduce new standards for working shoe tests. At the moment, in the presence of high frequency vibration that may lead to vibration-induced white toes, we suggest quantifying the effectiveness of the shoes using the procedure adopted in this paper or a procedure similar to that used for testing anti-vibration gloves.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Ethics Committee of Laurentian University (LU REB File #: 17 May 2016).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are openly available in Mendeley Data at doi:10.17632/bd672xpzbx.1.

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