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Neurosensory Response of the Hand and Foot to Vibration Exposure

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Abstract

Background: *This study investigated the vibrotactile perception threshold (VPT) changes in the fingers and toes of twenty-eight healthy subjects (15 males and 13 females aged 20 to 62 years) exposed to hand- and foot-transmitted vibration.* **Methods:** *The VPT was measured before and after the exposure of the hands and feet to 5 minutes of tri-axial white noise pseudorandom vibration. The post-vibration VPT was measured immediately after and 15 minutes after the end of the exposure to assess the temporary threshold shift (TTS) of vibration perception. The effects of the anatomical district (index finger and big toe), measurement time (before and after vibration exposure), test frequency (8, 31.5, and 125 Hz), age group (Under30s and Over 40s), and gender (male and female) on the changes in VPT were investigated.* **Results:** *The findings revealed that the index finger and the big toe exhibited comparable profiles in the vibrotactile sensitivity at the low-middle vibration frequencies and in the recovery of the perception threshold after vibration exposure. The big toe showed a higher perception threshold than the index finger, and the difference increased with the test frequency. In addition to vibration frequency, age and skin temperature influenced the results of VPT and TTS measurements.* **Conclusions:** *The findings of this study can contribute to outlining alternative frequency weighting functions for the neurosensory response of the hand and foot to vibration exposure, and to update the current guidelines for evaluating human vibration exposure.*

1. Introduction

In many activities, people are exposed to vibration affecting different parts of the body: hand-transmitted vibration (HTV) occurs when using hand-held powered tools, whole-body vibration (WBV) arises from sitting on vibrating surfaces. In contrast, foot-transmitted vibration (FTV) happens when standing on a vibrating floor [1, 2]. HTV may lead to vascular, neurological, and musculoskeletal disorders, collectively called the Hand-Arm Vibration Syndrome (HAVS). Symptoms and signs include numbness and tingling in the fingers, decreased tactile sensation, impaired manual dexterity, digital vasospasm (“white finger” or Raynaud’s phenomenon), and carpal tunnel syndrome [2,3]. The risk of developing HAVS is considered by the international standard ISO 5349 [4], but the ISO metrics for assessing neurosensory impairment are not fully understood [5]. Different frequency

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weightings of HTV showed comparable effectiveness in predicting the likelihood of finger numbness in the exposed workers, indicating no significant difference in their predictive accuracy. As a result, alternative frequency weightings of HTV should be investigated to provide valid predictions of neurosensory outcomes [6-9].

Risk assessment for FTV exposure follows the ISO standard 2631 [10], which details the measurement and evaluation of WBV and restricts the review of health effects to musculoskeletal disorders. Nevertheless, several studies [11-14] have shown that the ISO standard for WBV underestimates the neurological and vascular effects of FTV. Concerning the vascular effects, FTV exposure leads to "vibration white foot" (VWFt), which is characterized by episodes of Raynaud's phenomenon (blanching attacks) in the toes. VWFt occurs typically in workers who also have a history of disorders from HTV or who are directly exposed to FTV [15-18]. Specific methodologies for measuring FTV are currently under development within a working group of ISO TC108/SC4.

Vibration-induced neurosensory effects in the fingers and hands are assessed by detecting vibrotactile perception thresholds (VPT). The methods for measuring and interpreting the VPT are described in the ISO standard 13091 [19]. The similarities between the hand and the foot regarding pathophysiological effects and biomechanical response to vibration [1, 11] suggest that VPT could be used to detect vibration-induced sensorineural disorders of the foot.

VPT at the fingertips is used to investigate the changes in vibrotactile perception, either in HTV workers affected with neurosensory symptoms [20] or in a laboratory setting with short-term exposure to HTV to identify workers potentially at risk of developing neurosensory disorders [21]. There is a limited body of literature exploring vibration perception sensitivity in the feet; some studies focused on the dependence of VPT on contact pressure, frequency, locations on the sole, and skin mechanical properties [22-24]. Only two studies measured the vibrotactile perception in both hands and feet in an adult population. Morioka et al. [25] compared the sensitivity to vibration stimuli between the fingertip, big toe, heel, and volar forearm in different contact conditions. Ekman et al. [26] measured multi-frequency VPT at the finger pulps and metatarsal heads of the foot in 924 healthy subjects divided into different age groups to obtain normative values to be used in clinical and diagnostic practices. Neither of the studies above explored the acute effect of vibration exposure on tactile perception in the foot and hand in an age-stratified population.

Based on the similarities between hands and feet regarding vibration-induced neurovascular disorders, the present study examined the changes in VPT after exposure to vibration, as well as the recovery of VPT over time, in the fingers and toes. The aim was to provide valuable insights into the neurosensory impairment caused by FTV exposure in occupational settings compared to that provoked by HTV. The effect of age was also considered to investigate the potential influence of aging on the digits' response to vibration. To update the current normative guidelines, the study focuses on determining if the VPT method offers a valid approach for evaluating neurosensory effects in both hands and feet.

2. Methods

2.1. Participants

Twenty-eight healthy volunteers (15 males, 13 females) participated in the study. All subjects had no history of use of hand-held vibrating tools in occupational or leisure activities. They were divided into two age groups:

- Under 30s: 10 males and 8 females with the following mean ± standard deviation characteristics: age 24.1±2.8 years (males: 23.1±2.2 years, females: 25.3±3.1 years), body height 1.72±0.1 m (males: 1.79±0.6 m, females: 1.64±0.7 m), body mass 69.6±15.1 kg (males: 78.8±12.7 kg, females: 58±8.4 kg);
- Over 40s: 5 males and 5 females with the following mean ± standard deviation characteristics: age 53.5±8.4 years (males: 52.4±9.6 years, females: 54.6±8.0 years), body height: 1.70±0.1 m (males: 1.78±0.1 m, females:

1.62±0.0 m), body mass 72.9±15.9 kg (males: 85.2±11.4 kg, females: 60.6±7.8 kg).

The following exclusion criteria were applied: lower and/or upper limb injuries in the last 6 months; chronic orthopaedic conditions; diabetes; cognitive disabilities or developmental disorders; history of motion sickness; muscular or neurological diseases; cardiovascular and/or respiratory diseases; skin problems (e.g. burns and cuts). All subjects signed a consent form before the start of the experimental session, and data were collected according to the criteria of the General Data Protection Regulation. The experiments were approved by the Ethics Committee of Politecnico di Milano (n° 17/2024) and followed the Declaration of Helsinki.

2.2. Experimental Setup

The VPT was measured at 8, 31.5, and 125 Hz in the right hand's index finger and the right foot's big toe before and after exposure to HTV or FTV, respectively.

2.2.1. Vibration Stimulus

The hands and feet were exposed to 5 minutes of triaxial Gaussian white noise pseudorandom vibration (0.44 m/s^2 r.m.s acceleration) with frequencies between 8 and 50 Hz applied through a 3-dof vibrating platform [27]. The subjects were instructed to place their palms on the vibrating plate and maintain approximately 15% of their body weight during the HTV exposure. A force platform (KISTLER 9260AA - Kistler Instruments AG, Winterthur, Switzerland) was used under their feet to monitor the ground reaction force. During FTV exposure, the subjects stood barefoot on the vibrating plate. They were instructed to maintain the indicated posture throughout the exposure. Figure 1 shows the placement of the hands and feet during vibration exposure.

2.2.2. Vibrotactile Perception Measurement

The VPT was measured at the frequencies of 8, 31.5, and 125 Hz by means of the Von Békésy

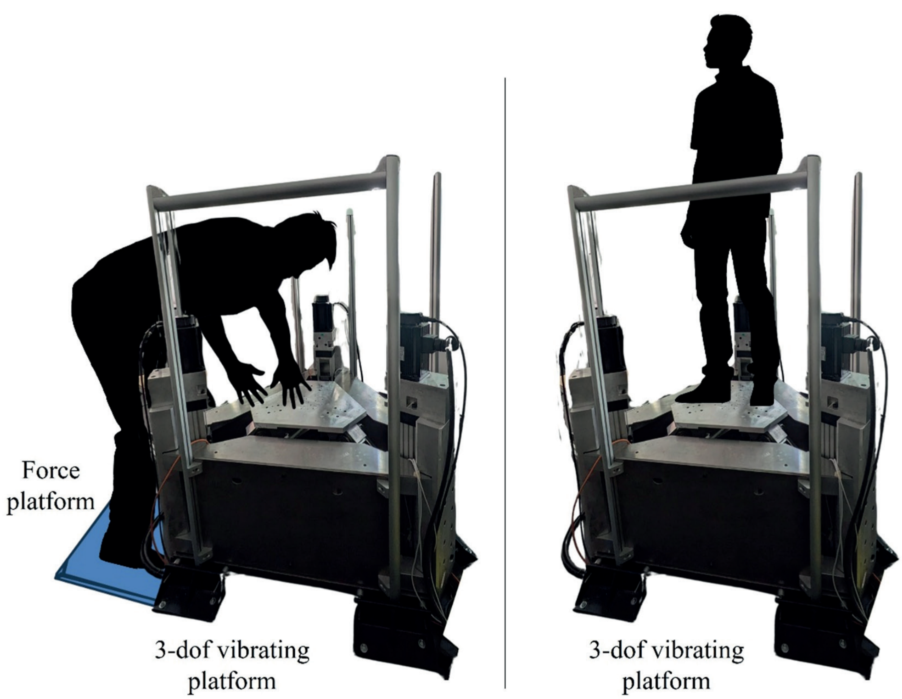

Figure 1. Hands (on the left) and feet (on the right) placement on the vibrating platform during HTV and FTV exposure, respectively.

algorithm using the HVLab Vibrotactile Perception Meter (VPM, University of Southampton, UK) equipped with a vibrometer probe. The test consists of increasing the vibration intensity of the probe on which the anatomical part of interest (i.e., the finger or toe) is laid until the subject perceives vibration and presses a hand-held button, and subsequently decreasing the vibration intensity until the subject no longer feels the vibration and releases the button. VPTs were expressed in decibels (dB) relative to a reference r.m.s. acceleration of 10^{-6} ms^{-2}. The vibrogram consisted of sequences of increasing and decreasing levels of vibration with different frequencies. We set an increasing/decreasing rate of 3 dB/s (with 5 dB/s for the first reversal) with the maximum duration of each measurement of 30 seconds to record at least four reversals. During the test, the subject was asked to maintain a constant contact force by applying 2 N with the toe/fingertip on the static surround around the vibrating probe and by monitoring the force display on the device. At the end of each test, the VPT was calculated as the geometric average of the cycles (excluding the first).

2.3. Test Protocol

The experiments were performed in the Human Vibration Laboratory of the Polo Territoriale di Lecco - Politecnico di Milano.

After preparing and familiarizing with the VPT test, the skin temperature of the tested anatomical district (i.e., index finger and big toe) was measured using a thermocouple. Then, each subject underwent the following experimental protocol:

1. Pre-exposure VPT

   The VPT_{Baseline} was measured at 8, 31.5, and 125 Hz in the distal phalanx of the right index finger and right big toe. The subject's posture and the position of the VPT Meter probe were adjusted to ensure that the constant contact force was applied without muscular tension in the arm and leg. In the case of the hand, the subject was seated on a chair with the arm placed on a flat surface, while in the case of the foot, the subject was sitting on the surface of a table with the leg supported by the table's leg. For both the palm and the sole, contact with any extraneous surface was avoided to ensure that only the targeted area was in direct contact with the vibrating probe. Consistent positioning of the hand and foot was achieved by stably supporting the wrist and heel, respectively, on the table surface or the table leg.
2. Post-exposure VPT

   The VPT measurement was repeated immediately after the end (VPT_{Acute}) and 15 minutes after (VPT_{15min}) the exposure to evaluate the vibration-induced shift in VPT. Between the two measurements, the subject did not use the examined hand or foot.

The protocol was repeated twice, once for the hand and once for the foot, in random order, with a total session duration of 1 hour. The VPT frequencies were randomized for each trial. The subjects wore noise-canceling headphones to prevent the results from being influenced by external factors.

2.4. VPT Shift

The post-vibration VPTs were compared with the baseline values by calculating the temporary threshold shift (TTS), which is the difference between post- and pre-exposure perception thresholds. The TTS was calculated for each of the post-vibration VPTs as follows:

$$TTS_{Acute} = VPT_{Acute} - VPT_{Baseline} \quad (1)$$

$$TTS_{15min} = VPT_{15min} - VPT_{Baseline} \quad (2)$$

These calculations were repeated for each of the selected frequencies and each anatomical district to evaluate the change in vibrotactile perception induced by vibration and its recovery over time.

2.5. Statistical Analysis

VPT and TTS data were summarized with the mean as a measure of central tendency and the standard deviation as a measure of dispersion. The repeated measure ANOVA statistic was used to investigate the effects of the test conditions (anatomical district, measurement time, test frequency) and personal covariates (gender, age) on VPT and TTS. In case of a significant ANOVA F-test, the Tukey or Dunnett (with baseline as control) post-hoc corrections were carried out.

The associations between VPT, TTS and age for each anatomical district at each frequency and measurement time, and the influence of skin temperature on VPT_{Baseline} and TTS_{Acute} were investigated by non-parametric statistics (Spearman rho).

A p-value of .05 was established as the limit of statistical significance.

3. Results

ANOVA results revealed that VPT and TTS were significantly influenced by all the investigated factors, except gender for VPT (Table 1).

Figure 2.(a) reports the means and standard deviations of VPT with the post-hoc significant comparisons between the different categories of the explanatory factors. Figure 2.(b) displays the VPT mean values for the index finger and the big toe in both age groups at each frequency and each measurement time.

All the considered factors significantly influenced the VPT and TTS measurements, which were both frequency-dependent. The index finger and the big toe showed similar threshold shift recovery profiles for both age groups. However, the big toe had a higher threshold than the finger, and the older subjects exhibited lower sensitivity.

Table 2 reports the associations between VPT/TTS and age at each tested frequency in the index finger and the big toe.

Significant associations between VPT and TTS with age were found. In particular, strong correlations (rho>0.60) were observed in the big toe with a positive association for the VPT_{Baseline} at 31.5 Hz and for the VPTs at each measurement time at 125 Hz.

Table 3 provides the results of the correlations for the VPT and TTS measured in the index and big toe at each test condition.

A significant correlation was found between the finger and the toe for the TTS at 125 Hz, both in *Acute* and *15min*. Instead, for the VPT, moderately significant associations (0.40<rho<0.60) were mainly present in the *Baseline* and *15min* measurement time at 8 and 31.5 Hz.

The skin temperature recorded at the beginning of the session averaged (± standard deviation) 26.7 (±4.2) °C in the big toe and 32.7 (±2.9) °C in the index finger. Skin temperature had a limited influence on the neurosensory response of the experimental subjects' digits, showing a negative correlation only for the TTS_{Acute} of the big toe at 31.5 Hz (r=-0.622, p=.001) and 125 Hz (r=-0.507, p=.008).

4. Discussion

The findings of this study indicate that vibrotactile perception measures are affected by factors such as the anatomical district, measurement time, test frequency, and age. VPT and TTS in both the big toe

Table 1. ANOVA results for the main and combined effects (F-test (p-values)) of the investigated factors (measurement time, test frequency, anatomical district, age group, and gender) on VPT and TTS. Only the significant combined effects are reported.

	Measurement time (m)	Test frequency (f)	Anatomical district (d)	Age group (a)	Gender (g)	Combined effect
VPT	F(2,483)=10.49 **(<.001)**	F(2,483)=542.51 **(<.001)**	F(1,483)=258.00 **(<.001)**	F(1,483)=42.17 **(<.001)**	F(1,483)=0.27 (.603)	f x d F(2,483)=44.75 **(<.001)**
TTS	F(1,321)=20.52 **(<.001)**	F(2,321)=8.49 **(<.001)**	F(1,321)=12.23 **(.001)**	F(1,321)=4.08 **(.044)**	F(1,321)=15.53 **(<.001)**	a x g F(1,321)=19.24 **(<.001)**

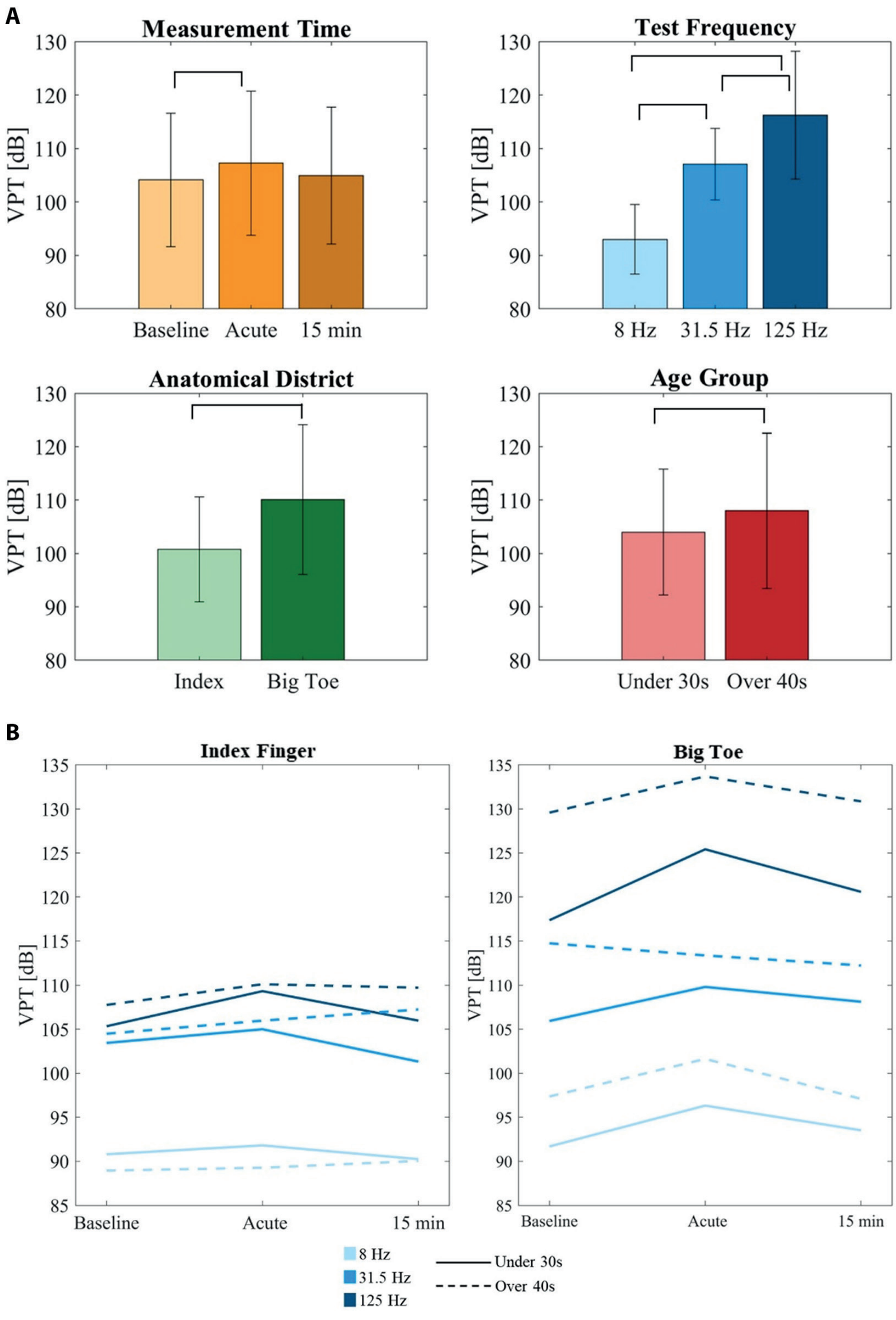

Figure 2. (**a**) The mean and standard deviation values of VPTs grouped by significant factors. The horizontal bars in the figures indicate the significant pairs after post-hoc correction; (**b**) The mean VPT trend over measurement time (i.e., Baseline, Acute, 15min after) for the index finger (left) and big toe (right) in both age groups at each frequency.

Table 2. Spearman correlation coefficients (p-values) between $VPT_{Baseline}$/VPT_{Acute}/VPT_{15min}/TTS_{Acute}/TTS_{15min} and age in the index finger and the big toe at each tested frequency.

Measurement	Anatomical district	Frequency 8 Hz	Frequency 31.5 Hz	Frequency 125 Hz
$VPT_{Baseline}$	Index Finger	-0.123 (.533)	0.076 (.702)	0.218 (.265)
	Big Toe	0.298 (.124)	0.612 **(.001)**	0.634 **(<.001)**
VPT_{Acute}	Index Finger	-0.104 (.597)	0.218 (.266)	0.135 (.492)
	Big Toe	0.224 (.253)	0.301 (.120)	0.478 **(.010)**
VPT_{15min}	Index Finger	0.099 (.617)	0.387 (.042)	0.210 (.284)
	Big Toe	0.189 (.335)	0.332 (.085)	0.654 **(<.001)**
TTS_{Acute}	Index Finger	-0.002 (.991)	-0.007 (.970)	0.014 (.945)
	Big Toe	-0.114 (.563)	-0.457 **(.015)**	-0.298 (.123)
TTS_{15min}	Index Finger	0.248 (.203)	0.382 **(.045)**	0.007 (.973)
	Big Toe	-0.196 (.317)	-0.360 (.060)	0.003 (.986)

Table 3. Spearman correlation coefficients (p-values) for the VPT and TTS measured in the index finger and big toe at each test condition (i.e. each combination of measurement time and test frequency).

	VPT			TTS	
	Baseline	Acute	15min	Acute	15min
8 Hz	0.402 **(.034)**	0.246 (.206)	0.625 **(<.001)**	-0.016 (.937)	-0.163 (.407)
31.5 Hz	0.456 **(.015)**	0.256 (.188)	0.463 **(.013)**	-0.105 (.595)	-0.129 (.512)
125 Hz	0.376 **(.048)**	0.172 (.382)	0.290 (.134)	0.507 **(.006)**	0.479 **(.010)**

and the index finger displayed a comparable trend concerning vibration frequency. Specifically, VPT_{Acute} and TTS_{Acute} in these two anatomical districts exhibited an increase as the vibration frequency escalated from 8 to 125 Hz. This observation aligns with the research conducted by Harada and Griffin [28], which reported significant variability in TTS_{Acute} at the middle fingertip following exposure to hand-transmitted vibration, particularly above and below the 63 Hz threshold. Notably, despite the observed similarities, the big toe demonstrated a higher threshold compared to the index finger, with this disparity becoming more pronounced as the test frequency increased, averaging 2.9 dB in the TTS_{Acute} at 125 Hz. These results may be partially explained by differences between the hand and foot concerning skin thickness, distribution, density, and the functional role of skin mechanoreceptors [25, 29]. The higher density of mechanoreceptors in the hand contributes to greater vibration sensitivity compared to the foot, facilitating a superior level of spatial acuity at the fingertips [25, 30, 31]. In contrast, mechanoreceptors in the foot are distributed sparsely along the sole and are primarily involved in balance control and weight-bearing [25, 29, 32]. Despite these distinctions, our findings reveal that fingers and toes exhibit analogous responses at 8 and 31.5 Hz test frequencies, implying that the same mechanoreceptors in the skin mediate thresholds at these frequencies.

The VPT trend over measurement time was similar in both age groups. Still, the Over 40s exhibited higher VPTs in each test condition (mean difference between Over 40s and Under 30s in VPT_{Baseline}: 6.9 dB in the toe and 1.1 dB in the finger). This finding aligns with the observation that the difference in tactile sensation between the hand and foot is correlated with aging [33]. It is known that vibrotactile perception declines with age as a sign of deterioration in the peripheral nervous system, leading to delays in stimulus detection [26, 34-37].

Our study found no effect of gender on VPT, while a significant interaction between age and gender was observed for TTS. The influence of gender on tactile sense perception is a controversial subject in the literature. Ekman et al. [26] did not find a significant effect of gender in VPT measured in the pulps of the index and little fingers and the first and fifth metatarsal heads. In contrast, Deshpande et al. [34] reported that males showed significantly higher VPTs than females, although the former were, on average, older than the latter.

The skin temperature affected the shift in vibrotactile thresholds. The TTS in the big toe at the middle-high frequencies increased as the temperature decreased. Cold temperatures influenced vibration response in the feet, suggesting that the combination of vibration exposure and lower air temperature could harm workers occupationally exposed to FTV. Harada and Griffin reported a similar result in the hand [28], finding that the vibration sense thresholds increased with the decrease in finger skin temperature.

4.1. Limitations and Future Developments

Our findings should be interpreted cautiously because of the small sample size and the homogeneity of the participants' occupational titles. The selected population is not representative of a working population exposed to vibration. In addition to gender and age, future studies should consider the effects of other possible confounders linked to lifestyles or occupational risk factors [21].

Since this study revealed that in the big toe, lower skin temperatures were associated with greater TTS immediately after the end of vibration exposure, accurate control of the ambient temperature in the laboratory room and acclimatization of the experimental subjects before testing should be considered.

Given the spatial summation activity of the mechanoreceptors, VPT is influenced by the contact area and pressure [22, 38, 39]. This study selected a contact force of 2 N and a 6 mm diameter probe according to a recommended testing procedure [40]. Although the subjects were instructed to maintain a constant force by monitoring the force display, variability in contact force among subjects could not be ruled out. For future studies, in addition to ensuring that participants are adequately familiarized with the tests to maintain constant force, it may also be beneficial to track the trends of vibrotactile thresholds and pressure over time to identify potential associations. To mitigate the temporal decay of the shift effect, only a single measurement per district and frequency was taken following vibration exposure. Future investigations should include repeated measurements within each condition to account for intra-subject variability and improve measurement accuracy.

Finally, only two anatomical districts and three vibration frequencies were considered to reduce the test duration. Different vibration frequencies and anatomical sites at analogous points of the hands and feet [11], including left laterality, could be explored better to characterize the similarities or differences between the hand and foot. A comprehensive profile of the vibrotactile perception response could provide a valuable basis for defining a specific weighting curve for the neurosensory effects associated with HTV or FTV exposures.

5. Conclusion

In this study, the index finger and the big toe exhibited similar profiles in vibrotactile sensitivity at low-middle vibration frequencies and in recovery of the perception threshold following vibration exposure. Although the big toe demonstrated a higher perception threshold than the index finger, this difference increased with rising test frequency. In addition to vibration frequency, age and skin temperature influenced the results of VPT and TTS measurements. Measuring VPT is a valid laboratory tool for assessing the neurosensory effects of HTV and FVT exposures. Our findings can help outline alternative frequency weighting functions for the neurosensory response of the hand and foot to vibration exposure and update current guidelines for evaluating human vibration exposure.

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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 Ethics Committee of Politecnico di Milano (n° 17/2024).

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

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Declaration of Interest: The authors declare no conflict of interest.

Author Contribution Statement: FM and MT contributed to the conception and design of the study, wrote the protocol, and obtained ethics committee approval. FM, NS, and JGS collected, analyzed, and interpreted the data. FM and NS drafted the manuscript. MT and MB revised the data analysis and interpretation. MT, MB, FR, AT, and EM critically reviewed the final draft of the manuscript. AT and EM contributed to the funding acquisition. All authors have reviewed and approved the final version of the manuscript.

Declaration on the Use of AI: None.

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