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Comparison between the Biomechanical Responses of the Hand and Foot When Exposed to Vertical Vibration †

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Abstract: Workers can be exposed daily to foot-transmitted vibration (FTV) from standing on mobile equipment or vibrating platforms and surfaces. This results in a consistent risk of developing neurological, vascular, and musculoskeletal problems. To date, there are no international standards describing procedures with which to evaluate the health risks deriving from long-term exposure to FTV. To study the applicability of hand–arm vibration (HAV) standards to the foot, the biomechanical responses of the hand and foot in terms of the frequency response function upon varying contact conditions were compared. Results evidenced similarities between the responses of the wrist and ankle, with differences in resonance for the fingers and toes. The study confirms that HAV standards are more suitable than whole-body vibration standards for evaluating higher frequency exposure to FTV.

Keywords: hand–foot vibration similarity; foot-transmitted vibration (FTV); hand–arm vibration (HAV); vibration-induced white-foot (VIWFt)

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1. Introduction

Occupational exposure to standing foot-transmitted vibration (FTV) occurs on different means of transport (e.g., boat cabin crew members, sailors, and train operators), in manufacturing industries (operators standing on metallic surfaces close to vibrating machineries) and on heavy mining equipment (e.g., jumbo drills and bolting platforms). Prolonged standing on a vibrating floor may cause musculoskeletal disorders, motion sickness, and neurological as well as vascular diseases [1–4].

Case reports have documented the fact that occupational FTV exposure can cause vibration-induced white-foot (VIWFt), which typically manifests as Raynaud's phenomenon, with decreased blood flow, blanching, and numbness in the toes [4,5]. These vascular and neurological effects are similar to those of hand–arm vibration syndrome (HAVS), affecting workers exposed to hand-transmitted vibration (HTV) [4–10].

The International Standards Organization (ISO) has established guidelines with which to minimize the effects of occupational vibration exposure [11,12]. At the moment, the health impacts of vibration on standing and walking workers are accounted for in ISO 2631-1 [11], whose focus is dedicated to the musculoskeletal effects of whole-body vibration (WBV) on sitting, supine, and standing subjects.

The biodynamic response of the foot [13–15] and the epidemiological data on FTV [4,5] suggest that the current ISO 2631-1 [11] method of evaluating standing WBV exposure is not appropriate for evaluating vascular risks to the feet. The weighting curves used completely neglect the vascular vibration effects that cause VIWFt. For this reason, ISO 5349 [12], focused on HTV, may be more appropriate with regard to FTV for preventing health risks deriving from exposure to high-frequency vibration [9,11,13].

Considering the anatomical, biomechanical, and occupational exposure symptom similarities between the hand and foot, it seems reasonable to expect comparable frequency response functions (FRFs) between a vibration entering at the driving point and a vibration measured on the hand or on the foot.

2. Methodology

We compared the transmissibility responses of 12 paired anatomical locations of the hand [14] and foot [13,15] when exposed to vertical vibration from 10 to 150 Hz under three conditions.

Concettoni and Griffin [14] measured vibration transmissibility at 41 anatomical locations of the hand–arm system in 7 different contact conditions for 14 participants. An electrodynamic shaker imposed a random vibration to a flat plate with an RMS of 17 m/s^2 in a frequency range between 5 and 500 Hz. The transmissibility functions between acceleration at the driving point and the acceleration measured by a laser Doppler vibrometer at each anatomical point were calculated.

Goggins et al. [13,15] analyzed the vibration transmissibility at 24 anatomical locations of the foot and ankle in 3 different standing center of pressure (COP) conditions during exposure to a sine sweep of 10 to 200 Hz with a constant peak velocity of 30 mm/s. Twenty-one participants stood on a vertically vibrating platform in their natural COP position, a forward COP position, with their body weight shifted towards the toes, and in a backward COP position, with their body weight shifted into the heels. The related transmissibility curves between the input stimulus of the vibration platform and the outputs at the anatomical locations were calculated.

Paired FTV–HTV Conditions and Anatomical Locations

In the present study, similar conditions and anatomical locations between hands [14] and feet [13,15] have been compared. The considered hand–foot paired conditions are as follows (Figure 1): (i) Condition 1: whole hand on the plate compared to the natural standing COP position; (ii) Condition 2: only the fingers entirely on the plate compared to the forward COP position; and (iii) Condition 3: only the palm on the plate compared to the backward COP position.

(**a**) (**b**) (**c**)

Figure 1. Hand–foot paired conditions. (**a**) Condition 1: whole hand–natural COP; (**b**) Condition 2: only the fingers–forward COP; and (**c**) Condition 3: only the palm–backward COP [14,15].

The considered hand–foot paired anatomical locations from both studies (Figure 2) were (i) the tips of the fingers compared to the tips of the toes (1–T1P1, 3–T2P1, 6–T3P1, 9–T4P1, and 12–T5P1), (ii) the knuckles compared to the metatarsal heads (2–T1P3, 5–T2P3, 8–T3P3, 11–T4P3, and 14–T5P3); and (iii) the wrist compared to the ankle (25–M4, 34–L4).

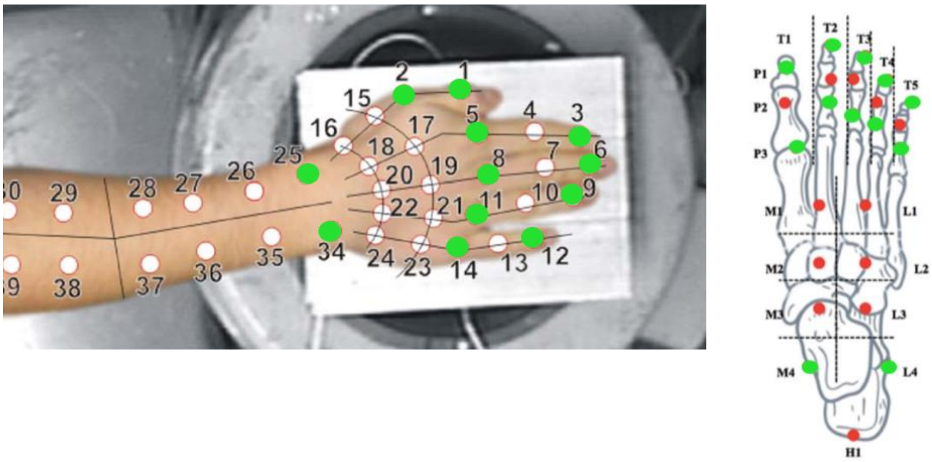

Figure 2. Anatomical locations analyzed in Concettoni and Griffin [14] as well as Goggins et al. [13,15]. Green dots represent the paired points considered in this study.

3. Results

The transmissibility response at 12 paired anatomical locations of the hand and foot were compared from 10 to 150 Hz in Conditions 1, 2, and 3 (Figure 3). In all three conditions, the transmissibility response at the wrist–ankle (i.e., 25–M4 and 34–L4) is similar, with a peak below 50 Hz and a decreasing magnitude up to 150 Hz. The transmissibility response at the finger and toe tips as well as the knuckles and metatarsal heads is similar until approximately 75 Hz. Generally, above 75 Hz, the transmissibility of the foot increases (i.e., greater than 1.5), while the hand transmissibility decreases below 1.

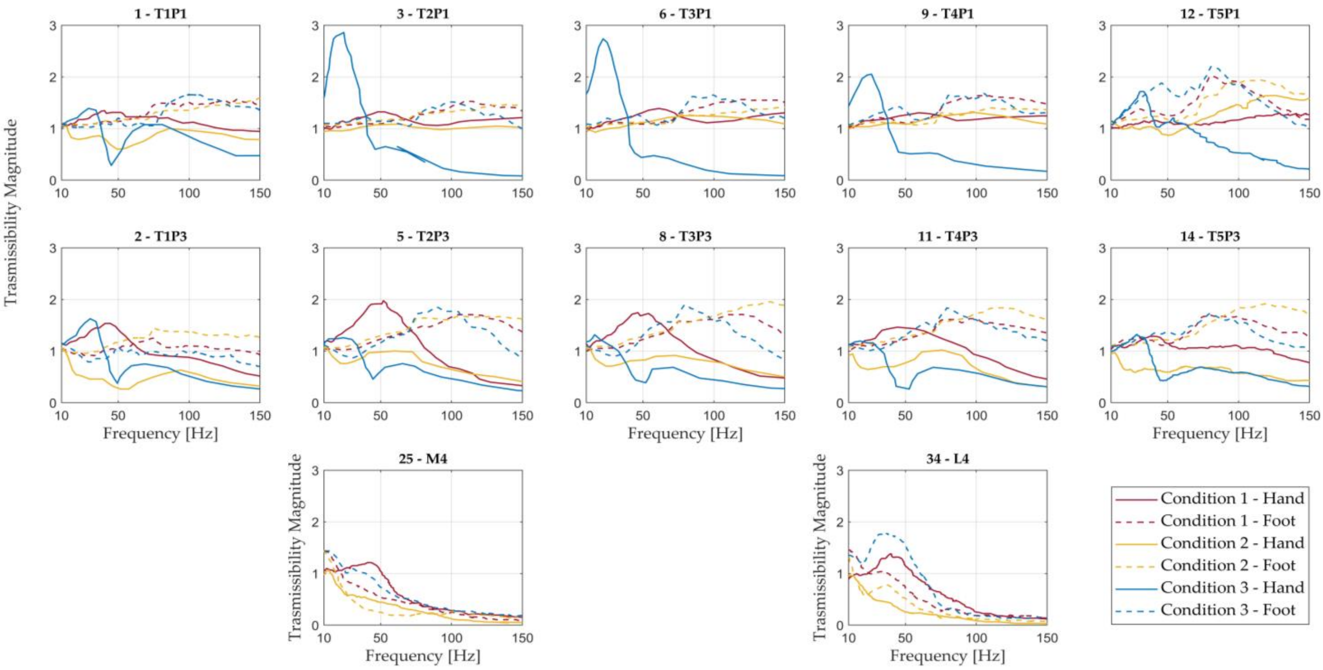

Figure 3. Hand (solid line) and paired foot (dotted line) transmissibility curves for Conditions 1 (red), 2 (yellow), and 3 (blue). Transmissibility data in Condition 3 for the wrist were not available from [14].

4. Conclusions

The comparison between the vibration transmissibility of HTV and FTV illustrates that the toes' resonance frequency (above ~80 Hz) is larger than the fingers' resonance frequency (10–60 Hz). The transmissibility response at the wrist was similar to the response at the ankle regardless of the contact condition, with the main resonance below 50 Hz in both cases. Variations in the posture, gripping/pushing forces, and usage of antivibration gloves or shoes alter the resonant frequencies.

The similarity between the vibration transmissibility of HTV and FTV suggest that using the HAV standards (i.e., ISO 5349 or its modifications) may be more appropriate for the feet; ultimately, specific standards for the evaluation of FTV exposure are necessary.

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References

1. Musculoskeletal Disorders and Workplace Factors. A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity, and Low Back; U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health: Washington, DC, USA, 1997. Available online: https://www.cdc.gov/niosh/docs/97-141/default.html (accessed on 15 January 2023).
2. Bovenzi, M. Health Effects of Mechanical Vibration. *G Ital. Med. Lav. Ergon.* **2005**, *27*, 58–64. [PubMed]
3. Tarabini, M.; Saggin, B.; Scaccabarozzi, D.; Gaviraghi, D.; Moschioni, G. Apparent Mass Distribution at the Feet of Standing Subjects Exposed to Whole-Body Vibration. *Ergonomics* **2013**, *56*, 842–855. [CrossRef] [PubMed]
4. Eger, T.; Thompson, A.; Leduc, M.; Krajnak, K.; Goggins, K.; Godwin, A.; House, R. Vibration Induced White-Feet: Overview and Field Study of Vibration Exposure and Reported Symptoms in Workers. *Work* **2014**, *47*, 101–110. [CrossRef] [PubMed]
5. Hedlund, U. Raynaud's Phenomenon of Fingers and Toes of Miners Exposed to Local and Whole-Body Vibration and Cold. *Int. Arch. Occup. Environ. Heath* **1989**, *61*, 457–461. [CrossRef] [PubMed]
6. Tingsgård, I.; Rasmussen, K. Vibration-induced white toes. *Ugeskr Laeger* **1994**, *156*, 4836–4838. [PubMed]
7. Bovenzi, M. Health Risks from Occupational Exposures to Mechanical Vibration. *Med. Lav* **2006**, *97*, 535–541. [PubMed]
8. Griffin, M.J. Measurement, Evaluation, and Assessment of Peripheral Neurological Disorders Caused by Hand-Transmitted Vibration. *Int. Arch. Occup. Environ. Health* **2008**, *81*, 559–573. [CrossRef] [PubMed]
9. Thompson, A.M.S.; House, R.; Krajnak, K.; Eger, T. Vibration-White Foot: A Case Report. *Occup. Med.* **2010**, *60*, 572–574. [CrossRef] [PubMed]
10. Shen, S.C.; House, R.A. Hand-Arm Vibration Syndrome: What Family Physicians Should Know. *Can. Fam. Physician* **2017**, *63*, 206–210. [PubMed]
11. *ISO-2631-1*; International Organization for Standardization (ISO) Mechanical Vibration and Shock—Evaluation of Human Exposure to Whole-Body Vibration—Whole-Body Vibration—Part 1: General Requirements. International Organization for Standardization (ISO): Geneva, Switzerland, 1997.
12. *ISO-5349-1*; International Organization for Standardization (ISO) Mechanical Vibration — Measurement and evaluation of human exposure to hand transmitted vibration—Part 1: General requirements. International Organization for Standardization (ISO): Geneva, Switzerland, 2001.
13. Goggins, K.A.; Tarabini, M.; Lievers, W.B.; Eger, T.R. Biomechanical Response of the Human Foot When Standing in a Natural Position While Exposed to Vertical Vibration from 10–200 Hz. *Ergonomics* **2019**, *62*, 644–656. [CrossRef] [PubMed]
14. Concettoni, E.; Griffin, M. The Apparent Mass and Mechanical Impedance of the Hand and the Transmission of Vibration to the Fingers, Hand, and Arm. *J. Sound Vib.* **2009**, *325*, 664–678. [CrossRef]
15. Goggins, K.A.; Tarabini, M.; Lievers, W.B.; Eger, T.R. Standing Centre of Pressure Alters the Vibration Transmissibility Response of the Foot. *Ergonomics* **2019**, *62*, 1202–1213. [CrossRef] [PubMed]