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Research on Simultaneous Impact of Hand–Arm and Whole-Body Vibration

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This article presents the results of laboratory tests on the combined effect of whole-body vibration (WBV) and hand–arm vibration (HAV). The reactions of subjects exposed to various combinations of vibration were recorded. The vibrotactile perception threshold (VPT) test identified changes caused by exposure to vibration. Ten male subjects met the criteria of the study. There were 4 series of tests: a reference test and tests after exposure to HAV, WBV, and after simultaneous exposure to HAV and WBV. An analysis of the results (6000 ascending and descending VPTs) showed that the changes in VPTs were greatest after simultaneous exposure to both kinds of vibration. The increase in VPT, for all stimulus frequencies, was then higher than after exposure to HAV or WBV only.

vibrotactile perception hand–arm vibration whole-body vibration combined exposure

1. INTRODUCTION

It is a side effect of operating most machines and mechanical devices that mechanical vibration reaches both the areas in which technological processes take place and the operators' bodies. The way the negative effects of vibration in the working environment are analysed depends on how they are transmitted to the human body. Hand–arm vibration (HAV) and whole-body vibration (WBV) are considered separately [1]. Relevant standards on methods of assessing vibration in the workplace (e.g., Standards No. ISO 5349-1:2001 [2], ISO 5349-2:2001 [3] and EN 14253:2003 [4]) follow this distinction, too. However, at many workstations (e.g., of drivers and operators of mobile machinery) the risk of HAV and WBV coincides. Their impact, of course, differs but it is clear that workers exposed to the simultaneous operation of both factors are in a worse position than if they were exposed to only one of them [5, 6]. Whereas it can be a simple summation of the vibration energy of HAV [7, 8] and WBV, the human body's reaction to this combined threat has not been sufficiently investigated yet.

The aim of this research was to confirm the need to distinguish between the human body's response to exposure to either HAV or WBV only, and its response to combined exposure to both types of vibration.

2. TEST METHOD—MEASURING SYSTEMS

The laboratory tests consisted of recording the reaction of a subject exposed to a combination of HAV and WBV. Vibrotactile perception threshold (VPT) tests identified changes caused by exposure to vibration. WBV and HAV were simulated at special test stands. Mechanical and electronic safeguards ensured full control of the vibration acting

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on the subject and helped avoid accidental, unexpected movements of the elements of the stand. Figure 1 illustrates a test stand for controlled exposure of seated subjects to vertical WBV. Figure 2 depicts a test stand for simulating HAV.

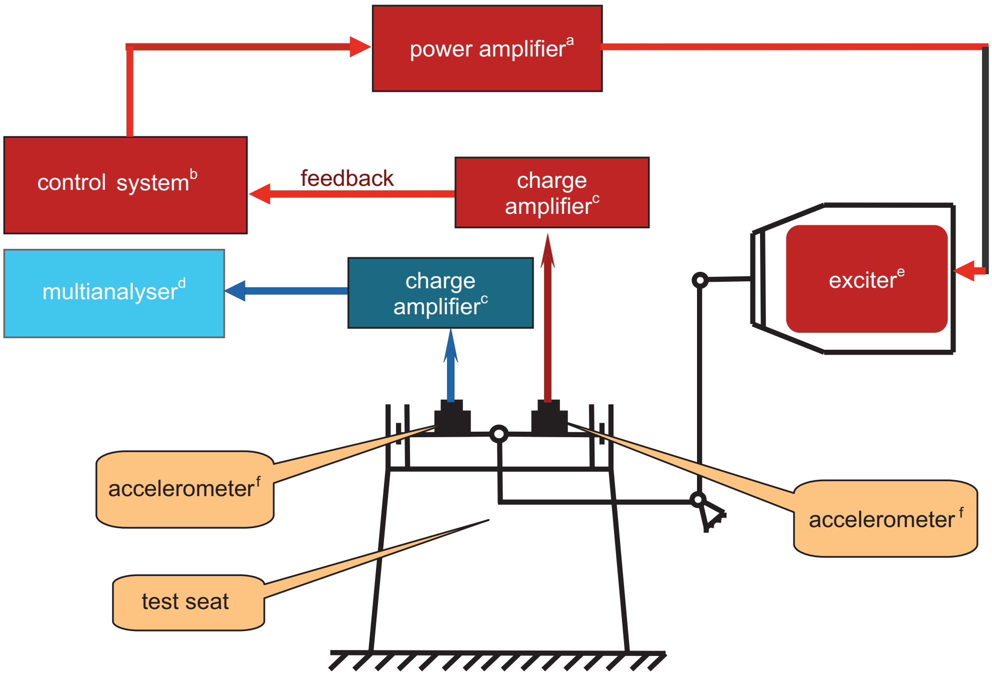

Figure 1. Diagram of the test stand for simulating whole-body vibration. *Notes*. a—PA 2000 (LDS, USA), b—VibPilot (M+P International, Germany), c—2626 (Brüel & Kjær, Denmark), d—PULSE (Brüel & Kjær), e—V721 (LDS), f—4371 (Brüel & Kjær).

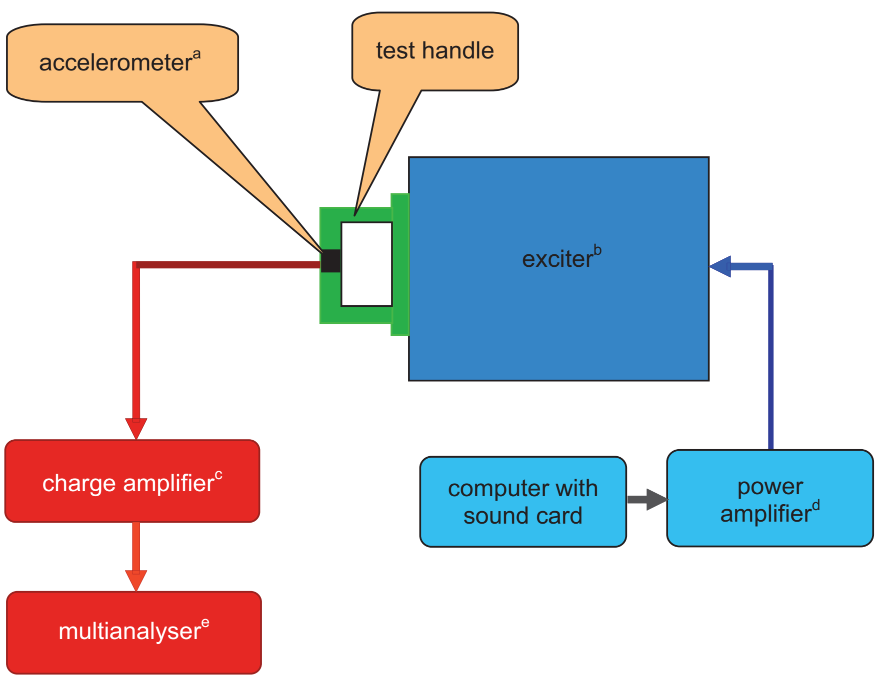

Figure 2. Diagram of the test stand for simulating hand–arm vibration. Notes. a—4384 (Brüel & Kjær, Denmark), b—4812 (Brüel & Kjær), c—2626 (Brüel & Kjær), d—2707 (Brüel & Kjær), e—PULSE (Brüel & Kjær).

Those test stands of independent sources of vibration enabled exposure to separate or simultaneous simulation of WBV and HAV. Two test signals were used, one simulated WBV, the other HAV. Both signals were shaped to contain frequency components most detrimental to the human body (Standards No. EN 14253:2003 [4], ISO 5349-1:2001 [2] and ISO 5349-2:2001 [3]). They corresponded to correction characteristics W_k and W_h used during measurements conducted at workstations in accordance with Standard No. ISO 8041:2004 [9]. Table 1 lists weighted acceleration values of the test signals, whereas Figures 3a and 3b shows their frequency characteristics.

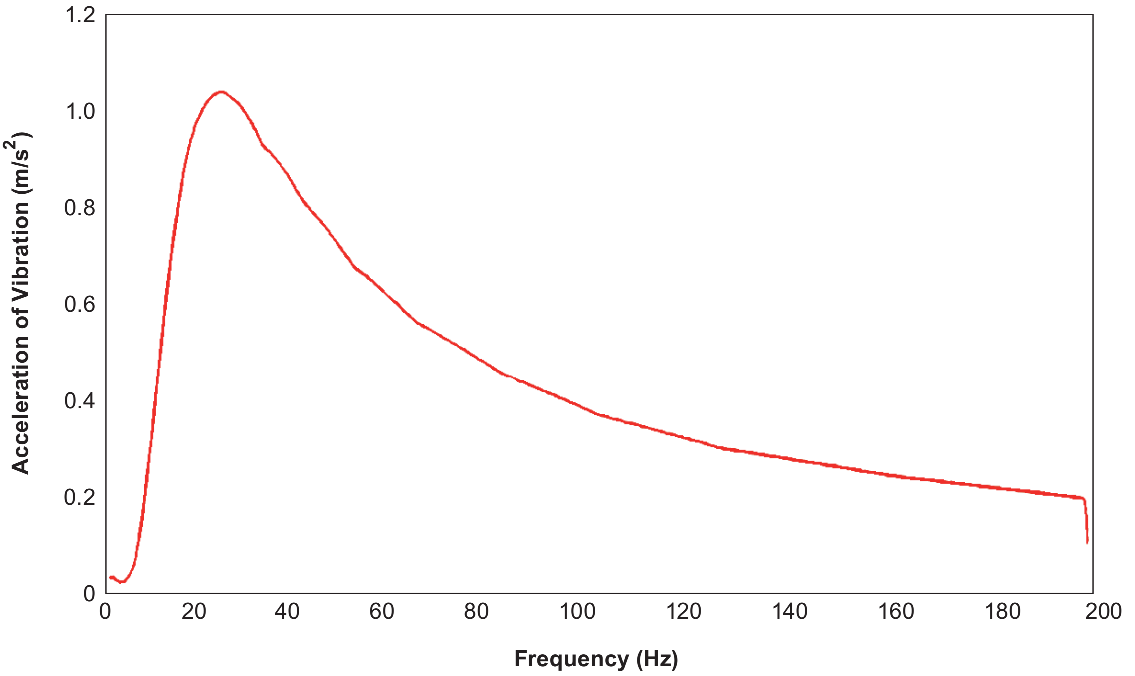

Figure 3a. Amplitude-frequency characteristic of the test signal for simulation of hand–arm vibration.

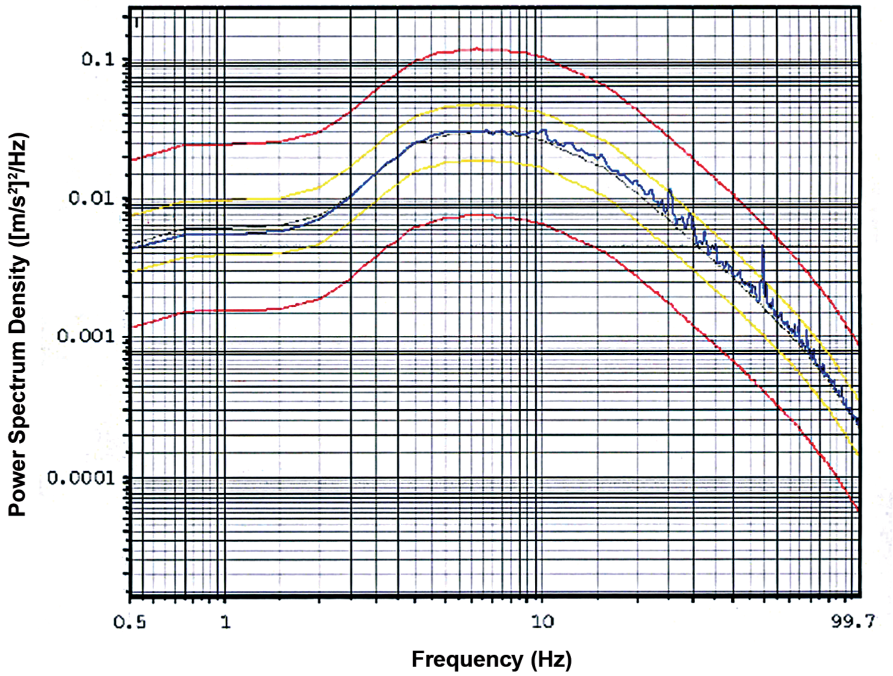

Figure 3b. Amplitude-frequency characteristic of the test signal for simulation of whole-body vibration.

TABLE 1. Weighted Acceleration Values of Test Signals

Vibration	Weighted Acceleration of Test Signal (m/s^2)
Whole-body	0.7*
Hand–arm	2.6

Notes. *—in accordance with Standard No. ISO 13090-1:1998 [10].

Duration of exposure to vibration excitation was strictly controlled. Exposure to WBV, exposure to HAV and simultaneous exposure to both kinds of vibration lasted 5 min (±3 s).

3. VPT TESTS

It was assumed that combined exposure to WBV and HAV caused a different reaction of the subjects than exposure to one kind of vibration only. VPT tests designed to detect those differences used the method described in Standard No. ISO 13091-1:2001 [11]. The computer system for measuring VPT complied with that standard. The measurement conditions were automatically controlled with continuous measurements of the ambient temperature, the temperature of the test fingertip and the finger pressure force on the probe. If even one of those parameters exceeded the assumed range, the test was repeated. There was an automatic prequalification of the measurement results (the criterion of permissible differences between the values of ascending and descending thresholds); it made eliminating the subjects' mistakes and repeating faulty measurements possible.

3.1. Test Conditions

Parameters of VPT tests follow:

- test finger: index finger of the right hand;
- finger pressure force on the probe: 0.1 N (±0.02);
- skin temperature: 27–35 ºC (continuous monitoring and recording);
- ambient temperature: 20–30 ºC (continuous monitoring and recording);
- background acceleration: 0.009 m/s^2 (79 dB ref. 10^{-6} m/s^2);
- background noise during the test: 35.6 dB(*A*) (ref. 20.0 µPa);
- maximum value of noise level during exposure to vibration: 69.8 dB(*A*) (ref. 20.0 µPa);
- 5 stimulation frequencies:
  - 4 Hz (for stimulating slowly-adapting type I mechanoreceptors),
  - 20, 31.5 Hz (for stimulating fast-adapting type I mechanoreceptors),
  - 100, 125 Hz (for stimulating fast-adapting type II mechanoreceptors),
- kind of stimulation: von Békésy algorithm (stimulus with a fixed frequency of alternating increasing and decreasing amplitude);
- number of stimulation repetitions during a single test: 5 (for each frequency);
- number of test repetitions during one series: 3;
- number of test series in one day: 1;
- number of test series: 4; and
- total number of identified ascending and descending thresholds for one person: 5 × 5 × 2 × 3 × 4 = 600.

Furthermore, the conditions listed in Standard No. ISO 13091-1:2001 [11] were ensured during the VPT tests:

- the subject was not exposed to any additional vibration signals from the environment or equipment that could mask the stimulus;
- the subject was not exposed to any sounds that could be an audio signal or another disturbance in the perception of the stimulus. According to Standard No. ISO 13091-1:2001, environmental noise or noise produced by equipment should not exceed 50 dB(*A*) [11];
- the position of the subject's arm was close to neutral during the test; and
- all possible distractions or sources of possible discomfort, which could affect the accuracy and repeatability of measurements, motivation or concentration, were eliminated.

The subjects also met the following conditions before the beginning of the test:

- they were not exposed to HAV, they did not engage in activities requiring repetitive hand and arm movements and they did not drink

alcoholic beverages for at least 3 h before the test;
- they did not consume anything else that was vascularly or neurologically active (e.g., cigarettes or caffeine-containing beverages) for at least one hour before the test;
- they did not have any electrophysiologic study of nerve conduction in their upper limbs for at least 2 h before the test;
- they did not have any objective vascular or sensory test of their hands for at least 30 min before the test;
- they rested seated in a room temperature of 20–30 ºC for at least 5 min or until fingertip temperature at potential measurement sites reached 27–35 ºC; and
- the subjects' hands were visually inspected for damage, scars, swelling or other skin defects that could affect the results.

3.2. Subjects

Ten male subjects qualified to take part in the tests. They fulfilled the following requirements:

- good overall health (especially no diagnosed occupational diseases);
- age: 25–50 years;
- no previous occupational exposure to vibration;
- results of preliminary studies of VPT: normal, exclusion of any disorder;
- nonsmoking;
- good motor co-ordination;
- fast response time mobility; and
- ability to concentrate for extended periods.

Table 2 lists the subjects' main physical characteristics. Verification of the declarations of compliance with the requirements was based on interviews and a preliminary study of VPT. Training on the conditions, requirements and method of testing preceded the preliminary study. It was conducted individually for each qualified subject the day before. Its duration, together with practice runs, depended on the subject's suitability and lasted 1–3 h.

TABLE 2. Subjects' Main Physical Characteristics

Subject	Age (years)	Height (cm)	Mass (kg)
EK	34	176	75
GM	52	174	70
JG	25	188	68
JR	25	170	63
JZ	25	174	74
PB	29	183	75
PK	44	174	65
PS	24	190	83
RM	30	182	80
ST	24	182	80

4. RESULTS

There were four series of VPT tests:

- before the subject's exposure to vibration, reference tests (series 1);
- after exposure to HAV (series 2);
- after exposure to WBV (series 3); and
- after simultaneous exposure to HAV and WBV (series 4).

Series 2–4 started immediately after the subject's exposure to vibration. To eliminate excessive fatigue and the subject's learning the stimulus, each series of measurements took place on a different day. In this way, the effect of vibration on the subject's body was limited (to one exposure), too.

The results for each subject with the following information were placed on test cards:

- identification information on the subject;
- VPT as a function of stimulus frequency in four measurement series;
- ambient temperature;
- fingertip skin temperature during each measurement;
- difference between the values of VPT after exposure to WBV and the reference values of VPT;
- difference between the values of VPT after exposure to HAV and the reference values of VPT; and

- difference between the values of VPT after simultaneous exposure to WBV and HAV and the reference values of VPT.

Table 3 is an example of a test card for subject EK. Each value on the card was determined on the basis of 10 measurements of VPT (5 ascending thresholds and 5 descending thresholds) [11].

The average value of VPT was calculated as the average of the observed VPTs from the relationship:

$$T\left(f_j\right)_{\mathrm{M}} = \frac{1}{n}\sum_{i=1}^{n} T(f_j)_i,$$

where $T(f_j)_i$—ith VPT at frequency f_j (dB) (ref. 10^{-6}m/s^2), $T(f_j)_{\mathrm{M}}$—average VPT at frequency f_j (dB) (ref. 10^{-6}m/s^2).

In total, 6000 ascending and descending thresholds were determined for the 10 subjects. On the basis of the results, averaged VPT runs were determined for each series of VPT tests (Figure 4).

After the subjects' test results had been analysed, ranges of changes in VPT values for the stimulus frequencies that had been used were determined (Table 4). The reference values (from the tests not preceded by exposure to vibration) were 85.9–91.3, 92.5–105.9, 100.0–111.8, 96.6–118.7 and 95.9–119.0 dB for 4, 20, 32, 100 and 125 Hz, respectively.

TABLE 3. Vibrotactile Perception Thresholds (VPTs) for Subject EK*

Measurement No.	Stimulus Frequency (Hz)	Reference Test		Test After WBV		Test After HAV		Test After WBV + HAV	
		T_a = 23.8 °C		T_a = 25 °C		T_a = 25.5 °C		T_a = 24.3 °C	
		VPT (dB)	T_f (°C)	VPT (dB)	T_f (°C)	VPT (dB)	T_f (°C)	VPT (dB)	T_f (°C)
1	4	88.4	26.6	88.7	26.6	90.5	27.9	88.2	25.4
	20	101.3	27.1	102.0	26.4	100.0	29.1	102.3	26.8
	32	109.6	26.4	109.4	26.0	105.7	29.5	109.1	25.2
	100	117.3	27.1	121.5	25.5	124.5	29.4	123.4	25.2
	125	119.1	27.2	122.0	25.8	123.7	29.6	126.0	26.2
2	4	87.5	26.0	90.5	26.8	90.7	28.1	89.4	25.7
	20	101.6	27.2	101.6	26.3	100.8	29.0	100.3	26.9
	32	106.1	26.7	108.6	25.9	107.1	29.5	109.0	25.1
	100	118.0	27.0	121.6	25.4	124.5	29.6	123.7	25.1
	125	118.4	27.1	121.3	25.9	122.8	29.6	126.5	26.3
Average of 2 measurements	4	88.0		89.6		90.6		88.8	
	20	101.5		101.8		100.4		101.3	
	32	107.9		109.0		106.4		109.1	
	100	117.7		121.6		124.5		123.6	
	125	118.8		121.7		123.3		126.3	

Stimulus Frequency (Hz)	WBV – ref[1]	HAV – ref[2]	WBV + HAV – ref[3]
4	1.6	2.6	0.9
20	0.4	–1.0	–0.1
32	1.2	–1.4	1.2
100	3.9	6.8	5.9
125	2.9	4.5	7.5

Notes. *—age: 34 years, height: 176 cm, mass: 75 kg; WBV—whole-body vibration, HAV—hand–arm vibration, T_a—ambient temperature, T_f—fingertip temperature; 1—difference between VPT values determined after exposure to WBV and reference values, 2—difference between VPT values determined after exposure to HAV and reference values, 3—difference between VPT values determined after simultaneous exposure to WBV and HAV and reference values.

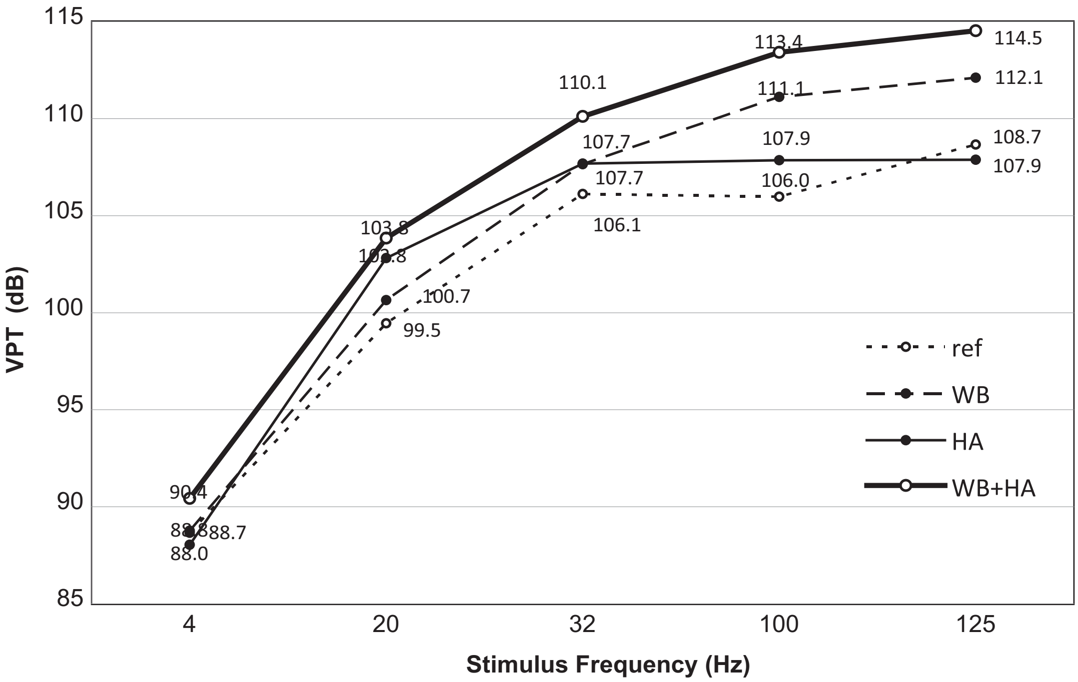

Figure 4. Averaged vibrotactile perception threshold (VPT) runs for 4 measurement series. *Notes.* ref—reference VPT run (before exposure to vibration), WB—VPT run after exposure to whole-body vibration, HA—VPT run after exposure to hand–arm vibration, WB+HA—VPT run after combined exposure to whole-body and hand–arm vibration.

TABLE 4. Changes in Vibrotactile Perception Thresholds (VPTs) After Exposure to Vibration for Different Stimulus Frequencies

	Changes in VPTs (dB)				
	Stimulus Frequency (Hz)				
Exposure to Vibration	**4**	**20**	**32**	**100**	**125**
WBV	–3.1–2.8	0.3–4.4	–0.2–5.2	1.3–14.7	0.3–10.8
HAV	–4.8–3.0	–1.0–10.0	–1.4–7.5	0.5–6.8	–2.4–4.5
WBV and HAV	–1.3–6.0	–0.1–8.7	–0.2–8.3	4.3–21.2	0.1–17.1

Notes. WBV—whole-body vibration, HAV—hand–arm vibration.

5. CONCLUSION

Conclusions drawn on the basis of the test results (6000 ascending and descending VPT) follow:

- after exposure to vibration, there were changes in VPT (compared to reference tests) in all subjects at all stimulus frequencies;
- after exposure to HAV, there was an increase in the values of VPT; there was a reduction only for stimulus frequencies of 4, 32 and 125 Hz;
- although WBV did not act directly on the subjects' finger mechanoreceptors, after exposure, there was an increase in VPT in all subjects (for some, VPT decreased at 4 Hz);
- changes in VPT were highest after simultaneous exposure to HAV and WBV. The increase in VPT at all stimulus frequencies was higher than after separate exposure to HAV or WBV;
- on the basis of the test results obtained to date, it can be assumed that the temporary movements of VPT recorded after exposure to WBV are not caused by adaptation of mechanoreceptors during the tests, and are probably associated with a disorder of nerve conduction; and

- the increased effect of a rise in VPT values after simultaneous exposure to HAV and WBV can indicate that the combined effect of both kinds of vibration has a more adverse impact on human health than exposure to HAV or WBV only.

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