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THE TRANSMISSION OF VERTICAL WHOLE-BODY VIBRATION TO THE BODY SEGMENTS OF STANDING SUBJECTS

B. Harazin and J. Grzesik

Institute of Occupational Medicine and Environmental Health, 41-200 *Sosnowiec*, 13 *Kościelna str*, *Poland*

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The effects of body postures in standing position on the transmission of whole-body vibration to body segments have been investigated. The magnitude acceleration in the Z-axis direction of six body segments: the metatarsus, ankle, knee, hip, shoulder and head has been measured during exposure to random vibration. Ten male subjects exposed to floor vibration stood in ten postures described as: relaxed standing, legs stiffened, legs bent, standing on the toes, standing on one leg with or without support of the other foot and standing in steps. The transmissibility of random vibration from the floor to the body points was calculated at frequencies ranging from 4–250 Hz in 1/3 octave bands. The body postures of the subjects modified both the width of the resonant bands and the transmissibility values. The squared multiple correlation coefficient (R^2) between the transmissibility and the 16 variables (10 postures, 6 body segments) was not very high at resonance frequencies in the range 4–12·5 Hz but above 25 Hz, 50% of the variability in the transmissibility was due to the postures and the body segments.

1. INTRODUCTION

Propagation of vibration in the human body depends on many variables characterizing the source of vibration, the system "source of vibration–human being" and the human organism itself. The body posture has been found to be predominant. It influences the surface of contact of man with the vibrating plane, the position of the spine, the degree of tension in different muscle groups of the trunk and extremities. Variations in body postures alter elastic and damping properties of the organism and determine the mutual positions of masses within its area. Not only does this lead to the change of resonances of body segments but it also results in substantial change of vibration transmission in particular frequency bands.

The first measurements of vertical vibration transmission of a standing man were carried out in 1939 by Bekesy [1]. In his studies he used sinusoidal vibration from 5–120 Hz and observed substantial damping of vibration at the head above 50 Hz. A year later similar results were published by Coermann [2], who measured vibration at the head using vertical vibration of the floor in the frequency range from 15–140 Hz. The same author observed in his next study [3] with one subject that in a standing erect posture there is generally no damping effect of vibration at the head in a frequency range of up to 20 Hz. According to the results obtained by Panovko *et al*. [4] the transmission of vertical vibration from the floor to the head diminishes following the angle of the knee joint bending while the basic resonant frequency of the body increases. Rao *et al*. [5] reached similar conclusions comparing vibration at the head of two subjects standing straight and with knees bent.

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Experiments including three different postures of the legs, legs locked, legs unlocked and legs bent, in with subjects exposed to vertical vibration were carried out by Paddan and Griffin [6]. Dieckmann [7] determined transmissibility of vibration from the floor to different parts of the body, namely the hip, shoulder and head, for subjects standing erect while Starck *et al*. [8] determined the propagation of vibration to the knee, hip and head in subjects in a relaxed standing posture.

From the studies mentioned above it appears that the investigation of the influence of different postures on the transmissibility of vertical vibration in standing subjects was carried out through the measurement of vibration at the head; in the case of studies of transmissibility to several places of the human body, the experiment was limited to one posture. The purpose of this study was to investigate the propagation of vertical vibration to different parts of the body in relation to postures being assumed.

2. METHOD

2.1. SUBJECTS

Ten male university students took part in the study. Their physical characteristics are shown in Table 1. Each subject had undergone a medical examination before being allowed to participate in these experiments. Prior to being exposed to vibration, all of the subjects were required to be fit and healthy.

2.2. APPARATUS

The experiments were conducted on an electromagnetic vibrator constructed by the I.O.M., Sosnowiec. The vibrator had a wooden platform (1·00 m by 1·00 m) which was connected to a vibration exciter system. In the study the vibration simulator was excited with a sinusoidal electric pulse signal with frequency of 5 Hz in order to extend the frequency spectrum in the low frequency range. The vibrator was capable of producing a random vertical acceleration with a frequency spectrum from 4–300 Hz and with the shape shown in Figure 1. The unweighted frequency r.m.s. acceleration magnitude of the input vibration on the platform surface was 4 m/s^2.

The motion of the body was measured with the accelerometer mounted at the six following points: the metatarsus (ossa metatarsalia), the ankle (malleolus medialis), the knee (epicondylus lateralis), the hip (crista iliaca), the shoulder (extremitas acromialis) and the head (vertex). A leather strap with a 2 mm thick metal plate (20 mm by 22 mm) was tightened around the measuring point. The accelerometer was fastened by a screw on the plate vertically in the Z direction on the right side of the body.

While measurements were made at the ankle, the knee and the hip, the accelerometer was fixed to a screw which was connected parallel to the surface of the plate. In the case of measurements at the metatarsus, the shoulder and the head, the screw was connected

TABLE 1

Characteristics of subjects

	Age (years)	Stature (m)	Weight (kg)
Mean	23·1	1·73	66·8
Standard deviation	1·3	0·05	5·7
Minimum	21	1·67	56
Maximum	25	1·82	78

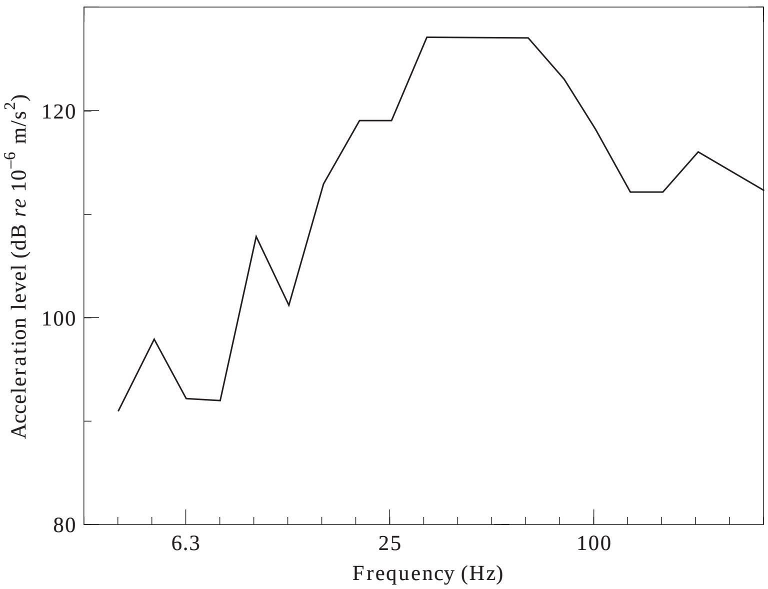

Figure 1. 1/3 octave band spectrum of vertical whole-body vibration.

to the surface of the plate at the angle of 90°. This made it possible for the accelerometer to be always oriented vertically during the measurement. The total mass of the strap with the accelerometer did not exceed 150 g.

So far it has not been possible to develop a non-invasive method of attaching the accelerometer directly to different parts of the human body. Various elastic straps have been used, made of either leather or aluminium with accelerometers attached to them which were then placed around the legs, the trunk and the head. The acceleration of the abdominal wall was measured with an accelerometer attached to the skin with adhesive tape [9]. None of these methods have been accepted as standard ones. The most often applied has been the method in which the subjects held a bit bar between their teeth [6, 10].

The measurement system consisted of two identical channels each of which included an accelerometer (B&K 4331), a pre-amplifier (B&K 2615) and an amplifier (BK 2107). The signals from the platform and from the body were simultaneously recorded on the two-track tape recorder (B&K 7001). Every recording was prepared as a closed loop and played via the amplifier, a 1/3 octave filter set (B&K 1614) and recorded on the level recorder (B&K 2305). The 1/3 octave filter switching occurred automatically at every full run of the loop.

The transmissibility $T(f)$ at the six parts of the body was calculated by the division of the acceleration spectra at the different points $a_b(f)$ by the acceleration spectra at the platform $a_p(f)$: $T(f) = a_b(f)/a_p(f)$ (ISO 7962, 1987 [11]). A set of ten transfer functions, for 10 postures, was obtained for each measurement point.

The room temperature was 24–25°C, since the subjects wore only shorts during their exposure to the vibration.

2.3. PROCEDURE

Prior to the experiment the subjects had practised the follow body postures (see Figure 2): 1, relaxed standing, hands at sides; 2, standing with legs stiffened in knee-joints; 3, standing on the right leg with the support of the left foot toes; 4, standing on the right leg, while the heel of the left foot was raised up to the level of the right medial ankle (in

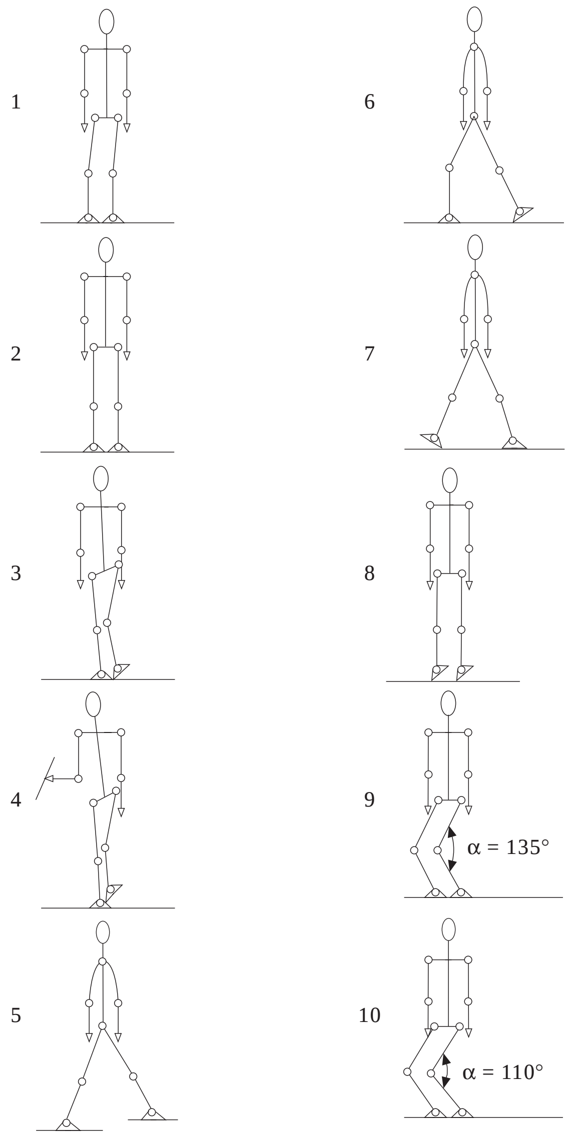

Figure 2. Body postures in standing position.

order to maintain the state of equilibrium the subjects placed their finger tips of their right hands against a support located at the height of their chest); 5, standing in step; 6, standing in step, the left foot behind, supported on the toes; 7, standing in step, the left foot ahead, supported on the heel; 8, standing on the toes with the heels raised about 2–4 cm depending on an individual's sensitivity to maximum vibration attenuation; 9, standing with feet astride, knees bent at the angle of 135°; 10, standing with feet apart, knees bent at the angle of 110°. The postures differed in the size of the contact surface between the feet and the vibrating surface and in the conditions of vibration transmission along the legs which were different for stretched and bent legs. Also considered were the walking cycles since workers exposed to whole-body vibration often walk on vibrating floors or other surfaces.

Before the experiment the subjects had also been exposed to vibration for a short period of time to familiarize them with the vibration stimulus. Ten signals were recorded from one point of the body for each posture. The duration of each vibration exposure was only 50 s to avoid non-linear and non-stationary effects on transmissibility [12]. There was a 30 s pause in exposure to vibration after every recording of the signal from the point of the body. The subject was allowed to rest for 10 min and sit down before measurements of transmission from another point of his body were taken.

2.4. STATISTICAL ANALYSIS

Multiple regression analysis and multiple correlation coefficients have been used to describe the results of the experiment. The multiple regression equations were

$$T(f_i) = \beta_i P_1 + \cdots + \beta_{10} P_{10} + \beta_{11} L_1 + \cdots + \beta_{16} L_6,$$

where $T(f_i)$ is the transmissibility at the central frequency f_i of the 1/3 octave band, β_{1-16} are the regression coefficients, P_{1-10} are the numbers of the ten postures, and L_{1-6} are the numbers of the six body segments. The regression coefficients, their standard errors, levels of significance and the squared correlation coefficient R^2 were obtained for each 1/3 octave band f_i. Moreover F ratios with degrees of freedom of 600-1-k and k were determined in the process of the multiple regression analysis of variance. The degree of freedom k was the number of regression coefficients with levels of significance $<0{\cdot}05$ and the number of 600 was equal to 10 subjects × 10 postures × 6 body segments.

Statistical tests with $p < 0{\cdot}05$ were considered to be significant.

3. RESULTS

The mean transmissibilities of vertical vibration, at the 1/3 octave band frequencies, to the six body segments of 10 subjects in ten postures are shown in Figures 3–8.

3.1. METATARSUS

Figure 3 shows how the mean transmissibilities of vibration to the metatarsus depend on the postures. There is evidence of the three resonances at the central frequencies of the 1/3 octave bands: 4–8 Hz, 12·5 Hz, 31·5–125 Hz and the least motion was recorded at the central frequencies of the 1/3 octave bands: 20–25 Hz. It may be observed that with the exception of the standing in step posture (no. 5) transmissibilities show similar characteristics for all of the postures. During exposure to vibration in posture no. 5 an important resonant response is exhibited in the range of the central frequencies of the 1/3 octave bands: 4–70 Hz. Above 200 Hz, vibration is damped and the magnitudes of floor-to-metatarsus transmissibilities do not exceed the mean value of 0·3–0·9.

3.2. ANKLE

The transmissibilities of vibration to the ankle are illustrated in Figure 4. The transmissibilities curves show three resonances at the central frequencies of the 1/3 octave bands: 4–8 Hz, 12·5 Hz and 25–63 Hz. The most noticeable changes in transmissibility of vibration to the ankle in comparison with the metatarsus are narrower and lower the frequency range of the third resonance. The standing on the toes posture (no. 8) produced definite changes in the mean magnitudes of vibration transmitted from the floor to the ankle. In this posture the magnitude of vibration is smaller than in the remaining postures in the 1/3 octave band frequency from 16–160 Hz. Above 80 Hz, the magnitude of the ankle vibration is smaller than the floor vibration.

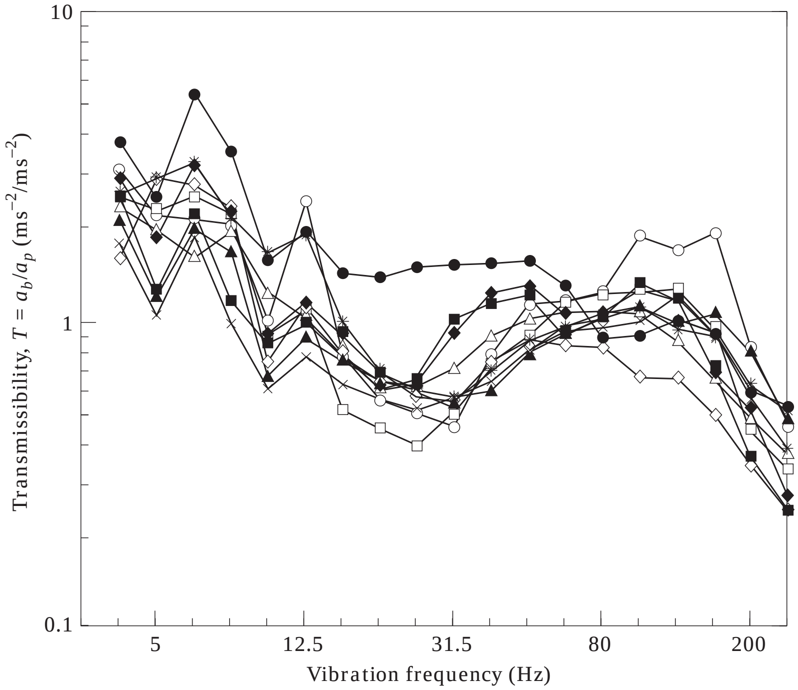

Figure 3. Mean transmissibilities between vertical floor acceleration and metatarsus acceleration for 10 subjects standing in ten postures. Key for postures: –◆–, 1; –■–, 2; –▲–, 3; –✶–, 4; –●–, 5; –○–, 6; –□–, 7; –◇–, 8; –△–, 9; –✡–, 10.

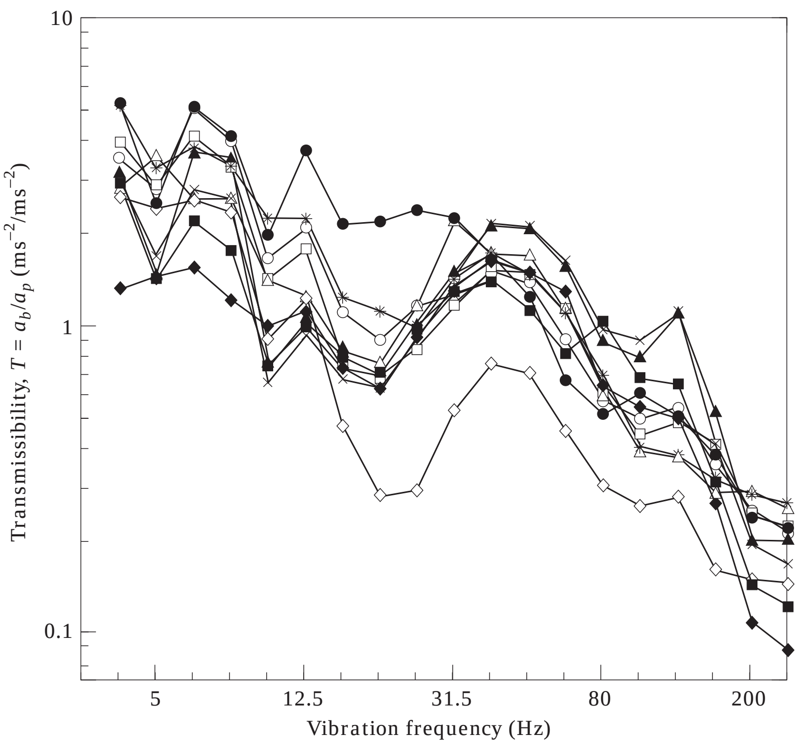

Figure 4. Mean transmissibilities between vertical floor acceleration and ankle acceleration for 10 subjects standing in ten postures. Key as for Figure 3.

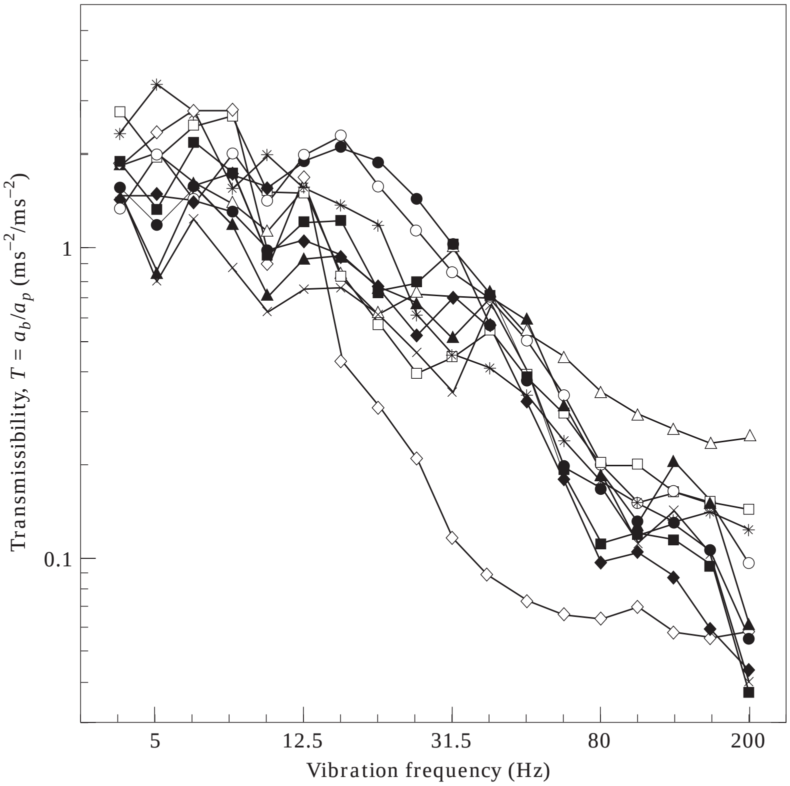

Figure 5. Mean transmissibilities between vertical floor acceleration and knee acceleration for 10 subjects standing in ten postures. Key as for Figure 3.

3.3. KNEE

Figure 5 illustrates the magnitudes of vibration transmitted from the floor to the knee. Two ranges of the resonance frequencies are observed: the first one at the 1/3 octave band frequency 4–8 Hz and the other one respectively at 12·5–25 Hz. The latter resonance is the most clear one in postures no. 5 and no. 6. In posture no. 8 a decrease of the vibration magnitude appears at the 1/3 octave band frequency near 16 Hz and it is the most substantial decrease in comparison with the other nine postures. Above the frequency band of 31·5 Hz, the magnitude of vibration at the knee is lower than at the floor.

3.4. HIP

The transmissibilities of vibration from the floor to the hip are shown in Figure 6. It may be seen that the postures play an important role in resonant response of the subjects from the 1/3 octave frequency band 4–10 Hz. In the three postures, namely the standing on the toes posture (no. 8) and legs bent at the knees posture (no. 9 and no. 10), the vibration magnitude is the most amplified in resonant range and the most damped above 25 Hz. The magnitudes of floor-to-hip transmissibility is decreased in all postures above 16 Hz.

3.5. SHOULDER

Figure 7 shows the magnitude of vibration transmitted from the floor to the shoulder. There are two resonances at 1/3 octave frequency bands of 4–8 Hz and of 12·5 Hz. The latter resonance does not appear in all of the postures; for example it does not exist in

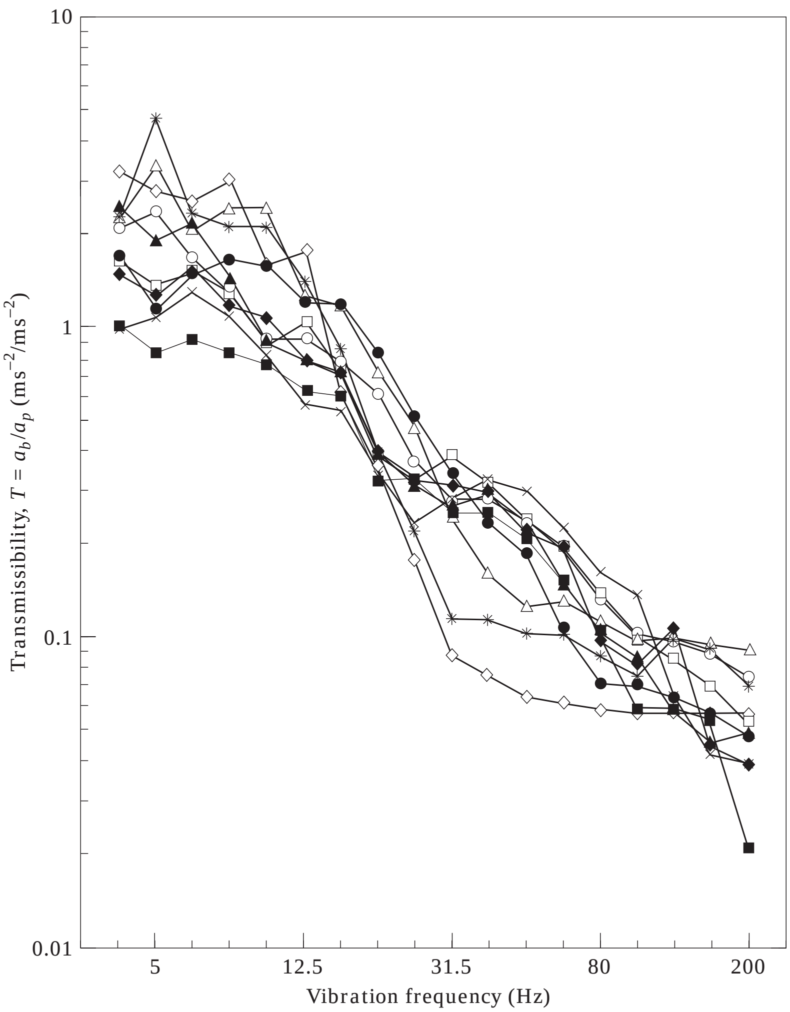

Figure 6. Mean transmissibilities between vertical floor acceleration and hip acceleration for 10 subjects standing in ten postures. Key as for Figure 3.

the standing on one leg postures (no. 3 and no. 4). Above the second resonance the vibration magnitudes are substantially decreased and above a frequency band of 16 Hz they are smaller than at the floor. In all of the postures there is a similar trend observed in which vibration magnitudes decrease with increasing frequency.

3.6. HEAD

The transmissibilities of vibration from the floor to the head are shown in Figure 8. It is seen that at the head there are two resonances, the first one at about 1/3 octave frequency bands 4–6·3 Hz and the other one at 12·5 Hz. A greater effect of postures on the transmissibility of vibration to the head is seen in comparison with the effect of postures on the transmissibility of vibration to the shoulder throughout the 20–40 Hz frequency range. In this frequency range the vibration magnitudes are higher at the head than at the shoulder. Postures no. 8 and no. 10 produce lower transmissibility of vibration magnitudes to the head in the frequency range of 16–63 Hz than those observed for the remaining

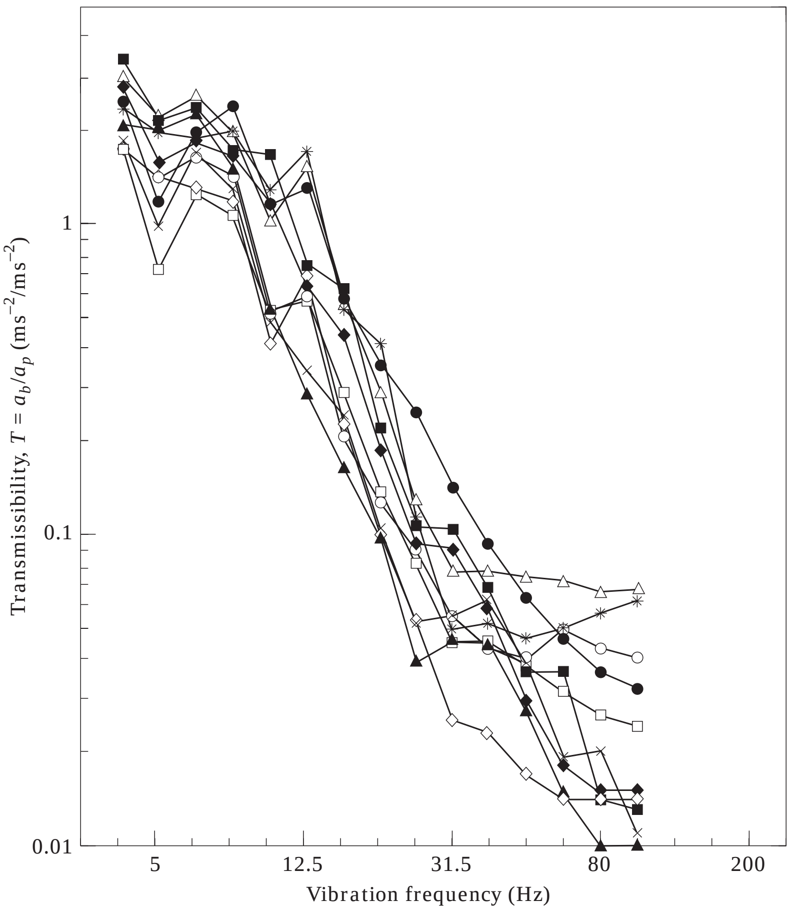

Figure 7. Mean transmissibilities between vertical floor acceleration and shoulder acceleration for 10 subjects standing in ten postures. Key as for Figure 3.

postures. In the second resonance range postures nos. 1, 2, 5 and 7 transmit vibration from the floor to the head more efficiently than the other postures.

4. DISCUSSION AND CONCLUSION

The mean transmissibility of vibration from the floor to individual parts of the body depends on the postures but not all the postures influence the examined parts of the body to the same extent. This is due to many reasons such as mutual positions of tissues, organs and their positions in relation to the direction of propagation of vibration from the source where the sources of vibration of the body segments situated farther from the vibrator are the body segments located below.

Analyzing the curves representing transmissibility to different parts of the body shows that in the region of low frequencies, up to about 8 Hz, vibration is amplified irrespective of the examined area of the body (see Figure 9). In view of the biomechanics individual body parts are linked and behave as one resultant mass in the region of the main resonance frequency [3]. The range of the first resonance band may be narrow, for example for postures 1, 2, 3, 4, 7, 8 and 9, or less concentrated for postures 6 and 10, or even substantially extended for posture no. 5. The squared multiple correlation coefficient R^2

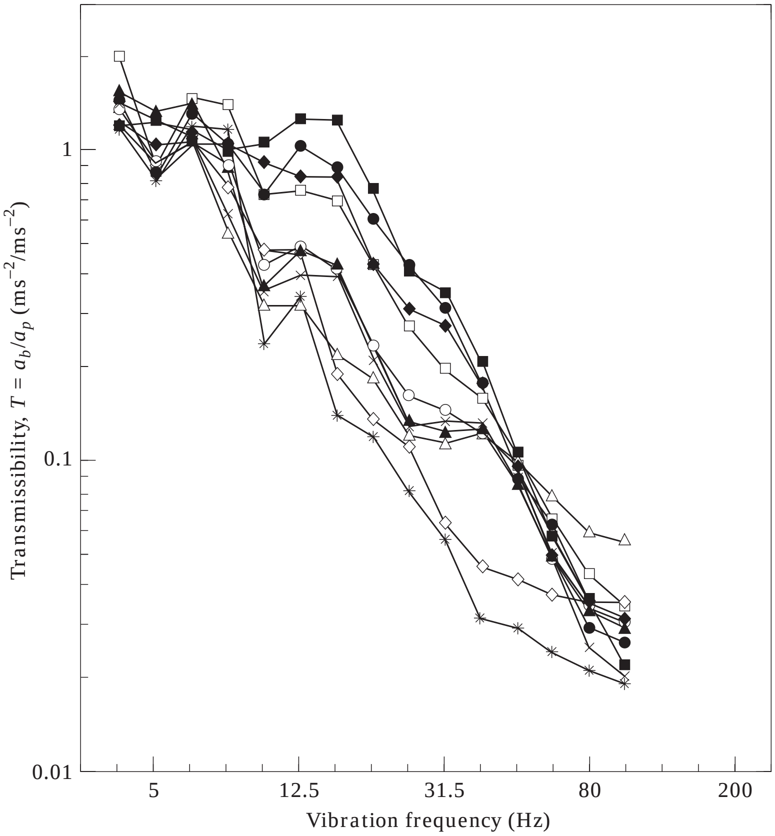

Figure 8. Mean transmissibilities between vertical floor acceleration and head acceleration for 10 subjects standing in ten postures. Key as for Figure 3.

between the transmissibility and the 16 variables (ten postures and six body segments) was not very high ($<0{\cdot}13$) in the 1/3 octave bands wtih central frequency from 4–12·5 Hz (see Table 2).

The next frequency band of interest begins, for most of the postures, from 16–20 Hz where vibration is damped and it should be noted that it is dumped to a slightly higher degree for the body segments located farther from the vibrator. In this damping frequency region the standing in step posture (no. 5) favours transmissibility and has the highest regression coefficient (0·23, 0·34 and 0·31, respectively), in comparison with other postures.

It is only above this damping frequency band where the differences in vibration transmissibility appear for individual body segments. The magnitude of vibration being transmitted by the foot is again amplified in the frequency region of 31·5–125 Hz at the metatarsus and respectively of 25–63 Hz at the ankle which indicate the formation of a local resonance (see Figures 3, 4). Then, beyond the band of the second resonance, the damping of vibration begins, which is very different for the metatarsus, ankle and knee. The standing on toes posture (no. 8) and legs bent at the knees posture (no. 10) are considered to be exceptions in which there is no second resonance peak at the knee. Panovko *et al*. [4] found a similar influence of the degree of knee bend on transmissibility. In the case of the standing in step posture (no. 5) there is only one resonance band even at the ankle or metatarsus.

TABLE 2

Multiple regression analysis between the transmissibility and postures and body segments. Regression coefficients at 1/3 octave band frequencies

	Frequency (Hz)																	
	4	5	6·3	8	10	12·5	16	20	25	31·5	40	50	63	80	100	125	160	200
Posture 2	–	–	–	–	–	–	–	–	–	–	–	–	−0·05	–	–	–	–	–
Posture 3	–	–	–	–	–	–	−0·09*	–	–	−0·07*	–	–	–	–	–	0·08*	–	0·10
Posture 4	−0·08*	–	–	−0·08*	–	−0·08*	−0·12	−0·08*	−0·07*	−0·08	–	–	–	–	0·09	–	–	–
Posture 5	–	–	0·10*	0·09	0·16	0·19	0·23	0·34	0·31	0·14	0·05*	–	–	–	–	–	–	–
Posture 6	–	0·08*	–	–	–	0·09*	–	–	–	−0·07*	–	–	–	–	0·07*	0·09	0·17	0·14
Posture 7	–	–	–	–	–	–	−0·09*	−0·07*	−0·07*	−0·09	–	–	–	–	–	–	–	–
Posture 8	–	0.12	–	–	–	–	−0.15	−0·13	−0·14	−0·20	−1·13	−0·12	−0·11	−0·08	−0·09	−0·11	−0·09*	–
Posture 9	–	0·15	–	–	0·12	–	–	–	–	–	0·07	–	–	–	–	–	–	0·11
Posture 10	–	0·21	–	–	0·15	0·11	–	–	–	−0·09	–	−0·05*	–	–	–	–	–	0·08
Metatarsus	−0·14*	–	–	−0·14	–	–	–	–	−0·26	–	–	−0·22	–	–	–	–	–	0·57
Ankle	–	–	0·12	–	–	–	–	0·10*	–	0·42	0·41	–	–	−0·28	−0·47	−0·40	−0·53	–
Knee	−0·27	−0·08*	−0·11*	−0·21	–	–	0·16	0·13	−0·25	−0·08*	−0·19	−0·58	−0·50	−0·66	−0·77	−0·73	−0·72	−0·19
Hip	−0·24	–	−0·13	−0·23	–	−0·11	–	−0·14	−0·48	−0·30	−0·35	−0·69	−0·57	−0·70	−0·80	−0·78	−0·77	−0·24
Shoulder	−0·17	−0·10	−0·10*	−0·23	−0·08*	−0·16	−0·24	−0·33	−0·64	−0·41	−0·45	−0·78	−0·65	−0·77	−0·85	–	–	–
Head	−0·33	−0·22	−0·22	−0·35	−0·20	−0·22	−0·15	−0·24	−0·54	−0·35	−0·41	−0·75	−0·64	−0·76	−0·85	–	–	–
R^2	0·112	0·120	0·121	0·113	0·099	0·129	0·235	0·376	0·482	0·651	0·676	0·642	0·599	0·619	0·699	0·561	0·540	0·583

(*) $p < 0{\cdot}05$, () $p < 0{\cdot}01$ levels of significance. R^2—the squared multiple correlation coefficient.

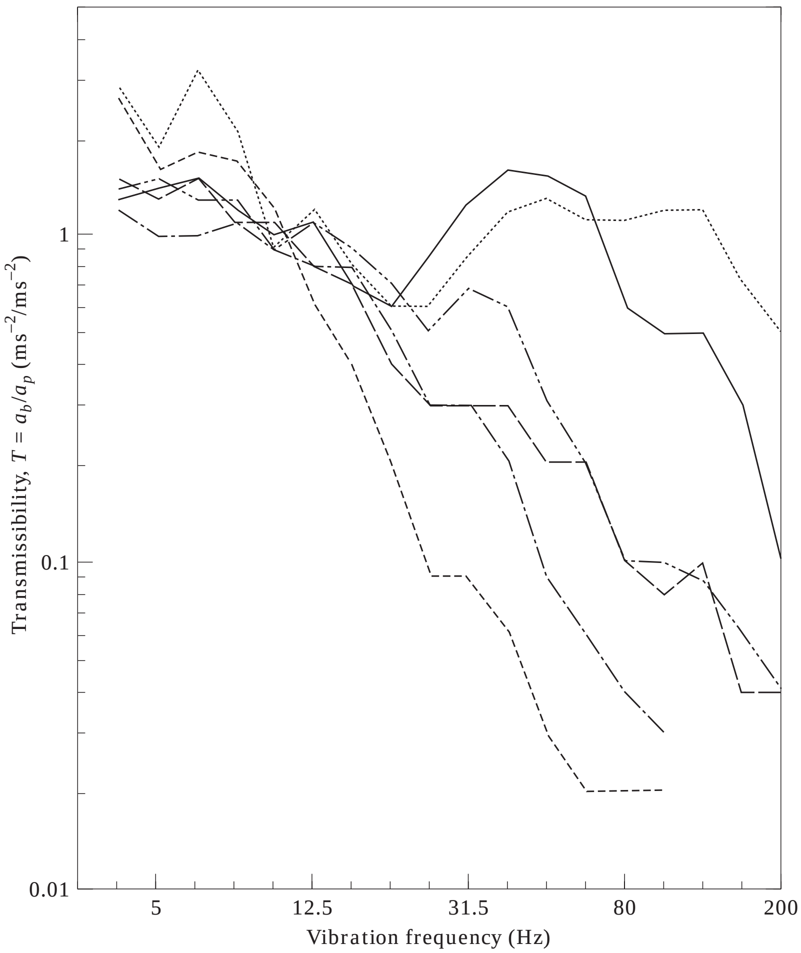

Figure 9. Mean transmissibilities between vertical floor acceleration and body segments acceleration for 10 subjects standing in the posture no. 1. Key: ····, metatarsus; ——, ankle, —‐‐—, knee; — —, hip, ---, shoulder; —‐—, head.

Above 16–20 Hz, the vibration magnitudes being transmitted by the hip, shoulder and head decrease quickly with the increase of frequency. With reference to the 1/3 octave band of 50 Hz the following mean percentage values of the acceleration produced on the vibration table are observed: 2% at the head, 3% at the shoulder and from 8% to 13% at the hip (see Figures 6, 7 and 8). In the frequency region above 25 Hz, the value for the correlation coefficient R^2 is higher than 0·5; that is, more than 50% the variability in transmissibility was due to the postures and the locations of body segments. The influence of postures on transmissibility is most clear for the hip. This is related to the fact that the propagation of vibration happens through the joints connecting long bones of the organism and there are no segments on the way containing soft tissue in which vibration, especially in higher frequencies, is substantially damped. Above the hip, vibration is strongly damped by the organs of the chest and this is why such a clear influence of postures at the level of the shoulder is not observed. A greater effect of postures on transmissibility of vibration to the head was observed in comparison with the effect of postures on transmission of vibration to the shoulder throughout the 20–40 Hz range. In this frequency region the vibration magnitudes were higher at the head than at the shoulder. Dieckman [7] investigated the transmission of vertical set vibration to the different body segments. He found that the magnitude of vibration transmitted to the head was less attenuated at 30 Hz than in the shoulder. This is the resonance frequency range at the head.

Studies of vibration transmission indicate large differences between individuals [6, 10]. In our experiments variations in transmissibility between subjects were on average as large as 6:1 for the vibration propagation from the floor to the ankle, the hip and respectively 8:1 to the metatarsus and the head. The largest differences between subjects were apparent in transmissibility of vibration from the floor to the shoulder. In this case the differences between individuals with the least transmissibility and the highest transmissibility were on average 10:1.

It may be concluded from the study that the postures conducive to vibration damping simultaneously cause the increase of vibration amplification in another frequency region. On the one hand the subject's posture influences the width of the resonance region and on the other hand the range of damping frequencies and effectiveness of vibration damping.

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