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DYNAMIC RESPONSE OF THE STANDING HUMAN BODY EXPOSED TO VERTICAL VIBRATION: INFLUENCE OF POSTURE AND VIBRATION MAGNITUDE

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The influence of the posture of the legs and the vibration magnitude on the dynamic response of the standing human body exposed to vertical whole-body vibration has been investigated. Motions were measured on the body surface at the first and eighth thoracic and fourth lumbar vertebrae (T1, T8 and L4), at the right and left iliac crests and at the knee. Twelve subjects took part in the experiment with three leg postures (normal, legs bent and one leg), and five magnitudes of random vibration (0·125–2·0 ms^{-2} r.m.s.) in the frequency range from 0·5–30 Hz. The main resonance frequencies of the apparent masses at 1·0 ms^{-2} r.m.s. differed between postures: 5·5 Hz in the normal posture, 2·75 Hz in the legs bent posture and 3·75 Hz in the one leg posture. In the normal posture, the transmissibilities to L4 and the iliac crests showed a similar trend to the apparent mass at low frequencies. With the legs straight, no resonance was observed in the legs at frequencies below 15 Hz. In the legs bent posture, a bending motion of the legs at the knee and a pitching or bending motion of the upper-body appeared to contribute to the resonance of the whole body as observed in the apparent mass, with attenuation of vibration transmission to the upper body at high frequencies. In the one leg posture, coupled rotational motion of the whole upper-body about the hip joint may have contributed to the resonance observed in the apparent mass at low frequencies and the attenuation of vertical vibration transmission at high frequencies. The resonance frequency of the apparent mass in the normal posture decreased from 6·75–5·25 Hz with increasing vibration magnitude from 0·125 to 2·0 ms^{-2} r.m.s. This "softening" effect was also found in the transmissibilities to many parts of the body that showed resonances.

1. INTRODUCTION

People experience various types of whole-body vibration in daily life: most commonly through a seat of a vehicle or while walking. In some public transportation, people are exposed to vibration when standing. Such whole-body vibrations could have adverse effects on health, activities and feelings. In order to minimize undesirable influences of vibration on the human body, an understanding of how the body moves when exposed to vibration is needed. Consequently, experimental studies of the biodynamic responses to vibration and impact have been conducted to observe body dynamic behaviour and develop mathematical models representing specific aspects of body response. Even so, the mechanisms of the dynamic responses of the body are not yet fully understood. The complexity of the structure of the human body, difficulties in making measurements, and differences in responses within and between individuals have impeded understanding.

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Two different methods are commonly used to represent the dynamic response of the body: driving-point frequency response functions (the ratios between motion and force at the driving point, e.g., mechanical impedance or apparent mass), and transmissibilities (ratio between two motions measured at distant points). The responses of the seated human body have been investigated with these methods in many studies, but there have been few investigations with standing subjects.

Previous studies in which the mechanical impedance, or the apparent mass, of subjects has been measured while standing in a normal posture during exposure to vertical whole-body vibration have found a main resonance at around 5 Hz [1–3] and, in some subjects, a second broad peak at 10–15 Hz. An exception is a study by Miwa [4] who found resonances at 7 and 20 Hz. A body resonance at about 5 Hz in a standing position is consistent with a resonance at this frequency in a sitting position (see, e.g. reference [5]).

An influence of posture on the driving-point response of standing subjects has been investigated in a few studies. Coermann [1] mentioned that the natural frequency of the mechanical impedance decreased to about 2 Hz with the legs bent, compared to 5·9 Hz when "standing erect with stiff knees posture", although no data were presented. Miwa [4] investigated mechanical impedance in various standing postures. In a "knee-bending" posture, three peaks with similar magnitude were found at 3 Hz (the lowest frequency investigated), at 20 and at 60 Hz. He stated that there was no obvious difference between two upper-body postures, "erect" and "relaxed", when the legs were in an "erect state", although no data were shown. When subjects stood on one leg, a single peak frequency of 5 Hz was lower than the lowest peak frequency in the "erect" posture (i.e., 7 Hz). Miwa also investigated mechanical impedance in other standing postures, such as "standing on heels".

Edwards and Lange [2] measured the mechanical impedance of the standing body at three different vibration magnitudes: 0·2, 0·35 and 0·5 g. One subject showed a decrease in the first resonance frequency (from 5 to 4 Hz) and a decrease in resonance magnitude as the vibration magnitude increased when in a "standing relaxed" posture, although the effect on another subject was within the limits of the accuracy of measurement. A decrease in the main resonance frequency with an increase of the vibration magnitude has been found in studies with the seated body (see, e.g. references [5–7]).

Hagena *et al*. [8] measured the vertical transmissibilities of the standing body from the sacral bone to the head and five points over the spine: the first, fourth and fifth lumbar vertebrae (L1, L4 and L5), the sixth thoracic vertebra (T6) and the seventh cervical vertebra (C7). By using Kirschner-wires (*K*-wires) inserted into the spinous processes with local anaesthesia, direct measurements of the movements of vertebral bodies were obtained. They found three peaks: at 4 Hz (at all the measurement points, particularly marked at L5, L1 and C7), at 8 Hz (with equally large magnitudes at all points), and at 18 Hz. It was said that the peak at 4 Hz corresponded with the entire body mode and that the independent resonance of the spine was represented by the peak at 8 Hz. The transmissibilities of seated subjects were also measured and showed there were small differences between standing and seated bodies.

The transmissibility to the spine of a standing subject exposed to impacts has been measured by Pope *et al*. [9] using the direct measurement method with *K*-wires. A single peak at about 5·5 Hz in the transmissibility to the third lumbar vertebra (L3) in the vertical direction was found when standing in a "rigid erect (at attention)" posture. The effect of posture was investigated and an attenuation of the response, with small peaks at about 2, 6 and 15 Hz, was found in a "knees slightly flexed (at 30°)" posture. It was found that the angle of the pelvis and muscle tone had some effect on the response of L3. There were only minor differences due to different energies of the impact. Herterich and Schnauber

[10] also measured the transmissibility to the spines and heads of standing subjects. By using transducers attached to the skin, the maximum transmissibility in the vertical direction was located at about 8 Hz for the lumbar spine and at 16–20 Hz for the head and cervical spine.

Paddan and Griffin [11], using a bite-bar to measure motion of the head in six axes in standing subjects exposed to vertical floor vibration, reported a distinctive peak at about 5 Hz, particularly in the mid-sagittal plane (i.e., in the vertical, fore-and-aft and pitch axes) in a "legs locked" posture. A "legs unlocked" posture did not change the transmissibilities, but in a "legs bent" posture, a resonance at about 3 Hz appeared in all axes, especially in the mid-sagittal plane. Other studies have shown similar results, but have not considered the potentially large effects of rotational motions on the translational motions of the head (see, e.g., references, [12, 13]).

To establish a better understanding of the dynamic responses of the standing body, more experimental data are obviously required with more subjects and more measurement locations. Data from standing subjects could also be helpful when interpreting studies of the dynamic responses of seated subjects. In this study, the apparent masses and transmissibilities to various body locations of standing subjects were measured. The objectives were to investigate the relation between the driving point response and body motions for subjects standing with different postures of their legs, and to investigate the effect of vibration magnitude on the dynamic response of the standing body.

2. EXPERIMENTAL METHOD

Vibration was measured at six locations on the surface of the body: at the first and eighth thoracic vertebrae (T1 and T8), the fourth lumbar vertebra (L4), the left and right iliac crests, and the knee of the left leg. Two types of piezoresistive accelerometer (Entran EGCSY-240D*-10 and EGA-125F-10D) were used for the measurements. One accelerometer of each type was orientated orthogonally and attached to a stiff paper card, 30 mm (horizontal) by 35 mm (vertical). The combined mass of the card and accelerometers was 12 g. The card was mounted to the skin, by double-sided adhesive tape and surgical tape, over the spinous processes of T1, T8 and L4 to measure the motions in both the vertical (z-axis) and the fore-and-aft (x-axis) directions, and over the left iliac crest to measure the vertical and the lateral (y-axis) motions. For the measurement of the vertical and fore-and-aft motion at the knee, a pair of small accelerometers (Entran EGA-125F-10D) were attached to a smaller card, 20 mm (horizontal) by 30 mm (vertical), weighing 2 g all together, and fixed to the patella of the left leg. A small accelerometer was attached to a 30 by 35 mm card and fixed to the skin over the right iliac crest so as to measure the vertical motion. The combined mass of the card and accelerometer was 2 g.

As shown by Pope *et al*. [14], a motion measured on the body surface over a bone may be modified by the tissue and skin between the bone and the transducer. Accordingly, data correction methods for surface measurements have been developed [15–17]. For these methods it is assumed that the local dynamic system consisting of the tissue and the accelerometer can be analogized with a single-degree-of-freedom linear system. In this study, the method developed by Kitazaki and Griffin [17] was applied. To use their correction method, the natural frequency and damping ratio of the local tissue-accelerometer system at each measurement point and in each direction was derived from the response to free damped oscillations. The method used in this study was identical to that of the former study [17] and was performed before vibration exposures. It was assumed that the behaviour of the local system was not affected by changes in subject posture.

A 1-m stroke electrohydraulic vibrator capable of producing vertical vibration over a wide frequency range from 0·05 to 50 Hz at acceleration levels up to about 10 ms^{-2} with low distortion was used. A force platform, Kistler 9281B, which incorporated four quartz piezoelectric force transducers having closely matched sensitivities, was secured to the vibrator platform to measure the force at the interface between vibrator and standing subjects. The sum of the four signals from the force transducers was obtained. The input motion of the top plate of the force platform, just under the feet of subjects, was measured with an accelerometer (Entran EGCSY-240D*-10).

A computer-generated random signal having a flat constant bandwidth acceleration spectrum over the frequency range of 0·5–30 Hz was fed to the vibrator. Subjects were exposed to this vibration at five different magnitudes, 0·125, 0·25, 0·5, 1·0 and 2·0 ms^{-2} r.m.s., for 60 s. Signals from the 12 accelerometers and the force platform were acquired at 128 samples/s after low-pass filtering at 31·5 Hz.

Twelve healthy male volunteers, median age 28 yr (from 24 to 35 yr), height 1·79 m and weight 73·5 kg, took part in the experiment. The effects of posture on the dynamic response of the standing body were investigated for three postures: (1) normal, (2) legs bent, and (3) one leg. The differences in the postures were in the legs. For the "normal" posture, subjects were ordered to keep their legs straight and locked with 0·3 m separation between their feet. The "legs bent" posture was defined as holding the legs bent so that the knees were vertically above the toes. In the "one leg" posture, subjects stood on their left leg and kept it locked as they did in the "normal" posture. In all postures, subjects were ordered to keep their upper-body in a comfortable and upright position and look forward. For safety purposes, subjects held lightly with both hands to a frame in front of them which was rigidly fixed to the vibrator platform; no subject needed to change upper body position to hold the frame. Measurements were obtained with subjects barefoot so as to eliminate any effects of footwear. Only two different magnitudes of vibration, 0·25 and 1·0 ms^{-2} r.m.s., were used for the "one leg" posture, so a total of 12 conditions completed the experiment.

3. ANALYSIS

The apparent mass, $M(f)$, was calculated by using the "cross spectral density method", that is, by dividing the cross spectral density function between the input acceleration and the resulting force at the driving point, $S_{af}(f)$, by the power spectral density function of the input acceleration, $S_a(f)$:

$$M(f) = S_{af}(f)/S_a(f). \tag{1}$$

A resolution of 0·25 Hz was used for the calculation of spectra. The measured force was caused not only by the body of the subject but also the mass of the top plate of the force platform. The apparent mass measured without a subject, which was identical to the static mass of the top plate, was subtracted from the apparent masses measured with subjects. A large variability in the apparent masses of subjects was partly attributed to their different static masses, as in previous studies with seated subjects (see, e.g., reference [5]). Hence, each apparent mass was normalized by dividing it by the measured value of the apparent mass at 0·5 Hz, which was almost equal to the static weight of the subject. This assisted the comparison of apparent masses across subjects.

Frequency response functions between the acceleration measured at the driving point and those at each measurement point of the body, the transmissibilities, $T(f)$, were also calculated by using the cross spectral density method with a 0·25 Hz resolution:

$$T(f) = S_{io}(f)/S_i(f). \tag{2}$$

Here $S_{io}(f)$ is the cross spectral density between the accelerations at two points and $S_i(f)$ is the power spectral density of the acceleration at the driving point. Each transmissibility was corrected by using the method developed by Kitazaki and Griffin [17], as mentioned above, to reduce the discrepancy between the motion of the skeleton and that measured at the body surface:

$$T_b(f) = C(f)T_s(f), \tag{3}$$

where $T_b(f)$ and $T_s(f)$ are the transmissibilities to the bone and to the surface over the bone, respectively, and $C(f)$ is a correction frequency function defined by the natural frequency and damping ratio of the local tissue–accelerometer system obtained by a free oscillation test:

$$C(f) = \frac{1 - (f/f_0)^2 + 2i\zeta(f/f_0)}{1 + 2i\zeta(f/f_0)}, \tag{4}$$

where f_0 and ζ are the natural frequency and damping ratio of the local system, respectively, and $i^2 = -1$.

The effect of the inclination of the body surface on the measurements seemed to be large at some measurement locations, particularly at the first thoracic vertebrae (T1). The angles of the body surface to the vertical axis were measured and found to range from 28 to 38° at T1 for the 12 subjects. The measured transmissibilities over the spine were therefore compensated linearly by the angles between the body surface and the vertical axis, θ, in the frequency domain:

$$T_x(f) = T_{x1}(f)\cos\theta + T_{z1}(f)\sin\theta, \tag{5}$$

$$T_z(f) = -T_{x1}(f)\sin\theta + T_{z1}(f)\cos\theta, \tag{6}$$

where $T_{x1}(f)$ and $T_{z1}(f)$ are measured transmissibilities in the fore-and-aft and vertical directions, respectively. After the correction, all the vertical transmissibilities over the spine at the lowest frequency were almost unity, which agreed with the expectation that the body would respond rigidly at low frequencies. The correction could reduce the fore-and-aft transmissibility to T1 of a subject from about 0·5 to about 0·1 at the lowest frequencies.

Rotational motions of the pelvis might contribute to the dynamic response of the body. On the assumption that the pelvis is rigid at frequencies investigated in this study, the transmissibilities between vertical floor vibration and the roll of the pelvis were obtained. Roll of the pelvis was calculated by dividing the difference between the vertical transmissibilities to the iliac crests on both sides by the distance between the two measurement points on the assumption that the roll displacement was small.

Pitch motion of the pelvis, which has a large effect on the lordosis of the lumbar spine, might be one of the more important factors affecting the dynamic response of the spine and, consequently, the whole body. Upon assuming that the relative motion between the pelvis and the lower lumbar spine was small enough to be neglected, the transmissibilities for vertical floor vibration to pitch motion of the pelvis were calculated. Pitch motion was obtained by dividing the difference between the mean values of the two vertical motions measured at the iliac crests and the vertical motion at L4 by the distance between the iliac crests and L4 measured in the sagittal plane. The calculation of rotational motion was conducted in the frequency domain.

4. RESULTS

4.1. APPARENT MASS: INFLUENCE OF POSTURE AND VIBRATION MAGNITUDE

The normalized apparent masses and phases of the 12 subjects in the normal standing posture at a vibration magnitude of $1{\cdot}0\ \mathrm{ms}^{-2}$ r.m.s. are shown in Figure 1. Variability between subjects (i.e., inter-subject variability) in the magnitude of the apparent mass was reduced by the normalization so that each curve shows a similar trend. A main resonance at around 5.5 Hz is observed in the normalized apparent mass of most subjects. The frequency and magnitude of the main resonance ranged from 4·0 to 6·0 Hz and from 1·2 to 1·7, respectively, at this vibration magnitude. A local broad peak can also be seen in the frequency range from 9 to 14 Hz, although it is ambiguous for some subjects. Inter-subject variability in the phase at frequencies above 10 Hz was relatively large.

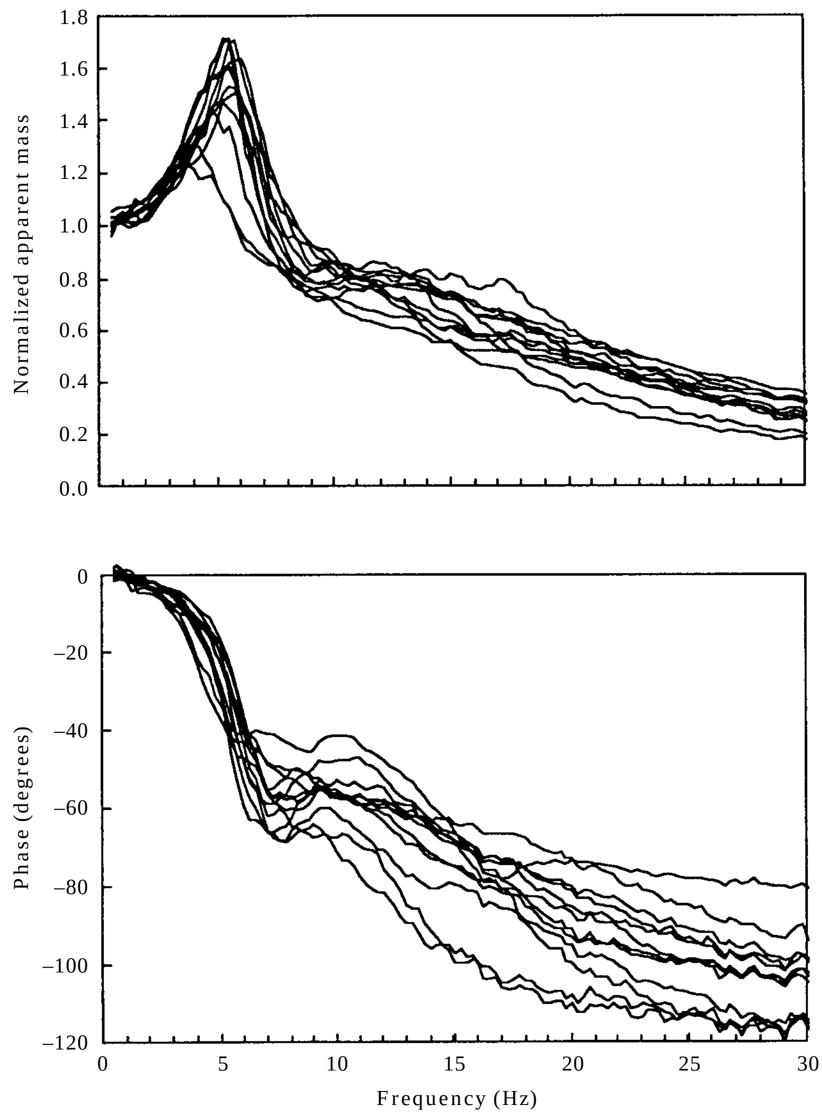

Figure 1. Normalized apparent masses and phases of 12 subjects in the normal standing posture at $1{\cdot}0\ \mathrm{ms}^{-2}$ r.m.s.

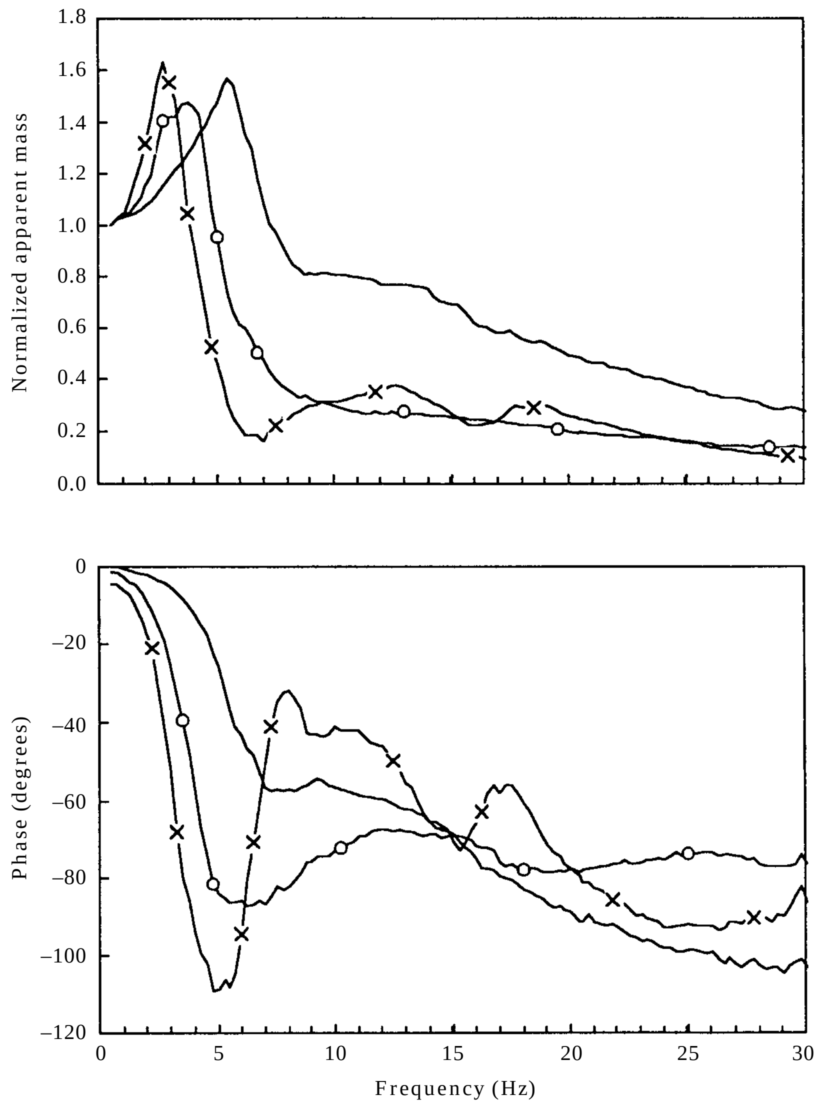

Figure 2. Median normalized apparent masses and phases from 12 subjects in three postures at 1·0 ms^{-2} r.m.s. ——, normal posture; —×—, legs bent posture; —○—, one leg posture.

There was an appreciable effect of leg posture on the apparent mass. Median normalized apparent masses and phases from the 12 subjects in three postures at 1·0 ms^{-2} r.m.s. are shown in Figure 2. With respect to the main resonance, both the legs bent and the one leg posture caused a decrease in frequency: a peak at 2·75 Hz in the legs bent posture and at 3·75 Hz in the one leg posture, compared to 5·5 Hz in the normal posture. These differences in the main resonance frequency were also observed in individual data at all vibration magnitudes and found to be statistically significant ($p < 0{\cdot}01$, Wilcoxon matched-pairs signed ranks test). However, there was no significant influence of posture on the magnitude of the apparent mass at the main resonance frequency. Two small broad peaks at about 13 and 18 Hz and troughs at around 7 and 16 Hz were seen in both the median and the individual apparent mass data in the legs bent posture. However, no obvious peaks, except for the main one, were found for the one leg posture.

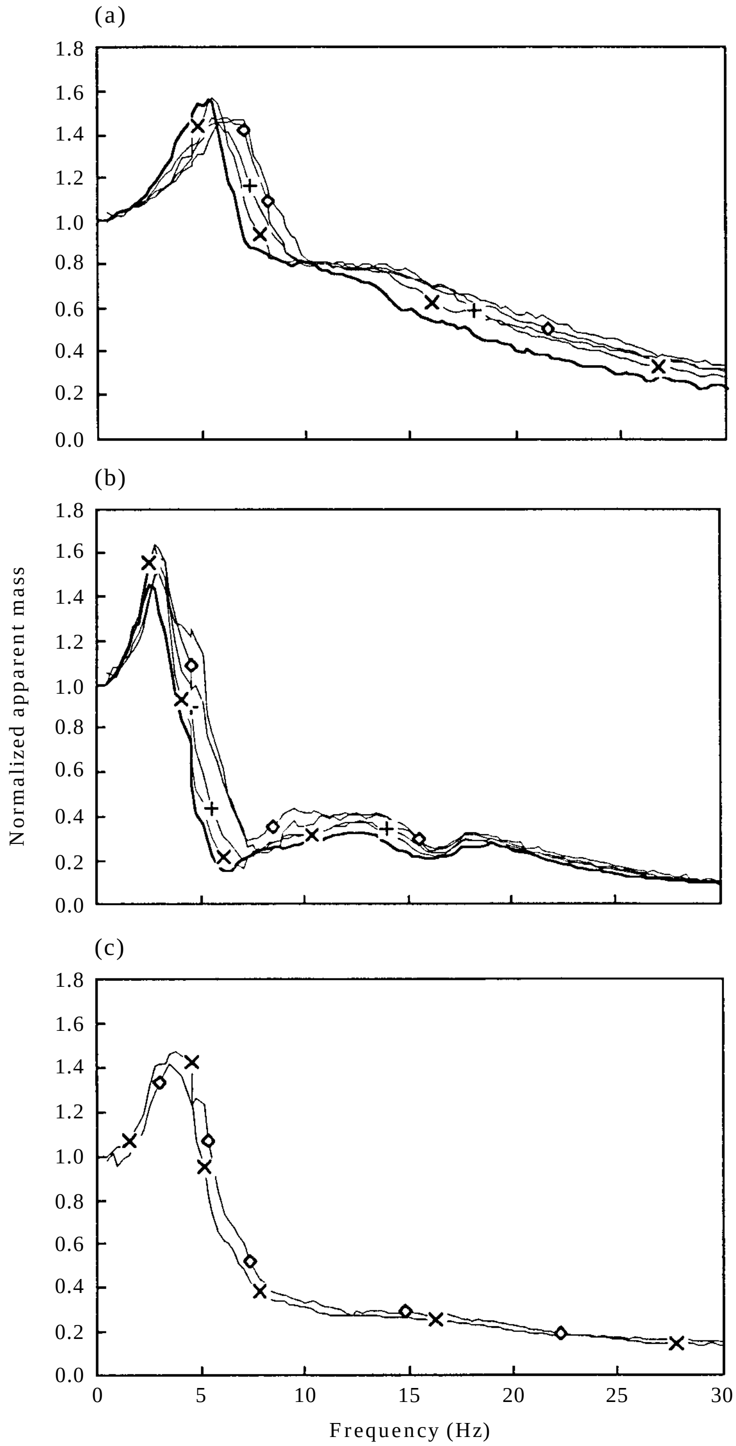

Figure 3. Median normalized apparent masses at different vibration magnitudes. (a) Normal posture; (b) legs bent posture; (c) one leg posture. ms^{-2} r.m.s. values; ——, 0·125 ms^{-2} r.m.s.; —◇—, 0·25; —+— , 0·5 ms^{-2} r.m.s.; —×—, 1·0; ——, 2·0.

Figure 3 shows median normalized apparent masses in the three postures at different vibration magnitudes. In the normal standing posture, a decrease in the frequency of the main resonance was caused by increasing vibration magnitude: from 6·75 Hz at 0·125 ms^{-2} r.m.s. to 5·25 Hz at 2·0 ms^{-2} r.m.s. in the median curves (Figure 3(a)). The decrease in the resonance frequency with each increase in the vibration magnitude was statistically significant ($p < 0{\cdot}05$, Wilcoxon matched-pairs signed ranks test), except for the increase from 0·125 to 0·25 ms^{-2} r.m.s. An influence of the vibration magnitude on the resonance magnitude was not found. The frequency of the broad peak at around 12 Hz also seemed to decrease as the vibration magnitude increased. A decrease in the main resonance frequency with an increase in the vibration magnitude can also be seen in the legs bent posture, from 3·0 Hz at 0·125 ms^{-2} r.m.s. to 2·5 Hz at 2·0 ms^{-2} r.m.s., although this is not so clear as in the normal posture (Figure 3(b)). In the legs bent posture, Friedman two-way analysis of variance showed a significant difference between the resonance frequencies at the five different magnitudes ($p < 0{\cdot}005$). By Wilcoxon matched-pairs signed ranks tests, only the difference between 0·25 and 0·5 ms^{-2} r.m.s. was statistically significant ($p < 0{\cdot}05$). There was not found to be any significant effects of the vibration magnitude on the apparent mass in the one leg posture (Figure 3(c)).

4.2. TRANSMISSIBILITY IN NORMAL STANDING POSTURE

The transmissibilities from the floor to each measurement point on the bodies of the 12 subjects in the normal posture at 1·0 ms^{-2} r.m.s. are shown in Figure 4. The phases of the transmissibilities in the vertical direction are presented in Figure 5. Because of the limitation of the data correction method, which is not effective above the natural frequency of the local tissue-accelerometer system [17], transmissibility data are presented at frequencies below 20 Hz. Relatively large inter-subject variability can be seen in the transmissibilities to some measurement points, compared to the variability in the normalized apparent masses. The main peak frequency of the transmissibility to the fourth lumbar vertebra in the vertical direction, for example, varied in the range between 5·5 and 9·75 Hz across subjects, although in ten subjects it was found below 7 Hz (Figure 4(e)). The transmissibility to the knee in the vertical direction showed a large variability at high frequencies (Figure 4(i)).

When subjects stood in the normal posture, transmissibilities to the pelvis and the lower lumbar spine in the vertical direction had a similar trend to the apparent mass (Figures 1 and 4 (e), (g), (h)). Most transmissibilities to the spine (T1, T8 and L4) in both the vertical and fore-and-aft directions show a peak at around 6 Hz, close to the main resonance frequencies of the apparent masses for most subjects in this posture (Figure 4 (a)–(f)). The transmissibilities to the thoracic vertebrae, T1 and T8, in the vertical direction were similar and remained about unity at high frequencies, even though those to the lumbar vertebra (L4) were greater at low frequencies and decreased below unity at high frequencies. The phase lags at T1 and T8 were also similar while those at L4 were much larger above 6 Hz (Figure 5).

4.3. INFLUENCE OF POSTURE ON TRANSMISSIBILITY TO PELVIS REGION

When subjects stood on one leg, the dynamic response of the pelvis region was different from when they stood on both legs (Figure 6). In the vertical direction, the transmissibilities to both sides of the iliac crests were similar to that to the fourth lumbar vertebra (L4) in both the normal and the legs bent postures (Figures 6(a) and (b)). However, when subjects stood on their left leg, the transmissibility to the right iliac crest was much larger at the resonance frequency, 2·63 at 4·25 Hz (median), than that to the left iliac crest and L4, 1.32 and 1.57, respectively, at the same frequency (Figure 6(c)).

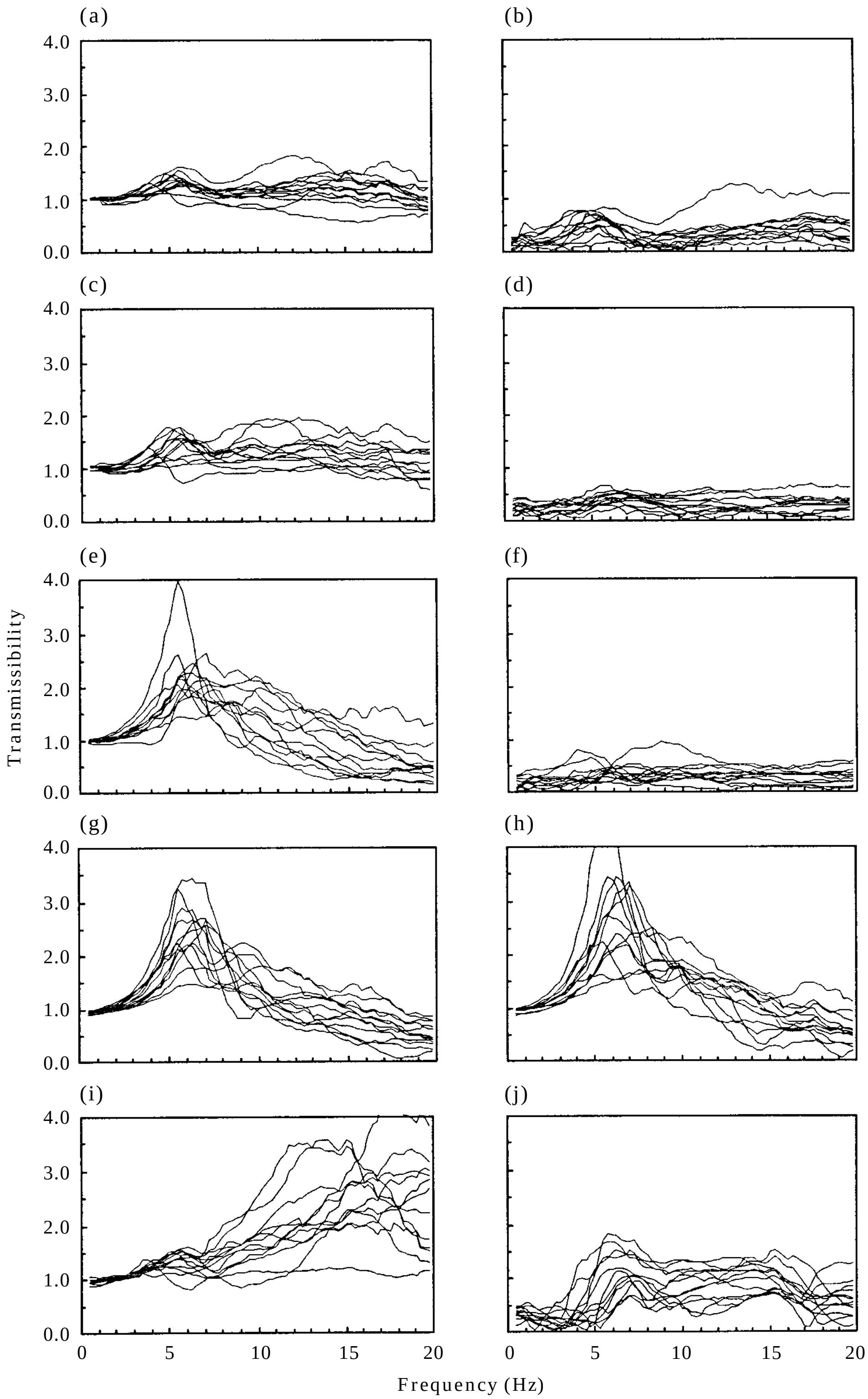

Figure 4. Transmissibilities to each measurement point of 12 subjects, in the normal posture at 1·0 ms^{-2} r.m.s. (a) T1 vertical; (b) T1 fore-and-aft; (c) T8 vertical; (d) T8 fore-and-aft; (e) L4 vertical; (f) L4 fore-and-aft; (g) left iliac crest vertical; (h) right iliac crest vertical; (i) knee vertical; (j) knee fore-and-aft.

Figure 7 shows the transmissibilities from vertical floor vibration to roll motion of the pelvis for twelve subjects in three postures at $1{\cdot}0\ \mathrm{ms}^{-2}$ r.m.s., calculated by the method mentioned above. It is clear that there were significant roll motions of the pelvis when standing in the one leg posture compared to the normal and legs bent postures: an increase in roll at the lowest frequencies and a peak region between 4 and 10 Hz.

The transmissibilities to pitch motion of the pelvis, particularly in the normal and the one leg postures, show a large variability between subjects (Figure 8). In the normal posture, the transmissibilities for nine of the subjects show a peak at frequencies below 10 Hz, although some had a greater peak at high frequencies (Figure 8(a)). It can be seen that pitch motion occurred at frequencies above about 5 Hz. However, because of the large inter-subject variability, it is difficult to identify general characteristics of the calculated pitch motion of the pelvis. The variability between subjects in the legs bent posture was smaller (Figure 8(b)). A peak at 3–4 Hz where the resonance of the apparent mass was located was clear in the transmissibilities for most subjects. In addition, two troughs at about 7 and 16 Hz were consistent, and could be found in both the apparent mass and in the transmissibilities to vertical motion at the thoracic vertebrae (Figures 3(b) and 8(b)).

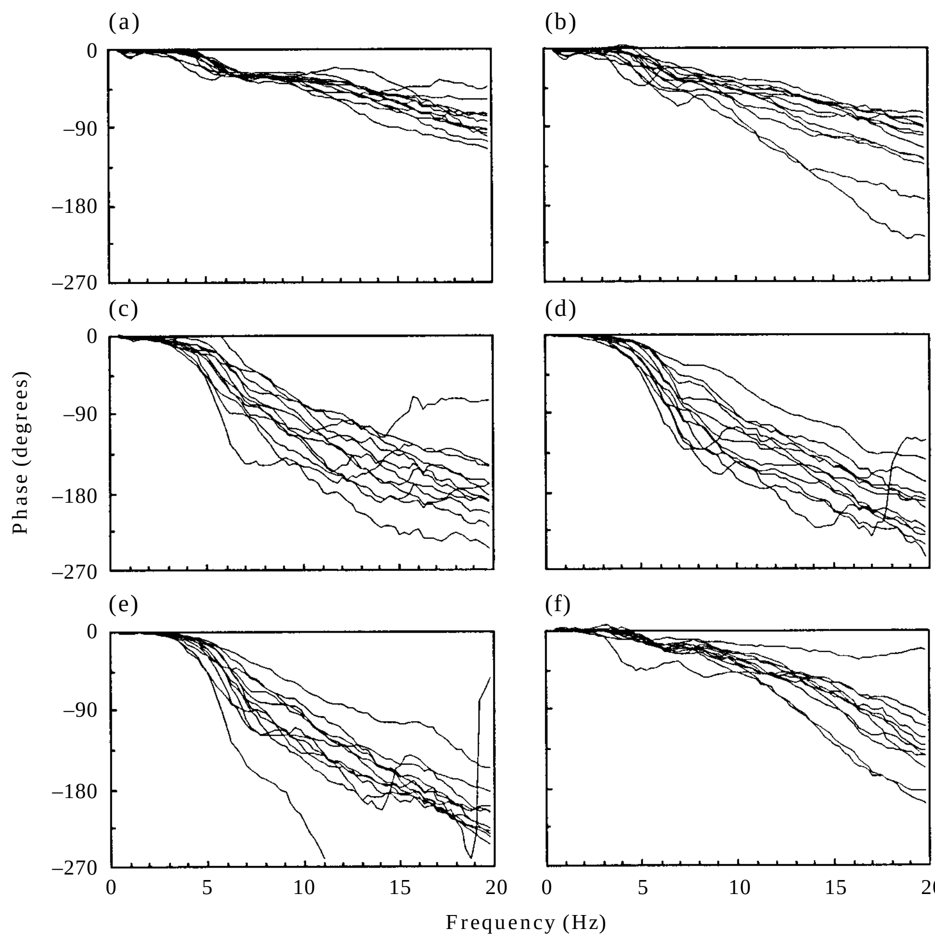

Figure 5. Phases of transmissibilities in the vertical direction of 12 subjects in the normal positive at $1{\cdot}0\ \mathrm{ms}^{-2}$ r.m.s. (a) T1; (b) T8; (c) L4; (d) left iliac crest; (e) right iliac crest; (f) knee.

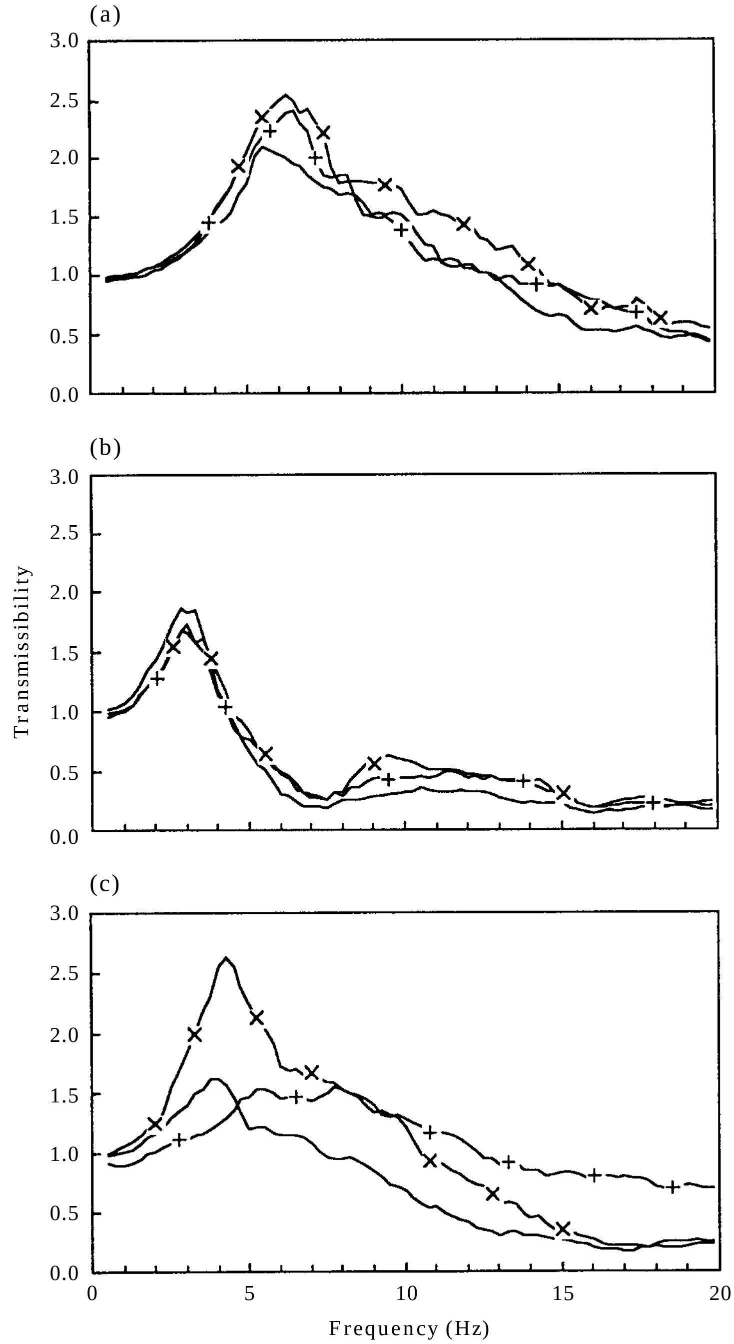

Figure 6. Median vertical transmissibilities to the pelvis region at 1·0 ms^{-2} r.m.s. (a) Normal posture; (b) legs bent posture; (c) one leg posture. ——, L4; —×— , right iliac crest; —+— , left iliac crest.

Some transmissibilities had relatively large magnitudes at high frequencies. The transmissibilities to pitch motion of the pelvis in the one leg posture tended to have greater magnitudes than those in the other postures for all subjects (Figure 8c). Relative movements between the pelvis and L4, resulting from lateral bending or roll motion of

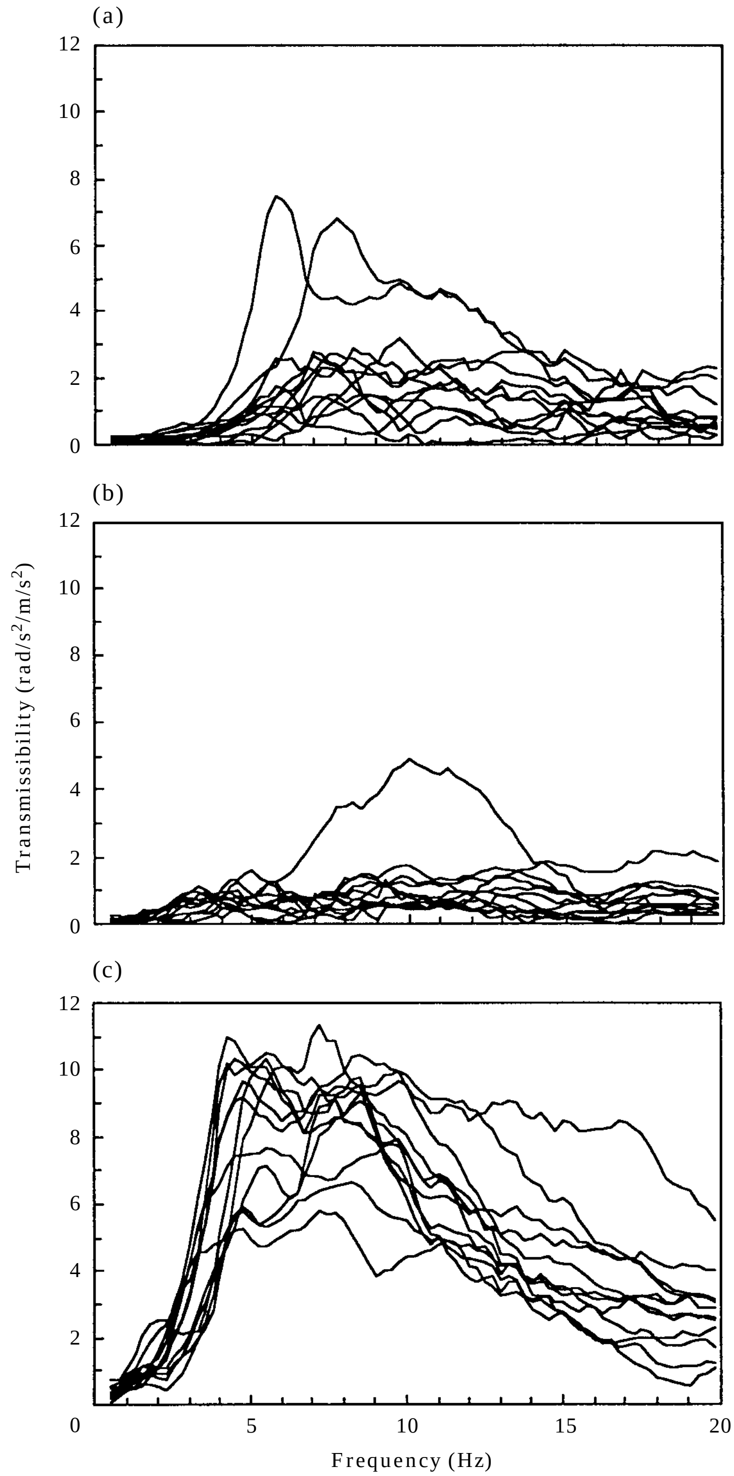

Figure 7. Transmissibilities to roll motion of the pelvis of 12 subjects at 1·0 ms^{-2} r.m.s. (a) Normal posture; (b), legs bent posture; (c) one leg posture.

the lumbar spine due to roll motion of the pelvis, may have affected the calculated pitch motion.

4.4. INFLUENCE OF POSTURE ON TRANSMISSIBILITY TO SPINE

The transmissibilities measured over the spine showed a peak at about the resonance frequency of the apparent mass in both the legs bent and the one leg postures, as for the normal posture (Figure 9). In the legs bent posture, there was substantial fore-and-aft motion over the spine at about 3 Hz, the resonance frequency of the apparent mass, which was greatest at T1 (Figure 9(d)). This implies a rocking or bending motion of the upper-body about the hip joint. In the legs bent posture, the vertical transmissibilities to the vertebrae at frequencies above about 7 Hz, where a trough was found for each measurement point, were much less than those in the normal posture. In the high frequency range, the transmissibilities in the vertical direction to the thoracic vertebrae, T1 and T8, were greater than to the lumbar spine, which showed greater transmissibility at around 3 Hz, the same trend as found in the normal posture. The vertical transmissibilities to the three measurement points over the spine in the one leg posture were almost identical at frequencies below 5 Hz (Figure 9(e)). This was also found in most individual data, although the data are not presented. In the one leg posture, the vertical transmissibilities to the thoracic vertebrae at high frequencies were much less than those in the normal posture.

4.5. INFLUENCE OF POSTURE ON TRANSMISSIBILITY TO KNEE

Figure 10 shows the median transmissibilities to the knee in the vertical and fore-and-aft directions at $1{\cdot}0\ \mathrm{ms}^{-2}$ r.m.s. in the three postures. There was a principal peak at about 3 Hz in the transmissibilities to the knee in the fore-and-aft direction in the legs bent posture (Figure 10(b)). A significant bending motion of the legs at the knee may have occurred at this frequency. In both the normal and the one leg postures, there was a peak in the vertical transmissibilities to the knee at around the resonance frequency of the apparent mass, although the peak magnitude was small compared to that of the transmissibilities to L4 and the pelvis (Figures 6 (a), (c) and 10(a)). These vertical transmissibilities to the knee tended to increase with increasing frequency. The fore-and-aft transmissibilities in these postures increased above unity at the resonance frequency of the apparent mass (Figure 10(b)).

4.6. INFLUENCE OF VIBRATION MAGNITUDE ON TRANSMISSIBILITY

An effect of vibration magnitude was found in the transmissibilities to the lower upper-body in all postures. As found in the apparent mass, the peak frequency of the vertical transmissibility to L4 in the normal posture decreased with increasing vibration magnitude (Figure 11(a)). The differences in the peak frequencies were statistically significant ($p < 0{\cdot}05$, Wilcoxon matched-pairs signed ranks tests), except for that between $0{\cdot}125$ and $0{\cdot}25\ \mathrm{ms}^{-2}$ r.m.s. The peak frequency of the vertical transmissibility to L4 in the legs bent posture was affected by changes in vibration magnitude in the same manner as in the case of the normal posture (Figure 11(b)). However, statistically significant differences were found only between $0{\cdot}125$ and $0{\cdot}25\ \mathrm{ms}^{-2}$ r.m.s. and between $0{\cdot}25$ and $0{\cdot}5\ \mathrm{ms}^{-2}$ r.m.s. ($p < 0{\cdot}05$). The peak frequency of the transmissibility to the right iliac crest in the one leg posture also decreased with increasing vibration magnitude from $0{\cdot}25$ to $1{\cdot}0\ \mathrm{ms}^{-2}$ r.m.s. ($p < 0{\cdot}01$), although no clear effect of the vibration magnitude on the apparent mass was found in this posture (Figure 11(c)).

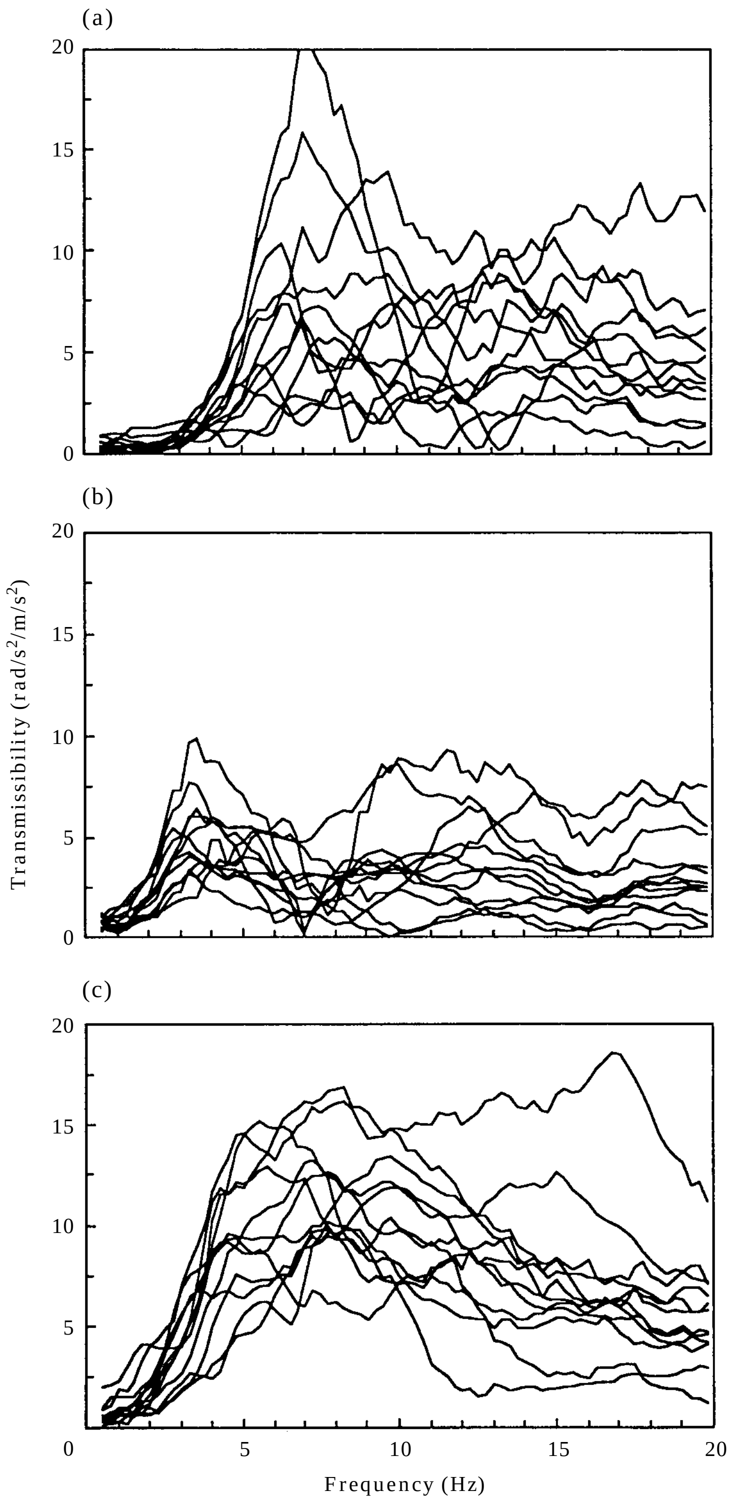

Figure 8. As Figure 7 but transmissibilities to pitch motion.

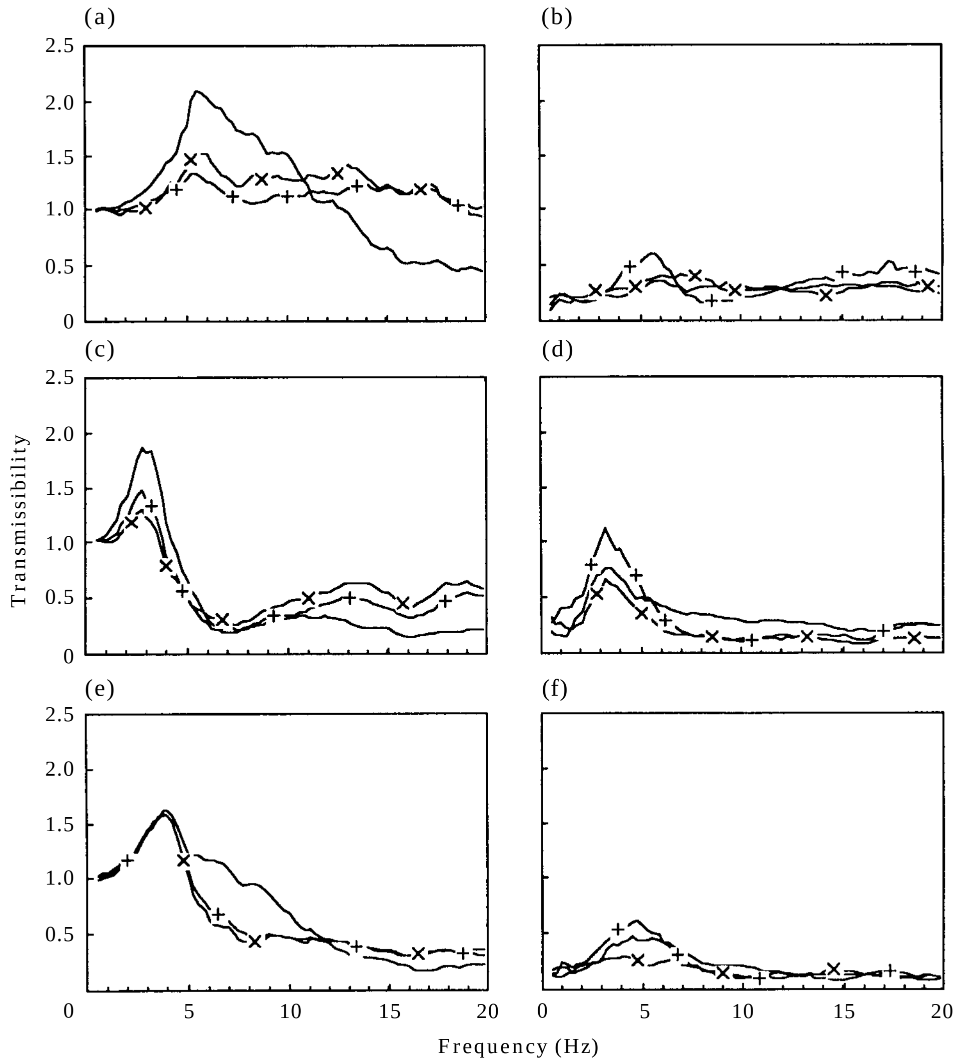

Figure 9. Median transmissibilities to the spine in the vertical and fore-and-aft directions at $1{\cdot}0\ \mathrm{ms}^{-2}$ r.m.s. (a) Normal, vertical; (b) normal, fore-and-aft; (c) legs bent, vertical; (d) legs bent, fore-and-aft; (e) one leg, vertical; (f) one leg, fore-and-aft. ——, L4; —×—, T8; —+—, T1.

The transmissibilities to the knee were also affected by changes in vibration magnitude. In the normal posture, the vertical transmissibilities to the knee at 10 Hz increased with increasing vibration magnitude ($p < 0{\cdot}05$ for the differences between 0·125 and $0{\cdot}25\ \mathrm{ms}^{-2}$ r.m.s. and between 0·5 and $1{\cdot}0\ \mathrm{ms}^{-2}$ r.m.s., Figure 11(d)). This implies either decreases in the main peak frequency or increases in the main peak transmissibility, because the main peaks of the transmissibilities were located above 10 Hz (see Figure 4(i) and 10(a)). The effect of the vibration magnitude on the transmissibility to the knee in the fore-and-aft direction in the legs bent posture was similar to that on the apparent mass (Figure 10(e)). The peak frequency tended to decrease as the vibration magnitude increased, although statistical significance was found only between 0·25 and $0{\cdot}5\ \mathrm{ms}^{-2}$ r.m.s. ($p < 0{\cdot}05$), as in the case of the apparent mass.

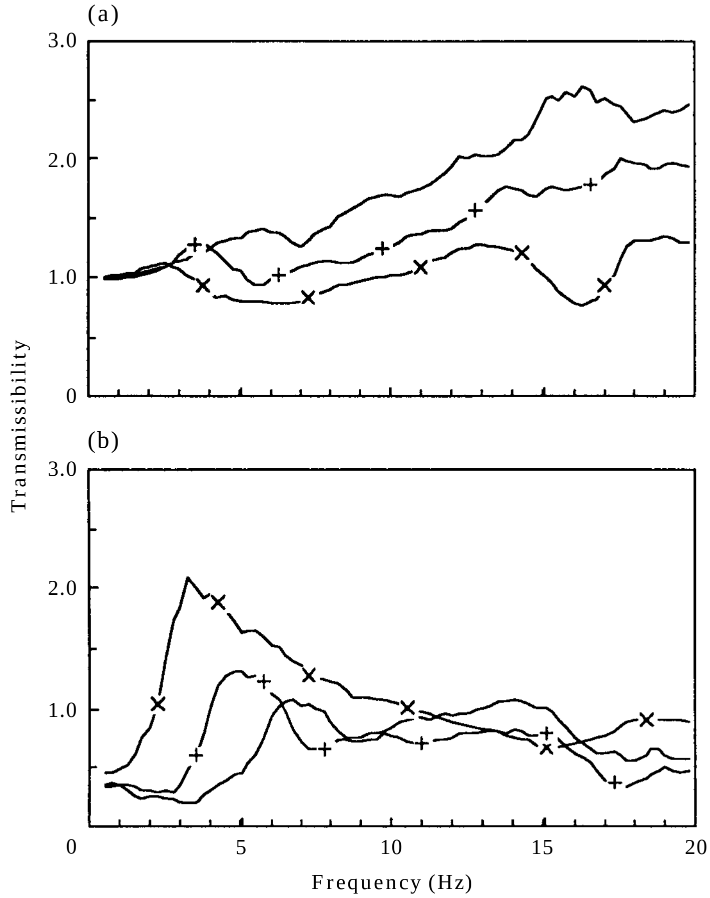

Figure 10. Median transmissibilities to the knee in the vertical (a) and fore-and-aft (b) directions at 1·0 ms^{-2} r.m.s.——, Normal posture; —×—, legs bent posture; —+—, one leg posture.

5. DISCUSSION

The apparent mass of each subject when standing normally showed a main peak at around 5 Hz. This is consistent with previously reported resonance frequencies for both the mechanical impedance and the apparent mass of subjects in similar standing postures (see, e.g., references, [1–3]). The resonance frequency in the normal standing posture found in this study was also close to that of the seated body measured in many studies [5]. This implies that the same dynamic mechanism of the upper body may contribute to the main resonance of the driving point responses of both standing and seated people. In addition, the frequency range of a second broad peak in the apparent mass is similar when standing and when seated. It is, therefore, likely that there is no resonance in the legs held straight that affects the driving point response to vertical vibration at frequencies below about 15 Hz. A small peak in the vertical transmissibility to the knee at around the resonance frequency of the apparent mass may be caused by the motion transmitted from the lower upper-body (Figure 4(i) and 10(a)). An increase in vibration transmission to the knee was found with increases in frequency above 5 Hz (Figures 4(i) and (j)).

Several studies of the dynamic response of the lumbar spines of seated subjects to either vibration or impact have reported a peak response at around 5 Hz (e.g. references [18, 19]), which is close to previously reported resonance frequencies for the mechanical impedance and the apparent mass (see, e.g., references [1, 5]). For many subjects used in the present study, vertical transmissibility to the fourth lumbar vertebra (L4) showed a prominent peak at a frequency close to the resonance frequency of the apparent mass in all three postures (see Table 1). Kendall correlation coefficients between the peak frequencies of the transmissibility to L4 and the resonance frequencies of the apparent mass were found to be quite high: 0·462 ($p = 0{\cdot}053$) in the normal posture, 0·720 ($p = 0{\cdot}010$) in the legs bent posture, and 0·600 ($p = 0{\cdot}011$) in the one leg posture. In the legs bent posture, the transmissibilities to the iliac crests also had a peak at the same frequency as that of the

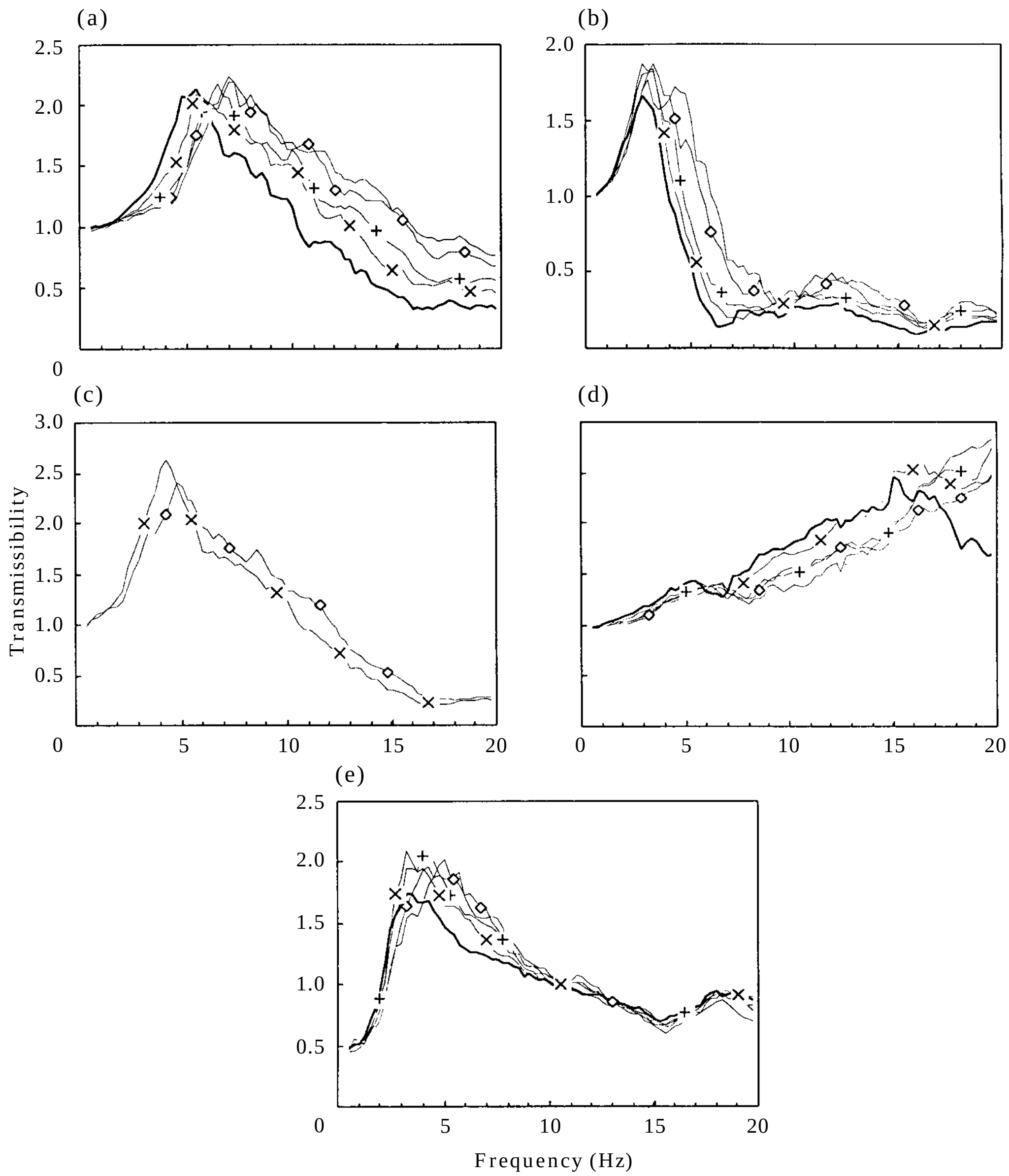

Figure 11. Median transmissibilities at different vibration magnitudes. (a) L4 vertical normal; (b) L4 vertical knees bent; (c) right iliac crest vertical, one leg; (d) knee vertical, normal; (e) knee fore-and-aft, legs bent. ms^{-2} r.m.s. values: ——, 0·125; —◇—, 0·25; —+—, 0·5; —×—, 1·0, ——, 2·0.

TABLE 1

Medians and quartiles of the peak frequencies of the apparent masses and the transmissibilities to the pelvis region at $1\cdot0\ ms^{-2}$ *r.m.s. and Kendall correlation coefficients between the peak frequency of the apparent mass and that of the transmissibilities* ($^*p < 0\cdot05$, $^{**}p < 0\cdot01$)

	Apparent mass	L4	Right iliac crest	Left iliac crest
Normal				
25 % (Hz)	5·14	5·70	5·76	5·95
Median (Hz)	5·51	5·89	6·51	6·51
75 % (Hz)	5·57	7·01	7·14	7·01
Correlation	—	0·462	0·050	−0·017
(Significance)		($p = 0\cdot053$)	($p = 0\cdot831$)	($p = 0\cdot943$)
Legs bent				
25 % (Hz)	2·75	2·75	2·75	2·75
Median (Hz)	2·75	2·75	2·75	2·75
75 % (Hz)	2·75	3·26	3·26	3·26
Correlation	—	0·720*	0·777**	0·786**
(Significance)		($p = 0\cdot010$)	($p = 0\cdot004$)	($p = 0\cdot004$)
One leg				
25 % (Hz)	3·26	3·20	4·01	5·51
Median (Hz)	3·76	3·76	4·26	6·51
75 % (Hz)	4·07	4·57	4·39	7·89
Correlation	—	0·600*	0·547	−0·464*
(Significance)		($p = 0\cdot011$)	($p = 0\cdot024$)	($p = 0\cdot043$)

apparent mass. This implies that the dynamic mechanisms producing increased motion at the lower spine may make a significant contribution to the resonance of the whole body. It is likely that the motion of the lower spine is closely related to that of the pelvis: the trends in the transmissibilities to the iliac crests were almost the same as those to L4 up to the peak frequency, when standing on both legs (Figures 6(a) and (b)).

Peaks in transmissibilities to the thoracic vertebrae at around 5 Hz were not so remarkable as those in the transmissibilities to the lumbar vertebra at this frequency. The transmissibilities to two measurement points over the thoracic spine (at T1 and T8) were found to be similar to each other but different from that to the lumbar spine, in both the normal posture and in the legs bent posture (Figure 4). The transmissibilities between adjacent measurement points over the spine in the vertical axis were calculated to investigate motions within the spine (Figure 12). It is clear that there was little amplification or attenuation of vertical motion between the first and eighth thoracic vertebrae (T1 and T8) for most subjects in all the postures: the transmissibility was almost unity over the frequency range used.

The transmissibility from the fourth lumbar vertebra to the eighth thoracic vertebra suggested that larger relative motions occurred in the lower spine than in the upper spine (Figures 12(a), (c) and (e)). The difference in the transmissibilities between subjects were small at low frequencies in all the postures. The magnitudes of the transmissibilities in the normal posture and in the legs bent posture decreased from unity as the frequency increased up to about the resonance frequency of the apparent mass: the vertical motion measured at L4 was greater than that at T8. However, as Sandover and Dupuis [20] and Hinz *et al*. [21] stated, axial motion of lumbar vertebrae may be accompanied by rotational

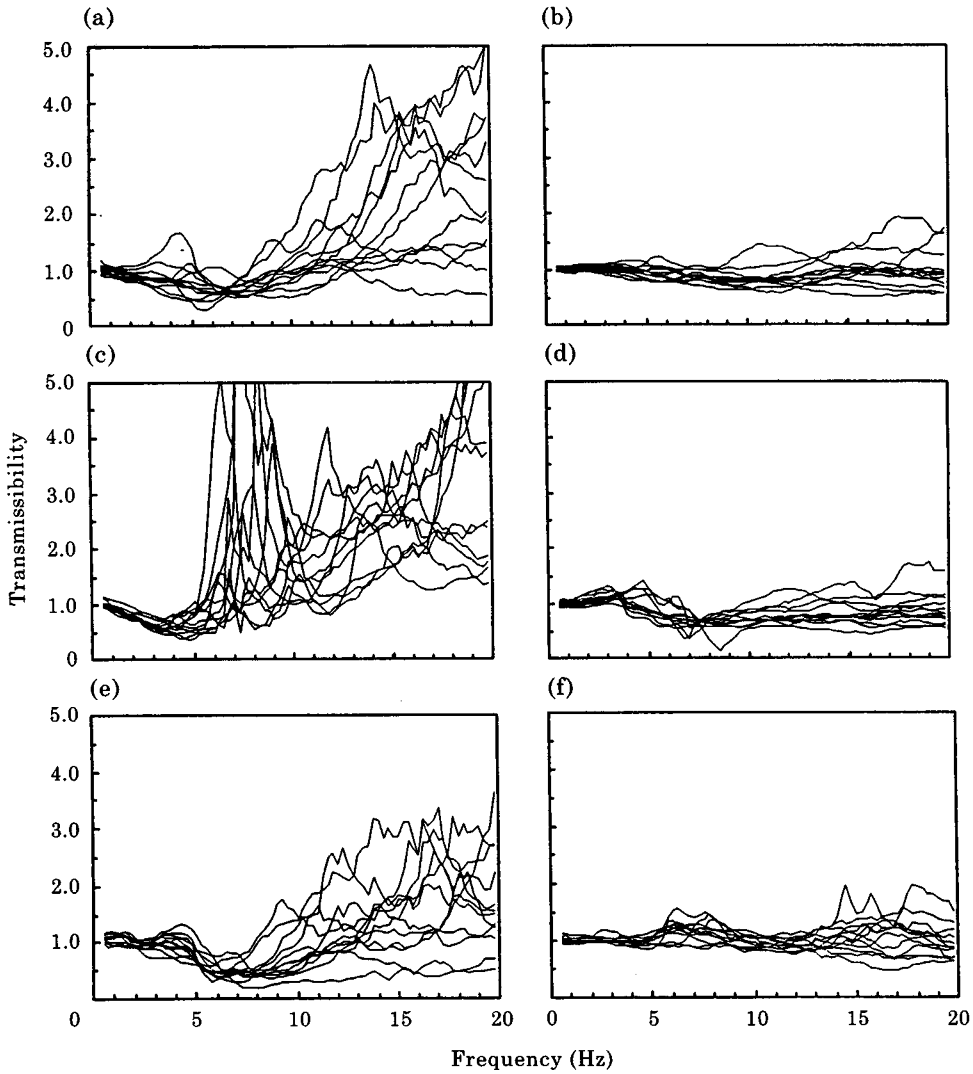

Figure 12. Transmissibilities between two points over the spines of 12 subjects at 1·0 ms^{-2} r.m.s. (a) T8/L4, normal posture; (b) T1/T8, normal posture; (c) T8/L4, legs bent; (d) T1/T8, legs bent; (e) T8/L4, one leg; (f) T1/T8, one leg.

motion that affects measurements over the spinous process of L4: a pitch motion of the vertebral body could have been measured as a vertical motion. The pitch motion could result from bending of the lumbar spine. If the lumbar spine flexed during upward movement of the floor, the spinous process of L4 would move upward more than the vertebral body of L4. There may be smaller rotational motions of the vertebral bodies in the thoracic region if the rib cage connected to thoracic vertebral bodies restricts relative rotational motion between adjacent vertebrae. Therefore, the relative motion found between L4 and T8 at low frequencies possibly arose from either a greater axial motion at L4 than that at T8, or a rotational motion of L4 while vertical motions of the vertebral bodies at L4 and T8 may have been similar, or both. It was not possible to separate vertical and rotational motions of the vertebral body by the measurement method used. In the one leg posture, the transmissibility between L4 and T8 remained unity up to the resonance frequency of the apparent mass, as did the transmissibility between T8 and T1.

A large inter-subject variability in the vertical transmissibilities between L4 and T8 was found at high frequencies for all postures (Figures 12(a), (c) and (e)). This large variability might be caused not only by the difference in the response itself but by small "input" motions at L4 not being accurately resolved. The very high variability in the transmissibility between L4 and T8 in the legs bent posture at around 7 Hz was also caused by little motion at L4 (Figure 12(c)). At high frequencies, the vertical motion measured at L4, in the lower part of the spine, was consistently smaller than that at T1 and T8, in the higher parts of the spine, for most subjects, although the variability was large. In addition, the phase lags in the transmissibilities from the floor to L4 were much larger than the phase lags to T1 and T8 in this frequency range (Figure 5, for the normal posture). It seems unlikely that the axial motions of the vertebrae were different enough to produce such a large relative motion and phase lag between the thoracic and lumbar spine. It may be hypothesized that vertical motion of the vertebral body is partially cancelled by a rotational motion which is out of phase with the vertical motion in this frequency range. It may also be hypothesized that in this frequency range the region around L4 tends to be a nodal point of the dynamic response of the standing body, where the effects of more than one vibration mode cancel each other due to the phase differences between the modes.

6. CONCLUSIONS

In a normal standing posture, with a vibration magnitude of $1{\cdot}0\ \mathrm{ms}^{-2}$ r.m.s., there is a main resonance of the apparent mass of the human body at about 5·5 Hz, with a second broad resonance in the range 9–14 Hz. Almost all transmissibilities to the spine measured in both the vertical and fore-and-aft directions showed a peak at almost the same frequency as that of the apparent mass, while some peaks, particularly in the fore-and-aft direction, were small. Transmissibilities to the fourth lumbar vertebra (L4) in the vertical direction, in particular, had a clear peak at this frequency. The relative vertical motions between two points within the thoracic spine (at T1 and T8) were smaller than the relative vertical motions between the thoracic and the lumbar spine (at T8 and L4) over the frequency range up to 20 Hz. Vertical transmissibilities to the iliac crests had similar trends to the transmissibilities to L4, although the peak frequencies for the iliac crests were slightly higher. Pitch motion of the pelvis, which might alter the lordosis of the lumbar spine and cause motion of the lumbar vertebrae, occurred at frequencies somewhat above 5 Hz. No resonance in the legs held straight that affected the apparent mass was found at frequencies below 15 Hz.

When the legs were bent, with a vibration magnitude of $1{\cdot}0\ \mathrm{ms}^{-2}$ r.m.s., the resonance frequency of the apparent mass decreased to about 2·75 Hz. There was a trough in the apparent mass at around 7 Hz and low magnitudes above 7 Hz, compared to those in the normal posture. The peak frequencies of the transmissibilities to L4 and the iliac crests were strongly correlated with the resonance frequency of the apparent mass. At the resonance frequency of the apparent mass in this posture, the fore-and-aft motions at the knee and at T1 were much greater than those in the other postures. A bending motion of the legs at the knee, which is probably coupled with a pitching or bending motion of the whole upper body about the hip joint, may be the cause of the resonance of the whole body. A bending motion of the legs also attenuated the vibration transmission to the upper body at frequencies well above the natural frequency of the bending mode, at about 3 Hz.

When subjects stood on one leg, with a vibration magnitude of $1{\cdot}0\ \mathrm{ms}^{-2}$ r.m.s., a main resonance of the apparent mass appeared at about 3·75 Hz, with no other distinguishable peaks at frequencies below 30 Hz. The vertical transmissibilities to three measurement points over the spine were almost identical up to 5 Hz, which implied that the upper-body tended to move as a whole. Both roll and pitch motions of the pelvis in the one leg posture were relatively large, particularly at frequencies below 10 Hz, compared to those in the other postures when standing on both legs. Coupled rotational motions about the hip joint may cause a whole upper-body movement at low frequencies, rather than a resonance of local body parts, and attenuate vertical vibration transmission at high frequencies.

The main resonance frequency of the apparent mass in the normal posture decreased from 6·75 Hz to 5·25 Hz as the vibration magnitude increased from 0·125–2·0 ms^{-2} r.m.s. This "softening" effect was also found for the second broad peak in the apparent mass for most subjects, as well as in the transmissibilities to most parts of the body where a clear peak was evident. The resonance frequency of the apparent mass in the legs bent posture also tended to decrease with an increase in vibration magnitude, although the change was small: 3·0 Hz at 0·125 ms^{-2} r.m.s. to 2·5 Hz at 2·0 ms^{-2} r.m.s. A similar effect was found in the transmissibility to the knee in the fore-and-aft direction which might be responsible for the resonance seen in the apparent mass. In the one leg posture, the "softening" effect was found to be significant in the transmissibility to the pelvis, although the influence of vibration magnitude on the apparent mass was not statistically significant.

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