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COMPARISON OF BIODYNAMIC RESPONSES IN STANDING AND SEATED HUMAN BODIES

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The dynamic responses of the human body in a standing position and in a sitting position have been compared. The apparent mass and transmissibilities to the head, six locations along the spine, and the pelvis were measured with eight male subjects exposed to vertical whole-body vibration. In both postures, the principal resonance in the apparent mass occurred in the range 5–6 Hz, with slightly higher frequencies and lower apparent mass in the standing posture. There was greater transmission of vertical vibration to the pelvis and the lower spine and greater relative motion within the lower spine in the standing posture than in the sitting posture at the principal resonance and at higher frequencies. Transmissibilities from the supporting surface (floor or seat) to the thoracic region had similar magnitudes for both standing and sitting subjects. The lumbar spine has less lordosis and may be more compressed and less flexible in the sitting posture than in the standing posture. This may have reduced the relative motions between lumbar vertebrae and both the supporting vibrating surface and the other vertebrae in the sitting posture. The characteristics of the vibration transmitted to the pelvis may have differed in the two postures due to different transmission paths. Increased forward rotation of the pelvis in the standing posture may have caused the differences in responses of the pelvis and the lower spine that were observed between the two postures.

1. INTRODUCTION

The dynamic responses of the human body to vertical whole-body vibration and shock have been investigated experimentally for more than four decades. Even so, their complex nature has prevented a clear understanding of the form of the dynamic responses of the body. Understanding of the mechanical responses of the body is essential to assist in reducing the undesirable influences on the health, the activities and the feelings of occupants caused by vibration.

The most common position of the body when exposed to vibration is the seated one, such as in a car. Consequently, most experimental studies have investigated the responses of seated subjects. However, we also experience vibration when standing, such as in public transport, in some industrial vehicles and in various types of building. Knowledge of the similarities in the body dynamic responses when standing and seated may assist understanding of the dynamic responses of the body and also suggest the degree to which various human responses in one posture can be assumed for the other posture.

There have been a few previous studies comparing the dynamic responses of standing and seated bodies. The driving-point impedance of the body was obtained with both standing

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and sitting subjects by Coermann [1] and Miwa [2]. Coermann [1] presented the mechanical impedance of one subject in three postures, "standing erect", "sitting erect" and "sitting relaxed". The main resonance was observed at 5·9, 6·3 and 5·2 Hz respectively. The impedance at the resonance frequency was greater in a "sitting erect" posture than in the other two postures. Miwa [2] found a main peak at 7 Hz, together with a minor peak at 20 Hz, in the mean mechanical impedance of 20 standing subjects. For seated subjects, there was a main peak at 6–8 Hz, with a minor peak in the 16–20 Hz frequency range.

Coermann [1] compared the vertical vibration transmissibilities to the head in standing and sitting subjects. It was observed in the data from one subject that the transmissibility to the head had a similar main peak at about 5 Hz when "standing erect" and "sitting erect", but there were differences at higher frequencies. Kobayashi *et al.* [3] and Rao [4] also measured the vibration transmission to the head with standing and sitting subjects exposed to vertical vibration. Kobayashi *et al.* [3] found reduced vertical transmissibility and greater fore-and-aft transmissibility at around 5 Hz for standing subjects than for seated subjects. The data from Rao [4] showed a trend in the transmissibility curves that was similar in both the standing and the sitting position.

Hagena *et al.* [5] presented vertical vibration transmission from the sacrum to six higher locations along the spine, including the head, for both standing and sitting subjects at seven discrete frequencies up to 40 Hz. The variation in the transmissions between the measurement locations was within about $\pm 15\%$ at all frequencies below 14·3 Hz for the standing position and all frequencies below 8·1 Hz for the sitting position. The transmission through the spine was less in sitting posture than in standing posture at 4 Hz.

It may not be possible to understand the causes of differences in the dynamic responses of standing and sitting bodies from only the driving-point response and the transmissibility to a single location in the body (i.e., the head) as measured in the previous studies mentioned above. Hagena *et al.* [5] monitored vibration at several locations along the spine but the measurements were made only in the vertical direction. Caution is required when comparing the dynamic responses of standing and seated bodies obtained in different studies since the experimental conditions, including the input stimuli, have differed and the human body, exhibits non-linear characteristics with respect to vibration magnitude [6, 7].

The objective of the present study was to identify differences in the apparent mass and transmissibilities between standing and seated postures by measuring the motions at several locations on the body in three axes in the mid-sagittal plane (i.e., vertical, fore-and-aft and pitch). Pitch motion was measured because rotational motion of the vertebrae may influence the translational motion measured at the body surface, as reported by Matsumoto and Griffin [8]. Possible causes of differences in the dynamic responses in standing and seated postures were hypothesized.

2. METHOD AND ANALYSIS

The experiment was conducted on the same occasion as the experiment with seated subjects presented in Matsumoto and Griffin [9]. The experimental methods, analysis procedures and subjects were, therefore, the same as those reported previously. Eight male subjects whilst standing and whilst seated, were exposed to vertical random vibration in the 0·5–20 Hz frequency range at a magnitude of 1·0 m/s^2 r.m.s. for 60 s. The experimental method with standing subjects has not been previously described.

The standing posture of the subjects was a "normal standing posture", defined as standing looking straight ahead with the upper-body in a comfortable, upright position and the legs straight and locked. When standing, subjects held lightly with both hands to a rigid frame in front of them, which was rigidly secured to the vibrator platform for safety purposes; no subjected needed to alter his upper-body position to hold the frame. Measurements were made while barefoot so as to eliminate any effects of footwear. The sitting posture of the subjects was a “normal sitting posture” defined as sitting looking straight ahead with the upper-body in a comfortable and upright posture without backrest. No footrest was used: the feet were allowed to hang freely. This study focused on the dynamic response of the upper-body by eliminating the effect of the height of a footrest. Subjects were asked to avoid any voluntary movements in both postures. Half of the subjects started with experiment with the standing posture and the rest started with the sitting posture.

A force platform, Kistler 9281B, was rigidly mounted on the platform of a 1 m stroke electro-hydraulic vibrator for the study with standing subjects. The force platform was secured to a rigid seat for the study with seated subjects. The acceleration on the vibrating surface (i.e., the seat or the floor) was measured at the centre of the top plate of the force platform with a piezoresistive accelerometer, Entran EGCS-DO-10. For both postures, the acceleration on the surface of the body in the vertical, fore-and-aft and pitch axes was measured at eight locations of the upper-body using the measurement method described in Matsumoto and Griffin [9]: at the head, at the first, fifth and tenth thoracic vertebrae, and at the first, third and fifth lumbar vertebrae (i.e., at T1, T5, T10, L1, L3, L5) and at the pelvis (on the posterior-superior iliac spine of the right ilium). The motions in the three axes at each location were obtained with three miniature translational accelerometers (Entran EGA-125*-10D) mounted on a T-shaped balsa wood block attached to the body surface. The pitch motion was obtained from the difference between the signals from the two accelerometers orientated in the vertical direction [9]. Additionally, vibration was measured at the left knee (just below the patella) in the vertical and fore-and-aft direction when subjects were standing. The motions at the knee were measured with two miniature translational accelerometers (Entran EGA-125*-10D) orientated orthogonally and attached to a balsa wood card, 20 mm (horizontal) $\times$ 30 mm (vertical) and 3 mm in thickness. The weight of the card, including the accelerometers and their cables, was about 2 g. The balsa wood card was attached to the body surface by double-sided adhesive tape and adhesive plaster, as were the blocks for the measurement of spinal motion. Signals from all the accelerometers and the force platform were acquired at 128 samples per second after low-pass filtering at 20 Hz.

The apparent mass was calculated by dividing the cross-spectral density function between the acceleration at the driving point (i.e., the seat or the floor) and the resulting force at the driving point, by the power spectral density function of the driving-point acceleration. The mass of the platform above the force cells was subtracted from the resulting values. By using a similar calculation procedure, transmissibilities were obtained between the input acceleration and the resulting accelerations in each axis at each measurement location. The transmissibility data obtained from the measurements at the body surface were corrected by three steps: (i) to reduce the effect of local vibration of tissue–skin–transducer system on the measurement at the body surface, (ii) to reduce the effect of inclination of the body surface (i.e., to obtain translational motions with respect to an earth-based co-ordinate system), and (iii) to estimate the translational motions at the centres of vertebral body from those at the tip of the spinous processes. The equations used in the data correction and the effects of each step of the data correction have been illustrated by Matsumoto and Griffin [7, 9]. As presented in Matsumoto and Griffin [9], a close agreement was found between the transmissibilities for the seated body obtained by the surface measurement method and those from previous studies in which the direct measurement method (i.e., transducers secured rigidly to the vertebra) has been used. It is concluded that the surface measurement method, combined with the data corrections used in the present study, provide reliable measurements of motions at locations along the spine.

Relative displacements between the centres of vertebral bodies were calculated with simulated 1·0 m/s^2 r.m.s. sinusoidal vibration at the principal resonance frequency of the apparent mass for the seated posture given by Matsumoto and Griffin [9]. The same calculations have been made for the standing posture using the moduli and phases of the transmissibilities measured. The measurements have been divided by the number of intervertebral discs between adjacent measurement points so as to indicate the approximate change in the distance between the centres of adjacent vertebral bodies.

3. RESULTS

The apparent masses in the standing and sitting postures are computed for each subject in Figure 1. Figure 2 compares the median normalized apparent masses of the eight subjects when sitting and standing. The principal resonance frequencies in the standing posture were significantly greater than those in the sitting posture, although the difference was small ($p < 0{\cdot}05$, Wilcoxon matched-pairs signed ranks test). The moduli of the apparent masses at the principal resonance frequency in the standing posture tended to be less than those in the sitting posture ($p < 0{\cdot}05$). For all the subjects, the apparent masses in the standing posture were greater than those in the sitting posture at frequencies greater than 10 Hz (see Figure 1).

With the subjects standing and sitting, the median transmissibilities from vertical input acceleration (at either the floor or the seat) to each measurement location on the upperbody in the vertical, fore-and-aft and pitch directions are shown in Figures 3, 4, and 5 respectively.

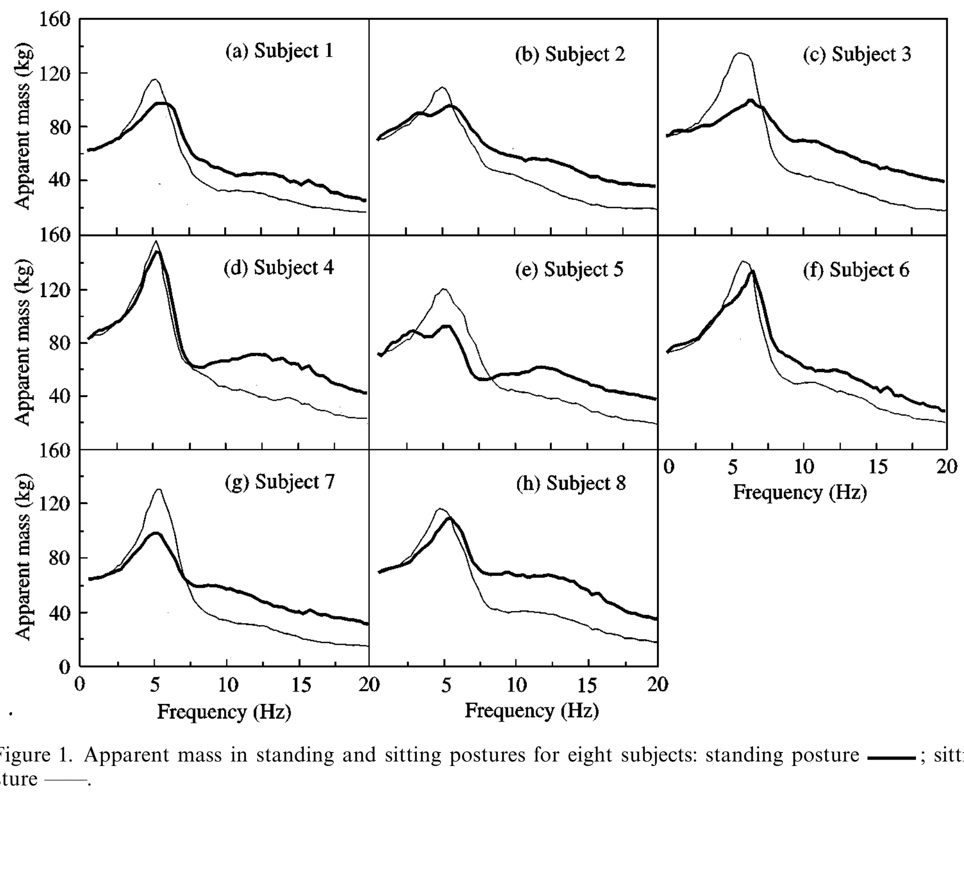

Figure 1. Apparent mass in standing and sitting postures for eight subjects: standing posture ——; sitting posture ——.

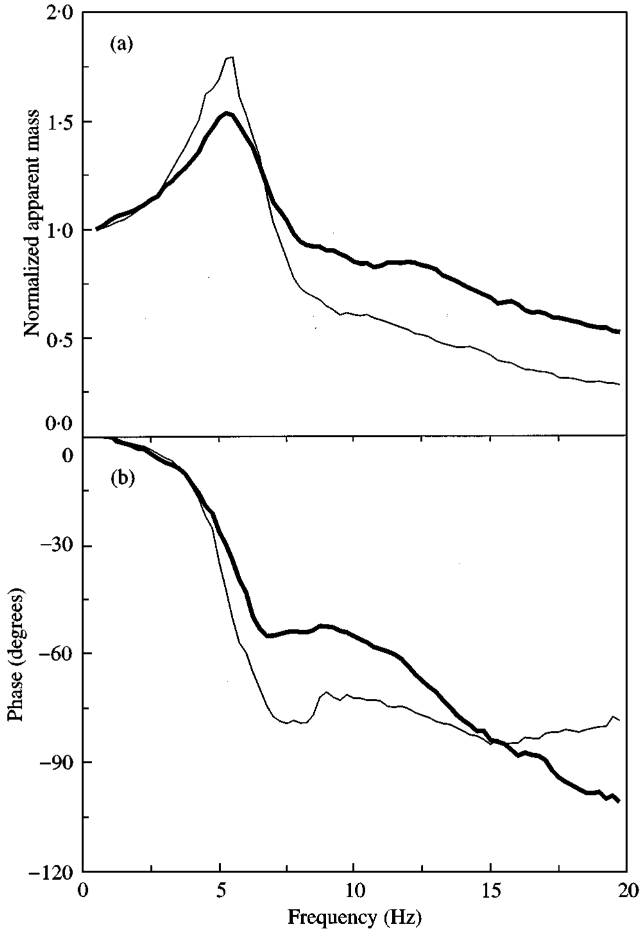

Figure 2. Median normalized apparent mass in standing and sitting postures: standing posture ▬▬ ; sitting posture ——.

For the vertical transmissibilities, differences between the standing and sitting posture were greatest in the lower spine (see Figure 3). The median transmissibilities showed similar magnitudes for the standing and sitting postures at the head and in the thoracic region, while the median transmissibilities in the lumbar region and at the pelvis were greater in the standing posture than in the sitting posture. The differences in the vertical transmissibilities between the standing posture and the sitting posture were statistically significant at frequencies greater than 6 Hz for L1, greater than 3 Hz for both L3 and L5, and between 6 and 7 Hz for the pelvis ($p < 0{\cdot}05$). A peak was observed in most vertical transmissibilities in the frequency range around 5–6 Hz in both the standing and the sitting posture. The principal peak in the vertical transmissibilities tended to be at a higher frequency in the standing posture than in the sitting posture, irrespective of the measurement location. For example, the frequency of the peak in the vertical transmissibility to L3 in the standing posture, 6·25 Hz, was significantly higher than that in the sitting posture, 5·0 Hz ($p < 0{\cdot}05$, (see Figure 3(f)).

The transmissibilities to the fore-and-aft motions at all measurement locations were similar in the standing and sitting postures, although some differences can be observed in Figure 4, for example in the measurement at T1. The transmissibilities to the pitch motions

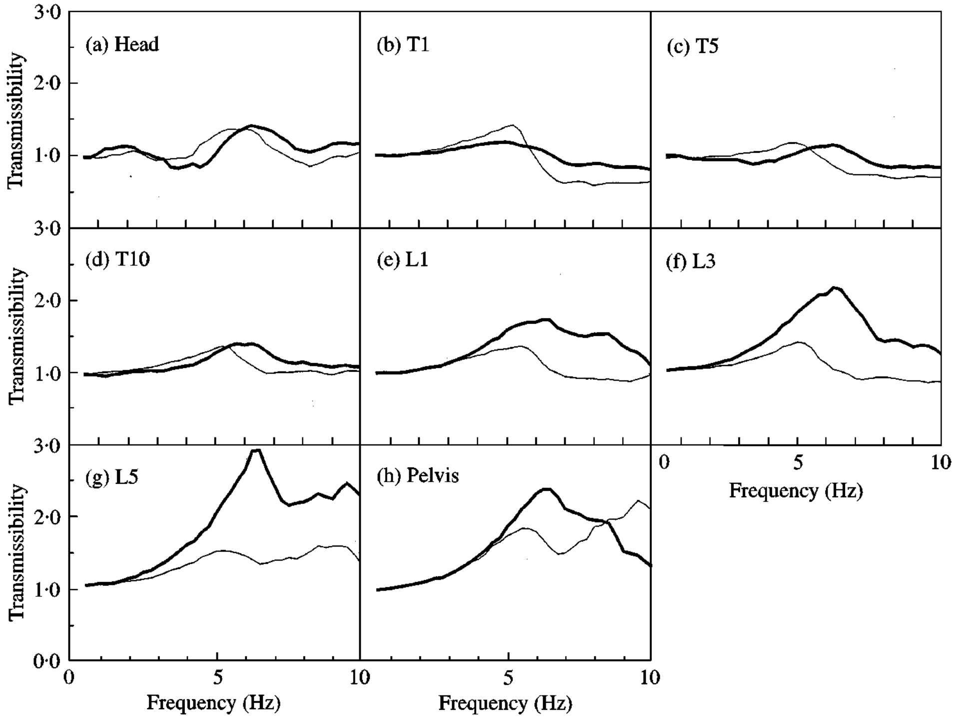

Figure 3. Median transmissibilities to vertical vibration at each measurement location measured with subjects in standing and sitting postures: standing posture ▬▬; sitting posture —— .

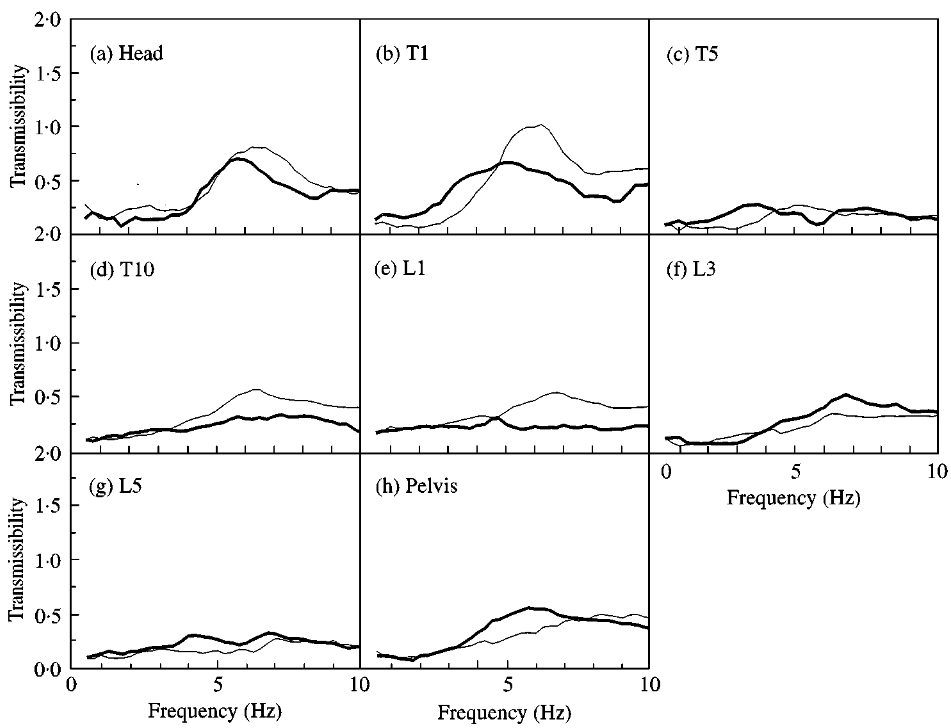

Figure 4. Median transmissibilities to fore-and-aft vibration at each measurement location measured with subjects in standing and sitting postures: standing posture ▬▬; sitting posture ——.

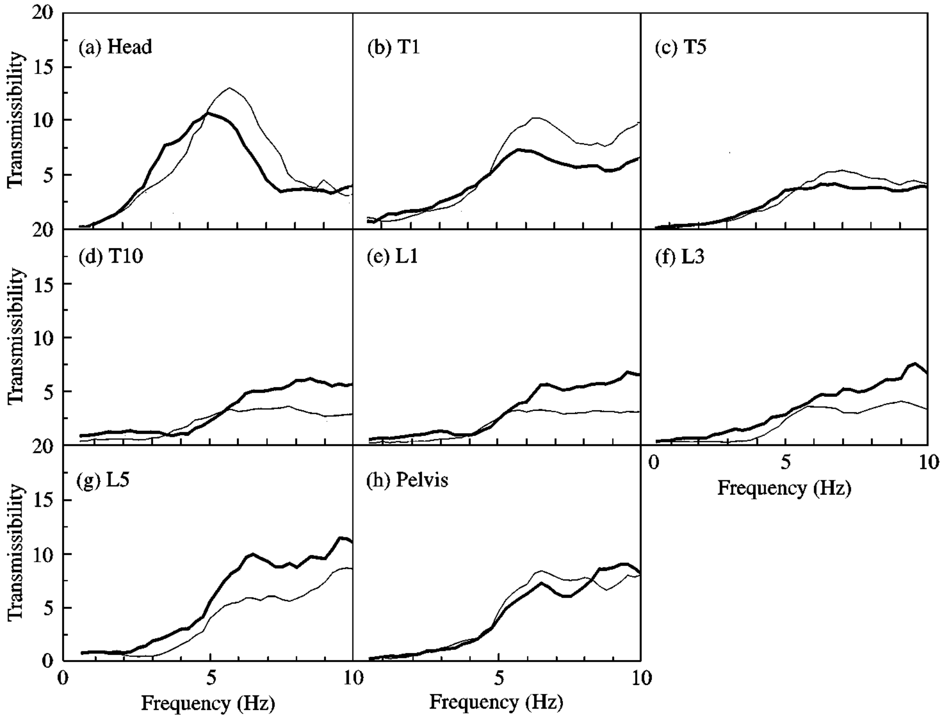

Figure 5. Median transmissibilities to pitch vibration at each measurement location measured with subjects in standing and sitting postures: standing posture ——; sitting posture ——. (The unit for the transmissibilities is [rad s^{-2}/m s^{-2}].)

also showed some differences between the standing posture and the sitting posture (see Figure 5). In the lower spine, the pitch transmissibilities tended to be greater for the standing posture than for the sitting posture, particularly at frequencies above 6 Hz (see Figures 5(d)–5(g)). This is similar to the trend in the vertical transmissibilities mentioned above. However, at the head and at T1, the pitch transmissibilities in the standing posture were less than those in the sitting posture at higher frequencies. In this body region, the frequency of the peak in the transmissibility was higher in the sitting posture than in the standing posture ($p < 0{\cdot}05$ for the head), which is inconsistent with changes in the apparent mass and vertical transmissibilities.

For the standing posture, the transmission of vertical floor vibration to the knee was measured in both the vertical and the fore-and-aft directions (see Figure 6). Vertical transmissibility to the knee generally showed a gradual increase with increasing frequency without any remarkable peaks at frequencies below 10 Hz. However, the fore-and-aft transmissibility to the knee had a peak in the 6–7 Hz frequency range, close to the frequency of the principal resonance of the apparent mass, but a little higher.

Calculated peak-to-peak relative motions between adjacent measurement points on the spine in the standing posture are shown in Table 1. The corresponding measurements in the seated posture have been presented by Matsumoto and Griffin [9]. In Table 1, simulated peak-to-peak relative displacements at the principal resonance frequency varied up to about 1·0 mm in the lower spine, below T10, except that between L3 and L5 for Subject 2 which appeared to be much greater than the others. In contrast, in the sitting posture, all calculated values were less than 0·4 mm, except that between L3 and L5 for Subject 2, which also appeared to be much greater than the others [9]. The calculated relative displacements

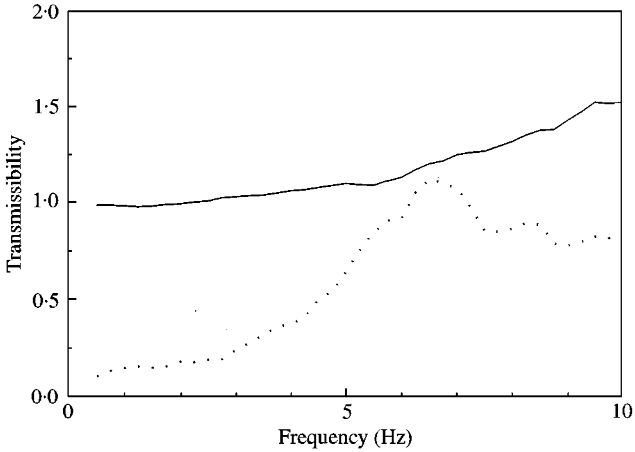

Figure 6. Median transmissibilities to the knees of subjects in the standing posture: vertical vibration ———; fore-and-aft vibration - - - -.

Table 1

Simulated peak-to-peak relative displacements between adjacent measurement points on the spine divided by the number of intervertebral discs between adjacent measurement points; calculations for the standing posture (a sinusoidal floor vibration at the principal resonance frequency with an acceleration of 1·0 m s^2 *r.m.s. was assumed; in millimetres (mm))*

	T1–T5	T5–T10	T10–L1	L1–L3	L3–L5
Subject 1	0·007	0·093	0·280	0·495	0·180
Subject 2	0·028	0·142	0·503	0·673	2·008
Subject 3	0·073	0·099	0·068	0·194	0·923
Subject 4	0·110	0·119	0·719	0·419	0·597
Subject 5	0·056	0·037	0·257	1·070	0·921
Subject 6	0·195	0·096	0·314	0·601	0·236
Subject 7	0·240	0·205	0·505	0·443	0·463
Subject 8	0·081	0·164	0·104	0·663	0·204

between two vertebrae in the region between T10 and L5 were significantly greater in the standing posture than in the sitting posture ($p < 0{\cdot}05$). There were no significant differences in the magnitudes of the relative displacements in the upper thoracic region between the standing and sitting postures.

4. DISCUSSION

4.1. APPARENT MASSES IN STANDING AND SEATED POSITIONS

The principal resonance of the apparent mass was found at about 5 Hz with subjects in both the standing and sitting postures. However, the principal resonance of the apparent mass in the standing posture was at a slightly higher frequency than that in the sitting posture. For individual subjects, the difference in the apparent mass resonance frequency between the standing and sitting postures were mostly less than 1 Hz (see Figure 1). It is therefore concluded that although there was a slight shift of the apparent mass principal resonance frequency between the standing and sitting positions studied here, this is generally less than 1 Hz. This is consistent with the difference in the mechanical impedances of one subject in a "standing erect" posture and a "sitting relaxed" posture reported by Coermann [1]. Miwa [2] may have also presented a similar difference in the frequencies of the peak in the mechanical impedance for standing and sitting subjects, although the peak frequencies reported were higher than those measured by Coermann [1] and in the present study.

The apparent mass at the principal resonance frequency was significantly greater for the sitting posture than for the standing posture. At frequencies higher than 7 or 8 Hz, the apparent mass was greater for the standing posture than for the sitting posture. Upon assuming that the apparent mass of the human body can be represented by a single-degree-of-freedom system, these differences in the apparent mass implies that the standing body has more damping than the seated body. This might be caused by difference in the dynamic characteristics of the tissue in contact with the vibrating surface and in the dynamic response of the legs in the two postures. In the standing posture, the apparent mass may be influenced by the compliance of the tissue of the feet and the legs work as a vibration transmission path. Whereas, in the sitting posture, the legs can be regarded as additional masses supported by the tissue beneath the pelvis and the thighs. In the sitting posture, the legs might move in phase with the upper body, both movements are caused by the tissue in contact with the seat surface. The damping property of the tissues beneath the pelvis and the thighs may be different from the damping property of the tissues of the feet. Additionally, when standing, there may be a damping effect of the joints in the legs, such as a viscoelastic effect of the joint fluid and the friction between the bones. It could be hypothesized that the damping of the tissue beneath the pelvis and thighs may be less than the damping caused by the tissue of the feet and the legs working as a vibration transmission path.

In previous studies, the principal resonances of the apparent mass of seated subjects in various postures were found mostly in the frequency region between 4 and 6 Hz (e.g., by Fairley and Griffin [10]). Matsumoto and Griffin [8] and Matsumoto [11] measured the apparent masses of standing subjects in different postures and found the principal resonance mostly at a frequency between 4 and 6 Hz when subjects stood with their legs straight. In both positions, the resonance frequency tended to reduce as the upper-body was in a more relaxed or slouched attitude. The difference in the principal resonance frequency between the standing posture and the sitting posture in this paper may be less than the variation in the resonance frequency with different sitting postures and with different standing postures. It seems likely that, although there were slight differences at the resonance frequency, common dynamic mechanisms in the upper-body contribute to the principal resonance of the apparent mass in standing and sitting postures.

4.2. VIBRATION TRANSMISSION TO AND THROUGH THE SPINE IN STANDING AND SEATED POSITIONS

The vertical transmissibilities of the standing body measured in this experiment are consistent with those obtained in a previous study by Matsumoto and Griffin [8]. The body responses were measured at three locations over the spine in two translational axes (i.e., in the vertical and fore-and-aft axes) in the previously study, compared to six locations in the three axes in the present study.

The 5–7 Hz peak in most transmissibilities tended to be at a higher frequency in the standing posture than in the sitting posture, consistent with changes in the apparent mass (see Figures 3–5). Transmissibilities to the lower part of the upper-body (e.g. L3) showed the most clear shifts in resonance frequency between standing and sitting positions, clearer than the shifts in the apparent mass (see Figures 2(a) and 3(f)). It is likely that the natural frequency of a vibration mode in the lower trunk slightly changed between the standing and sitting posture. This change might be attributed to postural differences (e.g., the pelvis angle, spinal curvature or muscle tension). The change in the dynamic response of the lower trunk might also be attributed to differences in the manner of vibration transmission to the upper-body. These possible causes for the difference in the dynamic response between the standing body and the seated body are discussed in the following sections.

Relative motions between the vertebrae in the lower spine and both the vibrating surface and other vertebrae within the lower spine appear to be greater in the standing posture than in the sitting posture. It was found in a previous study by Matsumoto and Griffin [9] that any axial motions along the spine in the seated body were less dominant than a bending motion of the spine at the principal resonance frequency of the apparent mass at around 5 Hz. The data in Table 1 imply that an axial motion along the spine may be more dominant in the standing posture than in the seated posture at the principal resonance frequency. A bending motion of the spine was also found to be dominant in the standing body [11]. A small axial motion along the spine could be inferred from the data presented by Hagena *et al.* [5] who presented similar magnitudes of vibration at measurement locations along the spine at about 5 Hz. However, they measured only those vertical motions, which might be affected by rotational motions so the axial motions along the spine cannot be calculated with reliability from their data.

When standing, the position of the pelvis and lumbar spine and the muscle tension in the lower upper-body tend to differ from those when seated. According to Pheasant [12], in an upright standing position, "the pelvis is more or less vertical and the first lumbar vertebra and sacrum make angles of about 30° above and below the horizontal plane respectively". The lumbar spine is concave to the rear (i.e., in a lordosis) when standing. When seated in a relaxed manner, the pelvis rotates backward by about 30° compared to the pelvis when standing, by passive tension in the hamstring muscles. In this posture, the lumbar spine may be "flexed close to the limit of its range of motion" (i.e., close to straight) with relaxed muscles. Muscular effort in the abdominal region is required to keep the pelvis vertical and regain the lordosis of the lumbar spine in an upright sitting posture. Back muscle activity may also be required "to support the weight of the trunk". The sitting posture used in this study is thought to fall between a relaxed posture and an upright posture. It has been reported that the pressure in the L3 intervertebral disc "in a person sitting upright' was '40% in excess of the value obtained in upright standing", although this upright sitting posture was not necessarily the same as the one defined above (see the papers by Nachemson and Morris [13], Nachemson [14]). This increase in the lumbar intradiscal pressure due to the postural change from the standing position to the sitting position might be caused by the increase in muscle activity and reduced lordosis in the lumbar spine.

It may be expected that the lumbar spine is more compressed and less flexible in a sitting posture than in a standing posture, due to both anterior and posterior trunk muscle activity and reduced lordosis. This might be one cause of the transmissibilities to each of the three locations in the seated lumbar spine, particularly for the vertical and pitch axis motion, being less than those for the standing lumbar spine (see Figures 3 and 5). The same mechanisms may have reduced the relative motions within the seated lumbar spine.

The different geometry of the lumbar spine in standing and sitting positions may also make some contribution to the observed differences in transmissibilities. The vertical load in the upper-body is mainly transmitted through the spine. The vertical transmissibilities in the thoracic region were similar in the standing and sitting postures, so the vertical dynamic load acting on the lumbar spine would also be similar (see Figure 3). However, more lordosis in the lumbar spine in the standing posture could result in longer lever arms for the vertical load for some spinal motion segments: a greater moment in the pitch axis acting on a motion segment with more inclination to the vertical axis. This might cause more bending motion in the lumbar region in the standing position than in the sitting position, which could result in greater pitch transmissibility and greater vertical transmissibilities. The more distinct lordosis in the lumbar spine in a standing posture than in a sitting posture might, therefore, be one of the causes of the differences in the transmissibilities.

It might seem inconsistent that there is less internal relative motion in the spine in the sitting posture than in the standing posture while the apparent mass at the principal resonance frequency is greater for the sitting posture than for the standing posture as observed in this experiment. Matsumoto [11] and Matsumoto and Griffin [15] have investigated the dynamic mechanisms associated with the principal resonance of the apparent mass by developing mathematical models. It was concluded that the principal resonance of the apparent mass might be mainly caused by the compliance of the tissue in contact with the supporting surface and the motion of the visceral organs. The bending motion of the spine seemed to have a minor contribution to the apparent mass resonance. Therefore, there may not be a direct association between the higher apparent mass at the principal resonance frequency and the less internal relative motion in the spine in the sitting posture.

4.3. VIBRATION TRANSMISSION TO THE PELVIS IN STANDING AND SEATED POSITIONS

In a standing posture, floor vibration is transmitted through the tissue beneath the feet and then the legs to the hip joints in the pelvis. In a seated posture, seat vibration is transmitted through the tissue beneath the pelvis to the ischial tuberosities in the pelvis. It can be observed in Figure 6 that the fore-and-aft transmissibility to the knee shows a peak at about 6–7 Hz in the standing posture. This implies the existence of some bending motion of the legs at the ankle and knee, or some shear deformation of the tissue beneath the feet at these frequencies. The vibration transmitted through the hip joint to the pelvis might, therefore, be in both the vertical and the fore-and-aft axes. In the sitting posture, the deformation of the tissue beneath the pelvis in the shear and axial directions might also alter the vertical seat vibration to a bi-directional motion which is transmitted to the ischial tuberosities. This motion transmitted to the pelvis in the sitting position would differ from that in the standing posture, even though both are bi-directional. Such combined vertical and fore-and-aft motions transmitted to the pelvis might result in motion of the pelvic body in vertical, fore-and-aft and pitch axes. The pelvis may tend to pitch about the hip joint in the standing posture but pitch about the ischial tuberosities in the sitting posture. In the present study, there were greater phase lags in the pitch transmissibility to the pelvis in the standing posture than in the sitting posture (see Figure 7). This occurred even though the phases of the vertical transmissibilities to the pelvis and the moduli of the pitch transmissibilities to the pelvis were similar in the two postures (see Figures 7 and 5(h)). At frequencies close to the resonance around 5 Hz, the pitch motion of the pelvis in the standing posture was almost out of phase (i.e., a phase of $-180°$) with the input motion: the pelvis rotated backwards when the floor moved upwards. The transmissibilities to the upper trunk were similar in the two postures, as observed in Figures 3–5. It therefore seems that the vibration transmitted to the pelvis and the upper-body differed between the standing and sitting postures. The dynamic mechanisms in the lower trunk associated with the phase response of the pitch motion of the pelvis may compensate for the difference in the vibration transmitted to the pelvis so that there was no remarkable difference in the vibration transmitted to the upper trunk. This difference in the dynamic response of the lower

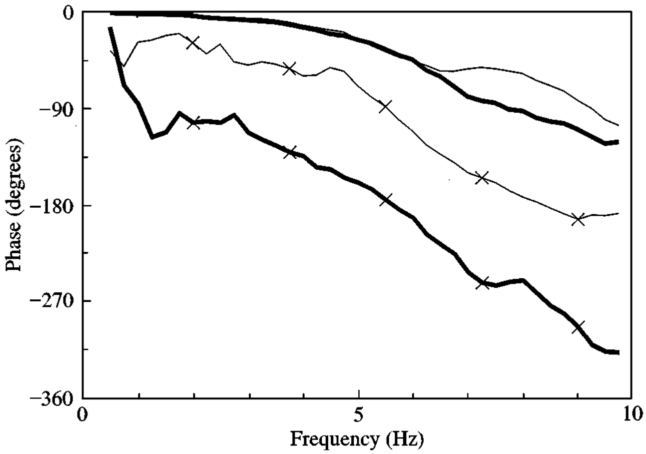

Figure 7. Median phases of the transmissibilities to the pelvis in the vertical and pitch axes in the standing and sitting postures: vertical vibration in the standing posture ▬▬; vertical vibration in the sitting posture ——; pitch vibration in the standing posture ▬✕▬; pitch vibration in the sitting posture —✕—.

upper-body, including the pelvis, may contribute to the differences observed in the transmissibilities to the pelvis and the lower spine region, as shown in Figure 3.

4.4. VIBRATION TRANSMISSION TO THE HEAD AND THE UPPER SPINE IN STANDING AND SEATED POSITIONS

At the upper locations in the body (i.e., the head and T1), an opposite shift in the peak frequency to that observed in the apparent mass and the transmissibilities to the lower locations was found: the peak frequencies in the pitch transmissibilities at those locations tended to be lower in the standing posture than in the sitting posture. This has not been presented in the previous studies by Kobayashi *et al.* [3] and Rao [4] who measured only translational head motions in standing and seated subjects. The observed shift in the peak frequency in the pitch transmissibilities to the upper locations may imply some local motion of the head, mainly in the pitch direction, that does not make any clear contribution to the driving-point response. Pitch motion of the head may be induced mainly by an eccentricity of the centre of gravity of the head relative to the location of the input motion transmitted through the neck. The position of the head–neck system, including the muscle tension in the neck will, therefore, significantly affect the resulting pitch motion of the head. In the present study, the posture of subjects was dependent on their interpretation of a "comfortable, upright position". This may have resulted in a variability in the head–neck between subjects. A large inter-subject variability in the vertical transmissibility to the head measured near the mouth in the previous study by Matsumoto and Griffin [9], and reported in other previous studies (e.g., by Paddan and Griffin [16]), might be attributed to this variability in pitch motion of the head.

5. CONCLUSIONS

In both standing and seated subjects a principal resonance in the apparent mass occurs in the 5–6 Hz frequency range. The frequency of the principal resonance tended to be higher for the standing posture than for the seated posture, although the differences were less than

1 Hz for most subjects. Compared to the standing posture, the apparent mass in the sitting posture was greater at the principal resonance but less at frequencies above about 7 Hz. The legs, part of the vibration transmission path in the standing posture and additional masses in the sitting posture, may have contributed to the differences in the apparent masses between standing and sitting postures.

The transmissibilities measured at locations in the lower upper-body showed differences between standing and sitting subjects. The vertical transmissibilities to lumbar vertebrae were greater in the standing posture than in the sitting posture at frequencies around the principal resonance of the apparent mass and at higher frequencies. The peak median vertical transmissibilities to L3 and L5 in the standing posture exceeded 2·0, while those in the sitting posture were less than 1·5. Relative motions in the lower spine were calculated to be also greater in the standing posture than in the sitting posture. The frequency of the first peak in the transmissibilities to the lumbar region tended to be higher in the standing body than in the sitting body, which was consistent with the trend observed in the apparent mass. Differences in the angle of the pelvis, the spinal curvature and muscle tension may be partially responsible for differences in the transmission of vibration to the lumbar region. Differences in the vibration transmission paths (via the legs or the ischial tuberosities) when standing and sitting may also contribute to differences in vibration in the lumbar region. In the two postures, transmissibilities to the thoracic region showed similar magnitudes in the frequency range investigated, although the frequencies of the peaks were higher in the standing posture. Local pitch motion of the head was observed but it did not make a major contribution to the apparent mass.

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