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THE VIBRATION DISCOMFORT OF STANDING PERSONS: EFFECT OF BODY SUPPORTS

Olivier Thuong and Michael J Griffin

Human Factors Research Unit

Institute of Sound and Vibration Research

University of Southampton, SO17 1BJ

United Kingdom

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Abstract

When standing and exposed to vibration in trains, passengers and crew may seek support by leaning on a surface or holding a bar or a handle that alters the transmission of vibration to their bodies. The effects of such contact on the discomfort caused by vibration have not been previously investigated. This study was designed to investigate the effects of postural supports on the discomfort caused by fore-and-aft and lateral whole-body vibration in the frequency range 0.5 to 16 Hz. Using the method of magnitude estimation, 12 standing male subjects judged the discomfort caused by five magnitudes of sinusoidal vibration at six frequencies (0.5, 1.0, 2.0, 4.0, 8.0 and 16 Hz) and in two directions (fore-and-aft or lateral) while using four different postural supports: no support, holding a vertical bar, leaning with back support, and leaning with shoulder support. Equivalent comfort contours were constructed, showing how discomfort depends on the vibration frequency over a range of vibration magnitudes with each support. Compared to standing with no support, holding a vertical bar had only a minor effect on the discomfort caused by either fore-and-aft or lateral vibration. At frequencies greater than about 2 Hz, leaning backwards against a back support increased the discomfort caused by fore-and-aft vibration and leaning sideways against a shoulder support increased discomfort caused by lateral vibration. Frequency weightings corresponding to the equivalent comfort contours were constructed and show that the weightings suggested in current standards do not provide good predictions of the frequency-dependence of discomfort caused by vibration when standing without any support or when supported and holding only a bar. It is concluded that leaning, with the back or shoulder supported, increases the discomfort caused by vibration in a direction normal to the body surface at frequencies greater than about 2 Hz. Currently standardised frequency weightings do not provide good predictions of the discomfort caused by horizontal vibration when standing without holding a support.

Keywords: vibration discomfort; standing; supports.

1. Introduction

In all modes of transport, passengers are exposed to vibration that can cause discomfort. The discomfort of seated passengers is influenced by vibration transmitted to the body through seats and has been investigated in many studies. The discomfort of standing passengers is influenced by vibration transmitted from the floor and has been investigated in fewer studies. The discomfort of standing people may also be affected by the use of supports (e.g. holding on leaning against a structure) used either to assist stability while exposed to motion or to relieve muscles used when standing unsupported. The influence of postural support on the discomfort caused by the vibration of standing passengers has not been previously reported.

The presence of various resonances and complex mechanisms in the perception of vibration prevents vibration discomfort being accurately predicted using a simple average measure of the overall acceleration, velocity, or displacement of the vibration. Vibration discomfort is dependent on the frequency and direction of vibration, as shown by 'equivalent comfort contours', and it has been found that the frequency-dependence of the contours can be highly dependent on the magnitude of the vibration [1,2].

International Standard ISO2631-1 [3] and British Standard BS 6841 [4] provide methods for evaluating whole-body vibration in relation to the discomfort of seated and standing persons. According to these standards, to evaluate a horizontal motion (i.e. lateral or fore-and-aft) so as to predict the discomfort of standing persons, the root-mean-square (r.m.s.) value of the motion should be calculated after the motion has been weighted in the frequency domain using the W_d weighting curve that emphasizes acceleration at frequencies in the range 0.5 to 2 Hz and attenuates higher frequencies. The W_d weighting was derived primarily from studies of the vibration discomfort of seated persons.

Although several studies have investigated the discomfort caused by vertical vibration of standing people (e.g. equivalent comfort contours in the range 3 to 80 Hz were determined at various magnitudes by Oborne and Clarke [5]), there has been little investigation with horizontal vibration. A recent experimental study with fore-and-aft and lateral vibration over the range 0.5 to 16 Hz concluded that, contrary to the guidance in current standards, frequency weightings for the horizontal vibration of seated people are not appropriate for standing people [6].

When standing in trains, passengers often hold, or lean against, some part of the structure of the train. This contact may be expected to modify the motion of their bodies and their comfort. For seated people, a backrest tends to increase the transmission of lateral and fore-and-aft vibration to the head [7]. The discomfort caused by vibration tends to be reduced by the use of a backrest when exposed to fore-and-aft vibration at frequencies in the range 0.2 to 2 Hz [8], but increased by a backrest when exposed to fore-and-aft vibration at frequencies greater than 4 Hz [9], or exposed to lateral vibration at frequencies greater than 0.315 Hz [9,10]. It seems reasonable to expect that any effect of supports on the vibration discomfort of standing people will also depend on the frequency and the direction of the vibration. Designers may use current standards to predict the vibration discomfort of passengers who stand without holding or leaning on a support, but they have had no means of anticipating discomfort when the passengers are supported. Knowledge of the effects of supports on vibration discomfort may assist the design of transport and also assist researchers seeking to improve understanding of the mechanisms involved in vibration discomfort.

This study was designed to determine how postural supports similar to those used in trains influence the discomfort caused by horizontal vibration over the range of frequencies that may be experienced by passengers standing in trains. It was hypothesised that postural supports would either improve or degrade the comfort of standing people exposed to fore-and-aft or lateral vibration, depending on the frequency of the vibration.

2. Method

2.1 Motions

All vibration stimuli were sinusoidal and 6 seconds in duration, including a 1-second cosine-tapered start and a 1-second cosine-tapered end. Subjects were exposed to pairs of motions: a ‘reference vibration’ followed by a ‘test vibration’ in the same direction (i.e. either fore-and-aft or lateral).

With both fore-and-aft and lateral vibration, the ‘test stimuli’ were presented at the six preferred octave centre frequencies: 0.5, 1.0, 2.0, 4.0, 8.0, and 16 Hz. At each frequency, the test stimuli were presented at five magnitudes, in steps of 4 dB (Figure 1). From preliminary studies, the magnitudes were chosen to have the same acceleration at frequencies from 2 to 8 Hz and the same velocity at frequencies less than 2 Hz and greater than 8 Hz.

FIGURE 1 ABOUT HERE

The motions were produced using a hydraulic horizontal vibrator capable of 1-metre displacement. Fore-and-aft or lateral vibration was obtained by orientating subjects relative to the axis of motion. The motion stimuli were generated using *HVLab* software (version 3.81) with a sampling rate of 1000 samples per second. The acceleration of the platform was monitored using piezoresistive accelerometers (Entran Model EGCSY-240D*-10) and an *HVLab* data acquisition system. The acceleration was sampled at 1000 samples per second, after low-pass filtering at 40 Hz.

2.2 Postural support

Subjects stood in four postures (Figure 2):

(i) 'free': a normal erect posture.

(ii) 'bar': identical to the 'free' posture, except the subjects held a vertical bar with their right hand at shoulder height with the elbow unlocked.

(iii) 'shoulder': the mid-sagittal plane was parallel to the support wall, with the right shoulder resting against the wall. The feet were parallel and together, 280 mm from the wall, and the body was straight, producing an angle of about 6 degrees to the vertical.

(iv) 'backrest': subjects rested their buttocks against a rigid board, with the remainder of the back free of support. The feet were 200 mm from the wall, so the legs were inclined about 13 degrees to the vertical. The back was straight and vertical.

Other than when using the shoulder support, the feet were separated by 250 mm, so the distance between the outer edges of the feet corresponded to the median shoulder breadth of adult males [11].

The three supports were attached to an extruded aluminium frame secured to the 120 cm by 90 cm table of the vibrator. The 'bar' support consisted of a vertical bar (diameter 45 mm) that was part of the aluminium framework. The supports of the 'shoulder' and 'backrest' were provided by plywood boards (¼-inch thick) screwed to the aluminium framework.

Acceleration was measured at each support, and the ratio of the acceleration to the acceleration of the vibrator platform in the direction of motion was calculated for all motions employed in the study. In the direction of motion, this ratio was between 0.9 and 1.1, except at 16 Hz where it varied between 1.1 and 1.4 for the back support, and between 1.2 and 1.4 for the shoulder support, depending on the vibration magnitude. For supports perpendicular to the direction of motion of the platform (i.e. in the cross-axis), the ratio between motion of the support and motion of the platform was less than 0.1, except at 16 Hz where it was between 0.2 and 0.3 for the shoulder support, and between 0.1 and 0.2 for the back support, depending on the vibration magnitude.

2.3 Procedure

In all postures, subjects were instructed to:

- Place their feet on marks on the floor (25-cm apart, except for the shoulder posture where the feet were together)
- Try to keep the weight equally distributed between the feet
- Maintain the knees locked (avoiding bending legs to reduce the transmission of vibration)
- Allow the arms to hang freely (except when holding the bar).
- Look straight ahead

The method of magnitude estimation, as used previously by Morioka and Griffin [1,2] and Wyllie and Griffin [8,10], was employed to determine the discomfort caused by each of the test motions relative to the discomfort caused by a reference motion having a frequency of 2 Hz and a magnitude of 0.5 ms^{-2} r.m.s. in the same axis as the test motion. The use of magnitude estimation to compare the discomfort of the test stimuli relative to the discomfort caused by the reference stimulus minimised the influence of any variations in the physical or mental state of subjects during the experiment.

The subjects attended two sessions in which they were exposed to either fore-and-aft or lateral vibration: half of the subjects were first exposed to fore-and-aft vibration and half of the subjects began with lateral vibration. During each session, the four supports were presented in random orders.

For each condition (i.e., each support and each direction of vibration), a ‘within conditions’ study and a ‘between conditions’ study were performed (except for the ‘free posture’).

Within conditions – effects of the frequency and magnitude of vibration

For both directions of motion and all postures, subjects were exposed to the reference motion (2 Hz at 0.5 ms^{-2} r.m.s.), followed by a test motion (at a randomly chosen frequency and magnitude from the range shown in Figure 1). After the presentation of the test motion, subjects were asked to provide a number reflecting the discomfort it caused, assuming the discomfort caused by the reference motion was 100. The subjects could ask for the pair of motions to be repeated if they were not sure. Prior to commencing the experiment, subjects practiced magnitude estimation by judging the lengths of lines drawn on paper and by judging a few selected vibration stimuli. This provided an opportunity to check that they understood the procedure and also familiarised them with the type of vibration stimuli.

Between conditions – effects of postural support

The procedure was identical to the 'within condition' part of the study, except that the reference motion was received with the subjects standing in the 'free posture' and exposed to 2 Hz at a magnitude of 0.5 ms^{-2} r.m.s., called the 'absolute reference'. After experiencing this reference motion, the subjects changed posture before receiving a test stimulus. The test stimuli were presented at five magnitudes of 2-Hz vibration in the same direction as the reference motion.

2.4 Subjects

Twelve healthy male university students and staff with median age 28 years (range 21 to 38 y), stature 177 cm (159 to 192 cm), weight 74 kg (56 to 90 kg) participated in the study. Subjects attended two sessions (one for each direction of motion), each lasting 60 minutes.

The subjects wore socks but not shoes and wore a loose harness in case they should fall (Figure 2). The harness did not provide support or restrict movement when subjects stood as instructed. They wore headphones delivering broadband noise at 65 dB(A).

The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

2.5 Analysis

Stevens' power law [12] was used to relate the magnitude estimates of subject discomfort, ψ, to the physical magnitudes of the motions, φ:

$$\psi = k \varphi^{n} \quad (1)$$

where k (the 'constant' in Stevens' power law) and n (the 'exponent') are assumed to be constant at any frequency. With both whole-body vibration of seated persons and hand-transmitted vibration, the exponent depends on the frequency of vibration [1,2,8,10].

Values of the exponent, n, at each frequency were determined by regression between the logarithms of the magnitude estimates and the vibration acceleration using bisquare weights to reduce bias from outlier values [13]:

$$\log \psi = \log k + n \log \varphi \tag{2}$$

For each individual, equivalent comfort contours were obtained for different values of discomfort, ψ, using individual values of k and n, assuming k and n depend on frequency:

$$\varphi(f) = \left(\frac{\psi}{k(f)} \right)^{\frac{1}{n(f)}} \tag{3}$$

This equation gives the acceleration, φ, needed at each frequency to achieve a given level of discomfort, ψ.

Two types of frequency weighting were constructed. Weightings showing the frequency-dependence of sensitivity to acceleration with each support were derived by inverting the equivalent comfort contours and normalizing them to have the same weighting at 0.5 Hz. Additionally, the inverses of the ratios between the comfort contours obtained with and without supports, referred to as ‘support weightings’, were calculated to show how vibration discomfort was affected by each support. A support weighting of 2, for example, means the discomfort experienced when holding the support would be similar to the discomfort when not holding the support but exposed to double the magnitude of vibration, so the support increases discomfort. The support weightings therefore show the frequency-dependent effects of each support on vibration discomfort and can be used to take account of the effect of a support when evaluating vibration.

Non-parametric tests (the Friedman two-way analysis of variance by ranks, the Wilcoxon matched-pairs signed ranks test, and the Spearman rank-order correlation coefficient) were employed in the statistical analysis.

3. Results

3.1 Equivalent comfort contours

Median equivalent comfort contours corresponding to a magnitude estimate of ‘100’ (i.e. discomfort equivalent to that caused without support when exposed to the reference motion of 2 Hz at 0.5 ms^{-2} r.m.s. in the same direction as the test motion) for all four support conditions and both fore-and-aft and lateral vibration are shown in Figure 3. Conditions where the equivalent comfort contours are significantly different with and without support (Wilcoxon, $p<0.05$) are marked. The equivalent comfort contours obtained without support are similar in shape to the contours obtained by Thuong and Griffin with the same posture [6].

FIGURE 3 ABOUT HERE

3.2 Effect of postural supports

For each support and at each frequency, support weightings were derived (as described in Section 2.5). A support weighting greater than 1.0 means the support increased discomfort (and greater values indicate greater discomfort), while a support weighting less than 1.0 means the support reduced discomfort. The median support weightings are reported in Table 1 and are shown with inter-quartile ranges in Figure 4. The support weighting for the back support with fore-and-aft vibration at 4, 8, and 16 Hz shows the greatest inter-subject variability, due to some subjects being very sensitive in this condition, including at the lowest vibration magnitudes. The conditions where the contours differ significantly with and without support are indicated in Table 1 with bold characters, and it is indicated whether the support increased or decreased discomfort.

TABLE 1 ABOUT HERE

FIGURE 4 ABOUT HERE

In two conditions with 0.5-Hz vibration (the back support with fore-and-aft vibration and the shoulder support with lateral vibration), the use of a support increased the acceleration on the comfort contour, meaning the support significantly reduced discomfort caused by the vibration (conditions marked with '+' in Table 1). In all other conditions where the support had a statistically significant effect, the use of a support increased the discomfort caused by the vibration (conditions marked with '-' in Table 1).

4. Discussion

4.1 Effects of supports

The effect of supports on the balance of subjects exposed to fore-and-aft transient motions was investigated by Robert [14] using supports similar to the vertical bar and the back support employed in the present study. The author concluded that the low-back support increased comfort because it

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prevented loss of balance being caused by low magnitude motions, whereas the bar did not prevent loss of balance, and a survey showed that a low-back support was the favourite support among passengers in public transport. However, for motion stimuli of high magnitude, when a loss of balance happened, the low-back support did not help recovery of balance, unlike the vertical bar, and so it was judged less efficient in respect of fall prevention. It is interesting to note that the posture preferred by the passengers was the most uncomfortable when there was vibration at higher frequencies (i.e. >2 Hz) in the present study, although this posture improved comfort when exposed to 0.5 Hz vibration (which is more likely to disturb balance).

Holding a horizontal bar 1.05 m above the floor either rigidly or lightly (only so as to prevent loss of balance only) has been shown to affect the transmission of fore-and-aft floor vibration to the heads of standing subjects [15]. When holding the bar rigidly, head vibration was increased at frequencies greater than 1.0 Hz but decreased at frequencies less than 1.0 Hz. In the present study, holding a vertical bar marginally increased vibration discomfort at frequencies greater than 1.0 Hz, although the increase was only statistically significant at 8 Hz. With 0.5-Hz vibration, discomfort was reduced when holding a bar, although the reduction was not statistically significant (Table 1 and Figure 4). The trends in the present study are therefore broadly consistent with the biodynamic findings.

When seated, a backrest increases vibration of the head during fore-and-aft excitation but has much less effect on the transmission of lateral vibration [7]. It was suggested that backrests may modify the transmission of vibration to the body in three ways: the addition of a vibration input path close to the head, a change in the dynamic properties of the body due to the modified posture, and a change in forces within the body.

When seated subjects were exposed to vibration in the range 0.2 to 1.6 Hz, a backrest tended to increase the discomfort caused by lateral vibration [10] but decrease the discomfort caused by fore-and-aft vibration [8]. At higher frequencies (2 to 60 Hz), a backrest appeared to increase the discomfort caused by fore-and-aft vibration and, to a smaller extent, lateral vibration [9]

The main detrimental effects of supports on the discomfort of standing subjects in the present study occurred at frequencies greater than 2 Hz, where the supports are most likely to have increased the transmission of vibration to the upper-body: a back support with fore-and-aft vibration and a shoulder support with lateral vibration. The back support also significantly increased the discomfort caused by lateral vibration in the range 1 to 4 Hz. The effects of the back support in the present study with standing subjects therefore seem broadly consistent with the effects backrests on the discomfort of seated people.

With the shoulder support and the back support, discomfort may have been increased by additional vibration input paths close to the head and upper-body. These inputs will have 'short-circuited' any isolation of vibration offered by the legs over the frequency range 2 to 16 Hz. The isolation of horizontal vibration provided by the legs can be observed in Figure 5: the transmission of horizontal vibration of the floor to the heads of standing people decreases with increasing frequency, and is much reduced at frequencies greater than about 2 Hz [16].

Wyllie and Griffin [8,10] suggested that, with low frequency non-vertical vibration, a backrest could improve the comfort of seated people. This benefit was observed at frequencies where the body amplified the vibration. With lateral vibration, the backrest restrained the body and prevented this amplification of the motion, but the benefit was observed only at frequencies close to 0.2 Hz [10]. With fore-and-aft vibration, the backrest reduced instability caused by the amplified motion over a wider range of frequencies and reduced discomfort at most frequencies in the range 0.2 to 1.6 Hz [8]. The natural sway of standing people is greatest at frequencies less than 1 Hz [17], consistent with the peak in floor-to-head transmissibility between 0.4 and 0.8 Hz, as shown in Figure 5 [16]. In the present experiment, the supports that increased discomfort at frequencies greater than 2 Hz (i.e. the back support with fore-and-aft vibration and the shoulder support with lateral vibration) also reduced discomfort at 0.5 Hz (Figure 4, Table 1), consistent with the supports reducing upper-body motion at the low frequency resonances and thereby reducing discomfort at low frequencies.

FIGURE 5 ABOUT HERE

The postures adopted by the subjects are broadly typical of postures commonly adopted by passengers when standing in trains. Although variations in posture may influence the findings, the principles may be generally applicable. The provision of support to the shoulder or back probably increased discomfort due to the direct transmission of vibration to parts of the body in contact with the support, and so similar findings may be expected whenever the body rests fully against a support (i.e. the feet are not too close to the wall) and the posture is comfortable (i.e. the feet are not too far from the wall) so the pressure on the support is similar to that in the conditions investigated here. The support from the bar involved a bent elbow (so the arm was 'unlocked'), and it seems unlikely that the distance from the feet to the bar will greatly affect vibration discomfort over a comfortable range of distances. Increasing the separation of the feet might improve stability with low frequencies of lateral vibration but this is unlikely to have a large effect on the discomfort caused by high frequencies of vibration.

4.2 Comparison with standards

Frequency weightings were derived from the equivalent comfort contours by inverting them and normalizing them to the same value (i.e. a weighting of 1.0) at 0.5 Hz. In Figure 6, these weightings are compared with the weightings advocated in current British and International standards [3,4]. In the standards, the weighting W_d is advocated for fore-and-aft and lateral vibration at the seat for seated persons and also at the floor for standing persons. For a seated person, if there is also vibration from a backrest, the overall discomfort is evaluated from the root-sums-of-squares of the weighted components at the seat and the backrest. At the backrest, fore-and-aft vibration should be weighted using W_c with a multiplying factor of 0.8, and lateral vibration using W_d with a multiplying factor of 0.5 (as summarized in Table 2). If the seat pan and the backrest are rigid so that they have the same vibration, the overall vibration discomfort due to a single frequency of vibration is given by the acceleration multiplied by $((W_d(f))^2 + (0.8.W_c(f))^2)^{½}$ for fore-and-aft vibration, and by $((W_d(f))^2 + (0.5.W_d(f))^2)^{½}$ (i.e. $1.12.W_d(f)$) for lateral vibration (Table 2).

TABLE 2 ABOUT HERE

FIGURE 6 ABOUT HERE

The weightings obtained in the 'free' posture (i.e. with no support) differ from the weighting W_d advocated in the standards: the W_d weighting is approximately unity at frequencies between 0.5 and 2 Hz, whereas the experimentally determined weighting decreases with increasing frequency over this range. When subjects used the back support, their posture might be likened to that of a seated person with a vibrating backrest, but the weightings that should be applied for a seated person (i.e. $((W_d(f))^2 + (0.8.W_c(f))^2)^{½}$ for fore-and-aft vibration and W_d for lateral vibration) do not match the experimentally determined weightings obtained for people standing with the back support (Figure 6).

The weighting obtained with lateral vibration and the shoulder support is close to the $((W_d(f))^2 + (0.8.W_c(f))^2)^{½}$ weighting applicable to seated persons exposed to fore-and-aft vibration with a backrest (Figure 6). For both a seated person exposed to fore-and-aft vibration with a backrest and a standing person exposed to lateral vibration with a shoulder support, vibration is transmitted directly to the chest – explaining the similarity in the response in these two situations.

5. Conclusion

The discomfort of standing persons caused by fore-and-aft or lateral vibration of the floor is not greatly affected by holding a vertical bar with an 'unlocked' elbow. However, at frequencies of vibration greater than about 2 Hz, the discomfort caused by fore-and-aft vibration is increased by leaning back against a back support, and the discomfort caused by lateral vibration is increased by leaning sideways on a shoulder support. A back support also increases discomfort caused by lateral vibration over the range 1 to 4 Hz. A back support reduces the discomfort caused by 0.5-Hz fore-and-aft vibration, and a shoulder support reduces the discomfort caused by 0.5-Hz lateral vibration. Weightings showing the effects of supports are offered so as to weight motions and take account of alternative postural supports when assessing the vibration discomfort of standing passengers.

The frequency-dependence of discomfort when standing without support, or when holding only a vertical bar, is not consistent with the frequency weightings provided for predicting the discomfort of standing people in current standards [3,4]. The discomfort caused by lateral vibration when standing with a shoulder support is broadly consistent with the standard method of predicting the discomfort of people seated with a backrest when exposed to fore-and-aft vibration.

6. Acknowledgements

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Table 1 Median support weightings for the contour corresponding to a magnitude estimate of '100' (i.e. the discomfort caused by 2-Hz vibration at 0.5 ms^{-2} r.m.s. presented without support in the same axis of motion). Conditions where the support had a statistically significant effect ($p<0.05$, Wilcoxon) on the acceleration contour are reported in bold characters: **(+)** greater acceleration (improved comfort with support); **(–)** smaller acceleration (degraded comfort with support).

	Fore-and-aft						Lateral					
	0.5 Hz	1 Hz	2 Hz	4 Hz	8 Hz	16Hz	0.5 Hz	1 Hz	2 Hz	4 Hz	8 Hz	16Hz
Bar	0.94	0.96	1.08	1.20	**1.32(–)**	1.15	1.06	0.98	1.04	0.99	0.99	1.28
Shoulder	1.09	1.20	**1.44(–)**	1.20	1.13	1.06	**0.77(+)**	1.43	**3.24(–)**	**2.11(–)**	**1.82(–)**	**2.73(–)**
Back	**0.92(+)**	0.97	**1.54(–)**	**2.57(–)**	**2.98(–)**	**2.96(–)**	0.96	**1.56(–)**	**2.28(–)**	**1.40(–)**	0.86	1.36

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Table 2 Frequency weighting curves advocated in BS 6841 (1987) and ISO 2631-1 (1997) or derived from these standards.

Point and direction	Weighting curve	Multiplying factor
x-axis (standing or seated)	W_d	k=1
y-axis (standing or seated)	W_d	k=1
x-axis, backrest	W_c	k = 0.8
y-axis, backrest	W_d	k = 0.5
x-axis, seat + backrest	$(W_d^2(f) + (0.8.W_c(f))^2)^{½}$	k = 1
y-axis, seat + backrest	$(W_d^2(f) + (0.5.W_d(f))^2)^{½}$ (i.e. $1.12.W_d(f)$)	k = 1

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Figure captions

Fig. 1 Frequencies and magnitudes of the vibration stimuli used in the experiment.

Fig. 2 Postures adopted by the subjects: (i) free; (ii) bar; (iii) shoulder; (iv) back.

Fig. 3 Equivalent comfort contours corresponding to a magnitude estimate of ‘100’ (i.e. the discomfort caused by a 2-Hz vibration at 0.5 ms^{-2} r.m.s. presented without support in the same axis of motion); ★: frequencies where the acceleration on the contour is significantly different with and without support (p<0.05, Wilcoxon).

Fig. 4 Median ‘support weightings’ and inter-quartile ranges with fore-and-aft and lateral vibration and the four support conditions.

Fig. 5 Median floor-to-head horizontal acceleration transmissibility of standing persons [17].

Fig. 6 Comparison of experimental median weightings and standard weightings.

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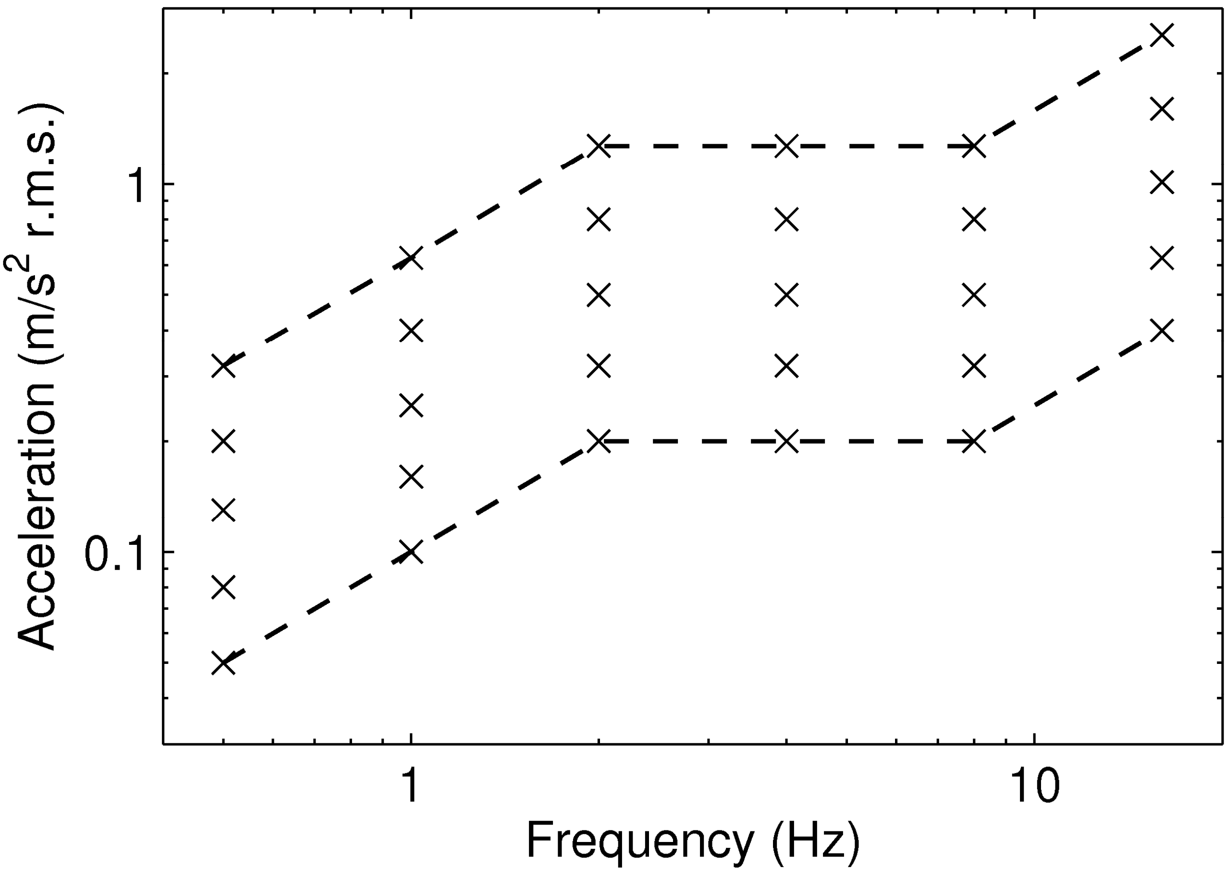

Figure 1

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Figure 2

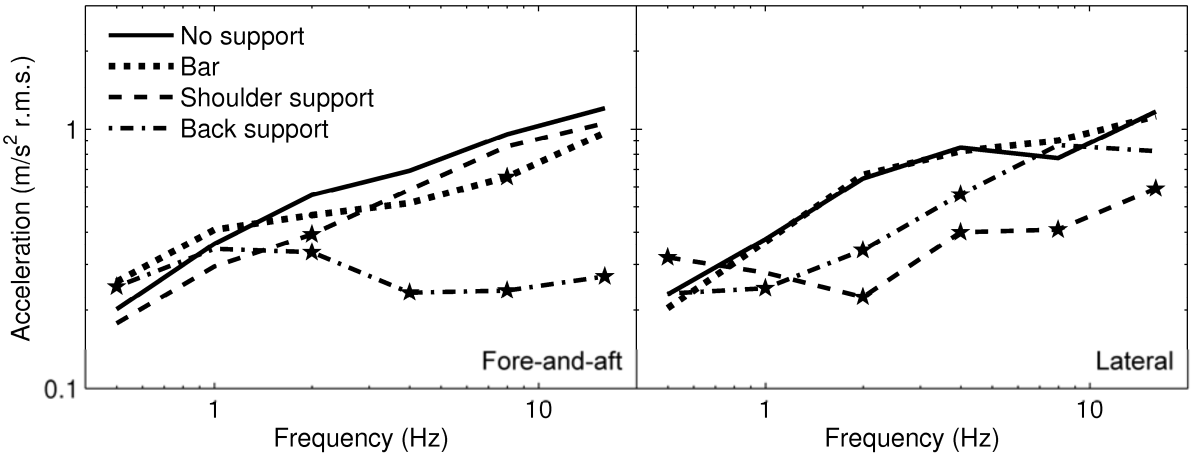
No support
Bar
Shoulder support
Back support
Acceleration (m/s2 r.m.s.)
1
0.1
Fore-and-aft
Lateral
1
10
1
10
Frequency (Hz)
Frequency (Hz)

Figure 3

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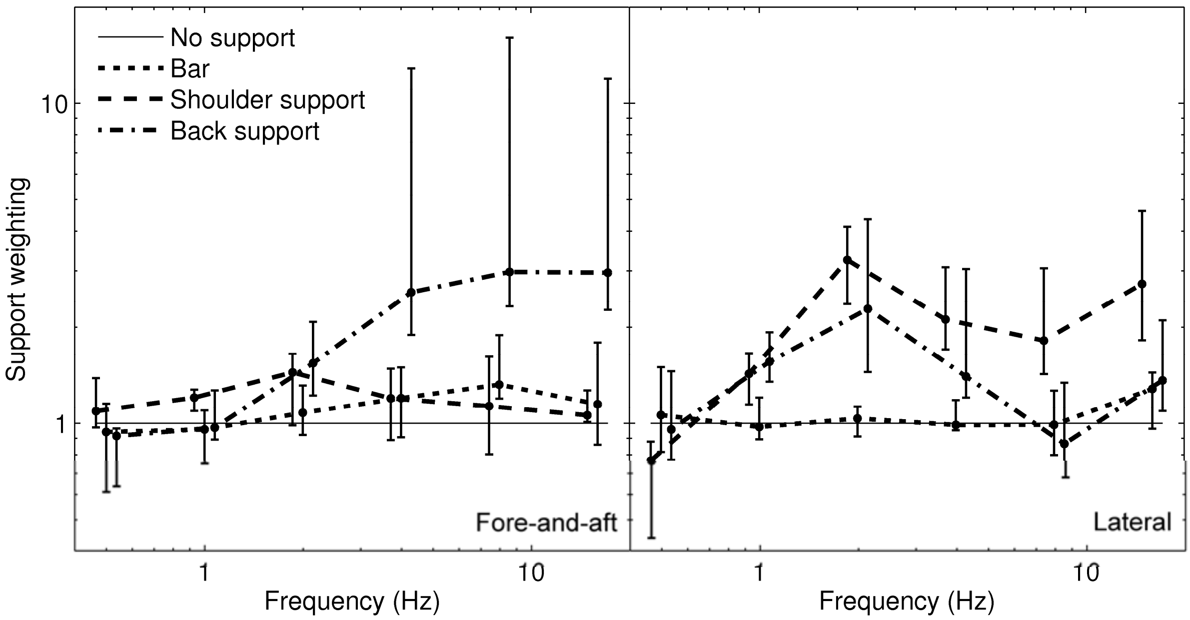

Figure 4

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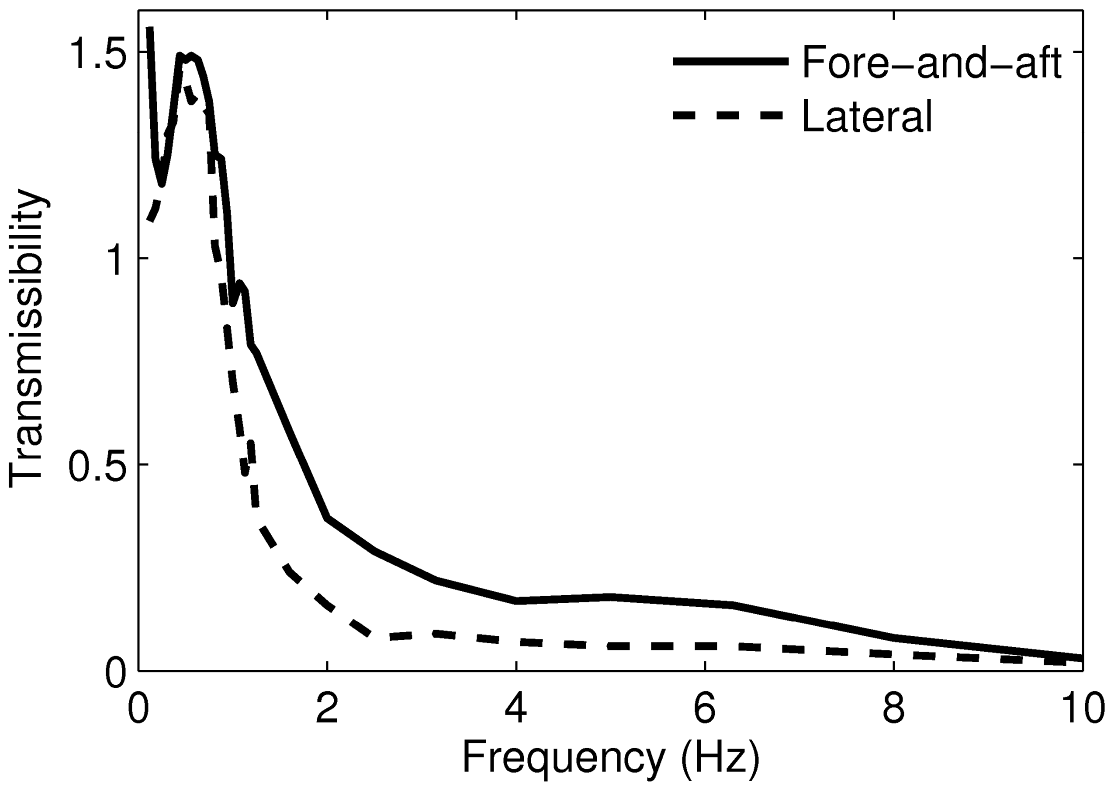

Figure 5

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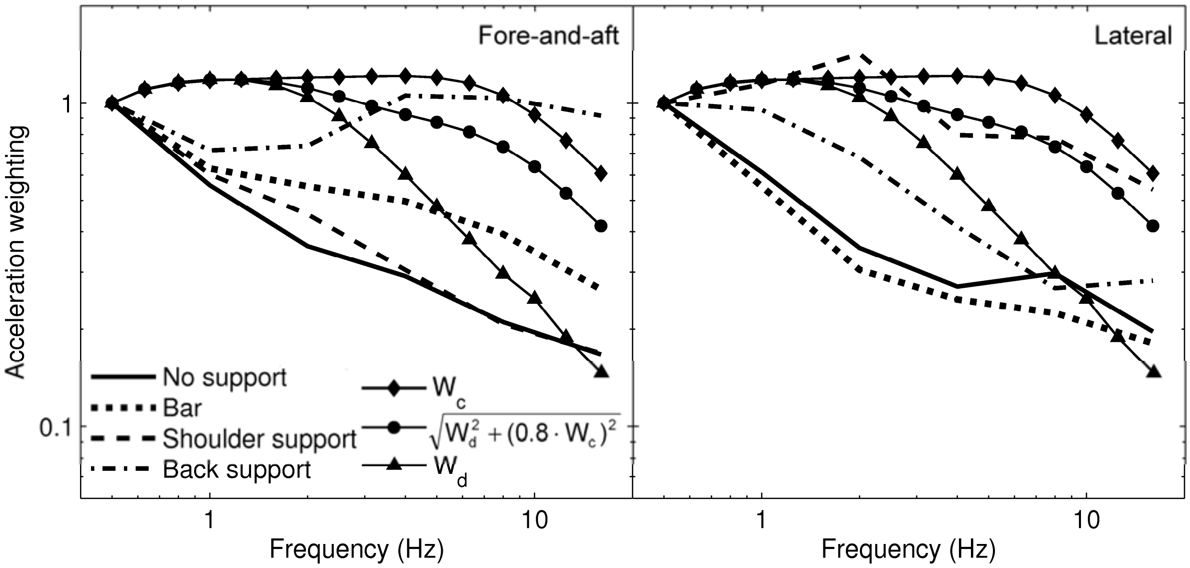

Figure 6