EFFECT OF BENDING THE LEGS ON THE DISCOMFORT CAUSED BY VERTICAL VIBRATION WHEN STANDING

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Abstract

The posture of the body affects the transmission of vibration through the body and so posture needs to be considered when assessing the risks associated with exposures to whole-body vibration and shock. When people are exposed to vibration they will want to stand in postures that minimise their discomfort, but it is unclear how the sensations produced by vertical vibration are affected by bending the legs. This study was designed to compare the discomfort caused by vertical vibration when standing with straight legs and standing with bent legs. Because bending the legs lowers the frequency of the principal resonance in the body it was hypothesized that greatest sensitivity to vibration acceleration would be at a lower frequency when standing with bent legs than when standing with straight legs. Fourteen subjects were exposed to 5-s periods of vertical sinusoidal vibration at the 16 preferred one-third octave centre frequencies in the range 0.5 to 16 Hz and at eight magnitudes in the range 0.3 to 3.2 ms^{-2} r.m.s. (unweighted), corresponding to frequency-weighted vibration dose values in the range 0.2 to 3.0 $ms^{-1.75}$ (W_b-weighting). Median equivalent comfort contours for unweighted acceleration showed greatest discomfort at frequencies in the range 2 to 3.15 Hz with bent legs and at frequencies greater than 5 Hz with straight legs. In both postures, the greatest sensitivity to vibration acceleration depended on the magnitude of vibration. It is concluded that when evaluating vertical vibration in respect of discomfort, the W_b frequency weighting is reasonable when standing with straight legs but underestimates the discomfort caused by 2 to 3 Hz vibration, and overestimates the discomfort at frequencies from 5 to 16 Hz, when standing with bent legs.

1. Introduction

Current standards specify methods for measuring, evaluating, and assessing the whole-body vibration experienced by standing, sitting, and recumbent people but do not define these postures precisely or indicate the effects of variations in these postures (British Standards Institution, 1987; International Organization for Standardisation, 1997). It is not clear, for example, whether the proposed methods are suitable when people stand with their legs bent. In British Standard 6841 (1987) a note in Section 4 (Guide to the evaluation of vibration and repeated shock with respect to effects on health) states: "*The method of evaluation is applicable to erect standing postures. However, slight bending of the knees can affect the transmission of vibration to standing persons so this application will not always be appropriate*". Standing with bent legs is common in many environments where people are exposed to vibration (e.g., high speed boats). Improved understanding of the effects of posture on perceived motion severity would be helpful in such situations.

Several studies of vibration discomfort have been conducted with standing subjects (e.g., Chaney, 1965; Ashley, 1970; Jones and Saunders, 1972; Oborne and Clarke, 1974; Thuong and Griffin, 2011).

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When standing with straight legs these studies suggest greatest sensitivity to acceleration in the frequency range 4 to 16 Hz, consistent with the frequency weightings advocated in current standards. However, the rate of growth of discomfort depends on the frequency of vibration, so the frequency-dependence of equivalent comfort contours varies with the magnitude of vibration, and a single frequency weighting is not optimum for all magnitudes of vibration (Thuong and Griffin, 2011).

A change of posture changes the dynamic mechanical properties of the body. The principal resonance frequency in the vertical transmissibility to the head is about 5 Hz when sitting or when standing with straight legs, but the resonance frequency drops to about 3 Hz when standing with bent legs (Paddan and Griffin, 1988, 1993). At frequencies greater than about 8 Hz, the vertical transmissibility is greater when 'standing with straight legs' than when 'standing with bent legs' (Paddan and Griffin, 1993). Similarly, the resonance frequency in the vertical apparent mass of the standing body decreases from around 5 Hz to about 2.75 Hz when the knees are bent, and there is increased fore-and-aft cross-axis transmissibility to the knees around 2.75 Hz (Matsumoto and Griffin, 1998; Subashi *et al*., 2006). It was suggested that bending motion at the knees contributes to the whole-body resonance in this posture. At frequencies greater than about 6 or 7 Hz, both the transmissibility to the head and the apparent mass are greater in a standing posture (with straight legs) than in a 'normal' sitting posture (Paddan and Griffin, 1993, 1998; Matsumoto and Griffin, 2000).

Large changes in the biodynamic responses suggest there will also be changes in subjective responses when the knees are bent during exposure to vertical vibration. This study was designed to investigate the extent to which a change in standing posture changes subjective responses to vertical vibration.

It was expected that equivalent comfort contours obtained when 'standing with straight legs' would be consistent with the W_b frequency weighting (as in BS 6841:1987). However, when 'standing with bent legs' it was hypothesised this weighting would underestimate discomfort at frequencies around 2 to 4 Hz and overestimate discomfort at higher frequencies. It was also hypothesised that in both postures the rate of growth of discomfort would depend on the frequency of vibration.

2. Methods

2.1 Subjects

Fourteen male students and office workers of the University of Southampton participated in the study. They were aged 22 to 37 years, had statures between 160 and 185 cm, and weights between 56 and 120 kg. The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (Reference number: 10565).

2.2 Apparatus

Vertical vibration was produced by a 1-m stroke vertical electrohydraulic vibrator (Servotest Testing Systems Ltd., Surrey, UK). All signals were generated using the *HVLab* Matlab Toolbox (version 2.0, ISVR, University of Southampton, UK), and equalized and reproduced by a Servotest Pulsar system. Accelerations were measured using a capacitive accelerometer 2260-002 (Silicon Designs Inc.) attached to the platform.

To protect subjects if they fell, they wore a loose whole-body harness secured to a metal frame mounted on the vibrator platform. The subjects were told to rest their hands on a handrail 105 cm above the platform, so that they could use it to maintain their balance if they thought they might fall.

A noise box (HFRU Noise system 001, ISVR, University of Southampton, UK) produced white noise at approximately 75 dB via a pair of headphones so as to mask any noise of the vibrator. For safety reasons subjects were provided with an emergency stop button.

2.3 Stimuli

The motions were vertical sinusoidal vibrations at the preferred one-third octave centre frequencies in the frequency range 0.5 to 16 Hz. All motion stimuli had durations of 5 s and were enveloped with a half cosine of frequency 0.1 Hz.

The motions were quantified in terms of their root-mean-square, r.m.s., and vibration dose value, VDV, both unweighted and frequency-weighted using weighting W_b (BS 6841:1987). At each fundamental frequency, eight magnitudes were presented in 2 dB steps. The magnitudes varied with the frequency of motion but were always within the range 0.3 to 3.2 ms^{-2} r.m.s. (unweighted) and within the range 0.2 to 3.0 $ms^{-1.75}$ (VDV frequency-weighted using W_b).

2.4 Procedure

Participants attended one session that was split into two parts, one for ‘standing with straight legs’ and the other for ‘standing with bent legs’ (Figure 1). The feet were separated so as to be placed beneath the outer portions of the shoulders. Between the two parts of the experiment there was a 5-minute break, during which the experimenter adjusted the harness. Half of the participants started with bent legs and the others started with straight legs. When the legs were bent, the front of the knees was directly above the toes. Subjects had their eyes closed during exposure to vibration.

The method of absolute magnitude estimation was used to obtain judgements of subject discomfort caused by each frequency and magnitude of vibration in both postures.

Before commencing the experiment, participants were trained how to use magnitude estimation to rate the apparent length of lines and, subsequently, 14 practice motion stimuli.

The session lasted about one hour and included a total of 256 test stimuli (i.e., 8 magnitudes at 16 frequencies in two postures).

2.5 Equivalent comfort contours

It was assumed that the subjective magnitude (i.e., vibration discomfort), ψ, was related to the objective magnitude (i.e., vibration magnitude), φ, through Stevens’ power law:

$$\psi = k\,\varphi^n$$

where k is a constant and the exponent n is called the rate of growth of discomfort. From the measured accelerations and the subjective data, the values of n and k were calculated by regression between log ψ and log φ at each frequency of vibration for all individual subjects.

Prior to calculating n and k, the subjective data from an individual were normalized by dividing each of their judgements by the median value calculated of their 256 judgements and then multiplying by 100.

Figure 1 The two standing postures: standing with straight legs (left) and standing with bent legs (right).

Having obtained the values of *n* and *k*, both individual and median equivalent comfort contours were calculated by determining the vibration magnitude, φ, required to obtain subjective magnitudes of ψ = 63, 80, 100, 125 and 160 at each frequency in the range 0.5 to 16 Hz.

The median equivalent comfort contours presented below were obtained using median values of *n* and *k* calculated from the individual values of *n* and *k*.

2.6 Statistical analysis

The rate of growth of discomfort and equivalent comfort contours were used to test the hypotheses. Non-parametric tests were used in the statistical analysis. In order to investigate differences between related samples, the Friedman two-way analysis of variance and Wilcoxon matched-pairs signed ranks were used. The probabilities shown are not adjusted for multiple comparisons.

3. Results

In both postures, the rate of growth of discomfort decreased with increasing frequency of vibration (p<0.001, Friedman; Figure 2). There were significant differences in the rate of growth of discomfort between postures at 2.5 Hz (p=0.041), 4 Hz (p=0.007) and at 5 Hz (p=0.048), where the rate of growth was greater with straight legs.

Median equivalent comfort contours for the two postures are compared in Figure 3, for subjective magnitudes of ψ = 63, 80, 100, 125 and 160.

The unweighted VDV required for a subjective magnitude of ψ = 100 varied with the frequency of vibration in both postures (p<0.001, Friedman). In the frequency range 2 to 3.15 Hz a greater unweighted VDV was required to cause the same discomfort (i.e., ψ = 100) with straight legs than with bent legs (p<0.01, Wilcoxon). In the frequency range 5 to 16 Hz, a greater unweighted VDV was required to cause the same discomfort with bent legs than with straight legs (p<0.041, Wilcoxon).

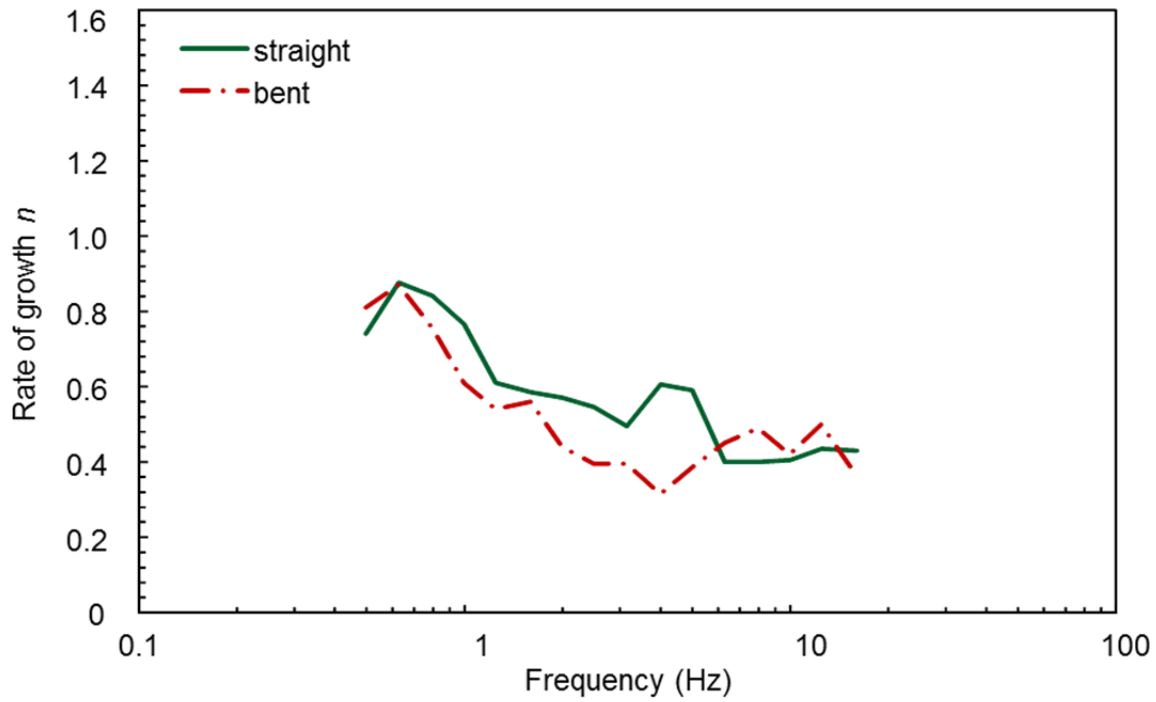

Figure 2 Rates of growth of discomfort, *n*, obtained with 'straight legs' (▬▬) and with 'bent legs' (▬ ▪). Median values for 14 subjects.

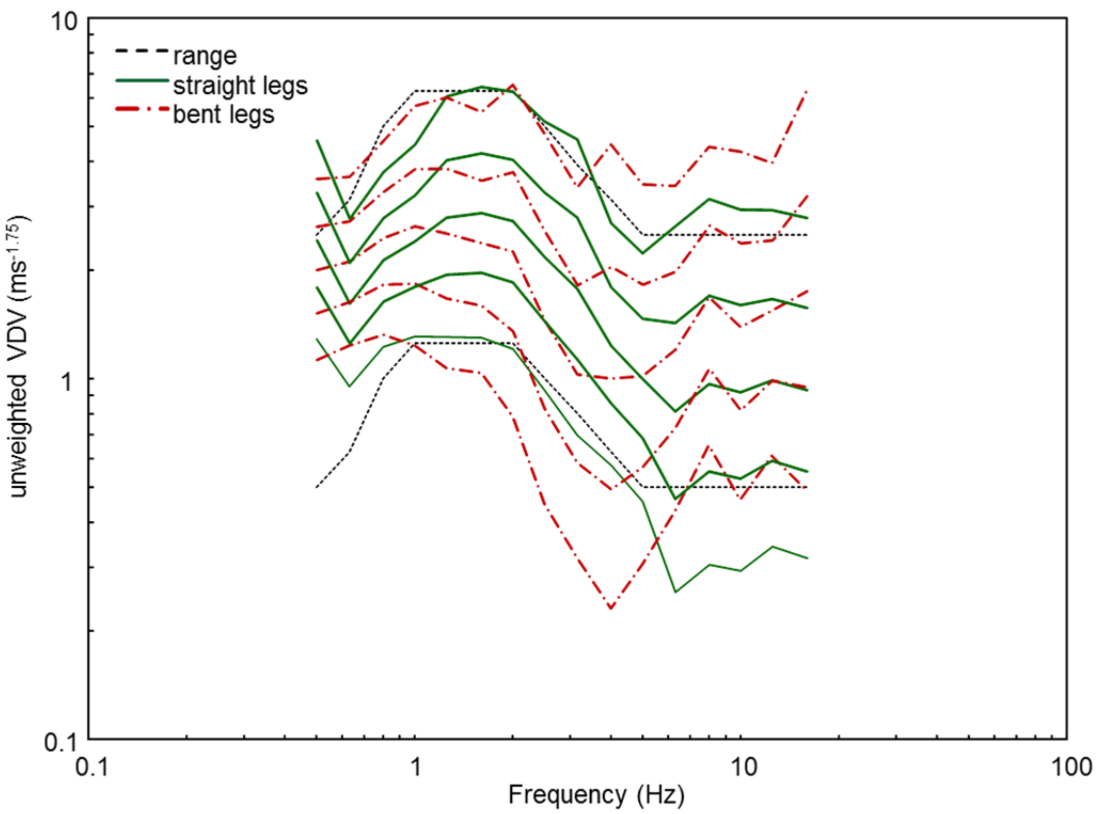

Figure 3 Equivalent comfort contours obtained with 'straight legs' (▬▬) and 'bent legs' (▬ ▪). Contours shown for ψ = 63, 80, 100, 125 and 160. Median values for 14 subjects. Range (- - -) shows the lowest and highest magnitudes presented to subjects.

4. Discussion

The rate of growth of discomfort varied greatly with the frequency of vibration (Figure 2), causing changes in the shapes of the equivalent comfort contours as the magnitude of vibration changed (Figure 3). Many previous studies of vibration discomfort have found an effect of vibration magnitude on the frequency-dependence of vibration discomfort using different magnitudes and frequencies (e.g., Morioka and Griffin, 2006), different stimuli (e.g., Ahn and Griffin, 2008) and different postures (e.g., Basri and Griffin, 2013; Thuong and Griffin, 2011). The effect of magnitude on the frequency-dependence of vibration discomfort found with the two postures in the present study shows that no single frequency weighting will give an accurate prediction of vibration discomfort in either of the two postures.

The frequency of greatest sensitivity to acceleration decreased from the range 5 to 7 Hz with straight legs to the range 3 to 4 Hz with bent knees (Figure 3). Biodynamic studies with similar standing postures found the resonance in the vertical transmissibility to the head reduced from around 5 Hz with straight legs to around 3 Hz with 'bent legs' (Paddan and Griffin, 1993). In the same study, head motion in the fore-and-aft axis was more pronounced when subjects stood with bent legs than with straight legs. The principal resonance of the apparent mass in an upright standing posture (straight legs locked) was around 5 Hz (and close to the apparent mass resonance of the seated body) but decreased to around 2.75 Hz with bent knees (Matsumoto and Griffin, 1998). In the same study, transmissibility to the knees in the fore-and-aft direction presented a main peak around 3 Hz, suggesting the resonance was associated with bending of the knees. A resonance around 3 Hz suggests increased motion of the whole body that could compromise comfort.

When expressed in terms of unweighted r.m.s. acceleration, the equivalent comfort contours obtained with straight legs seem consistent with contours reported previously (Figure 4).

Some differences between the contours obtained in different studies might be attributable to the use of different psychophysical methods and different experimental settings (e.g., absence of a handrail). However, in all conditions where subjects were either sitting upright or standing with their legs straight, the acceleration required to cause a degree of discomfort decreases as the frequency of vibration increases from 2 Hz to 5 or 6 Hz. The similar findings when sitting upright with no backrest and when standing with straight legs is consistent with the use of frequency weighting W_b when evaluating exposures to vertical vibration in these two postures. However, when standing with bent legs, the acceleration required to cause a degree of discomfort decreases as the frequency of vibration increases from 1.6 to 3 Hz, after which the contours gradually rise. A frequency weighting that gives greatest weight to frequencies from 5 to 16 Hz, such as W_b will therefore not provide a good prediction of vibration discomfort when standing with bent legs.

Figure 5 compares the two median equivalent comfort contours (both postures with ψ = 100 for 16 frequencies from 0.5 to 16 Hz) in terms of vibration dose values frequency weighted by W_b. If the weighting was perfect for evaluating vertical vibration when standing in either posture, the two contours would be two coincident horizontal lines.

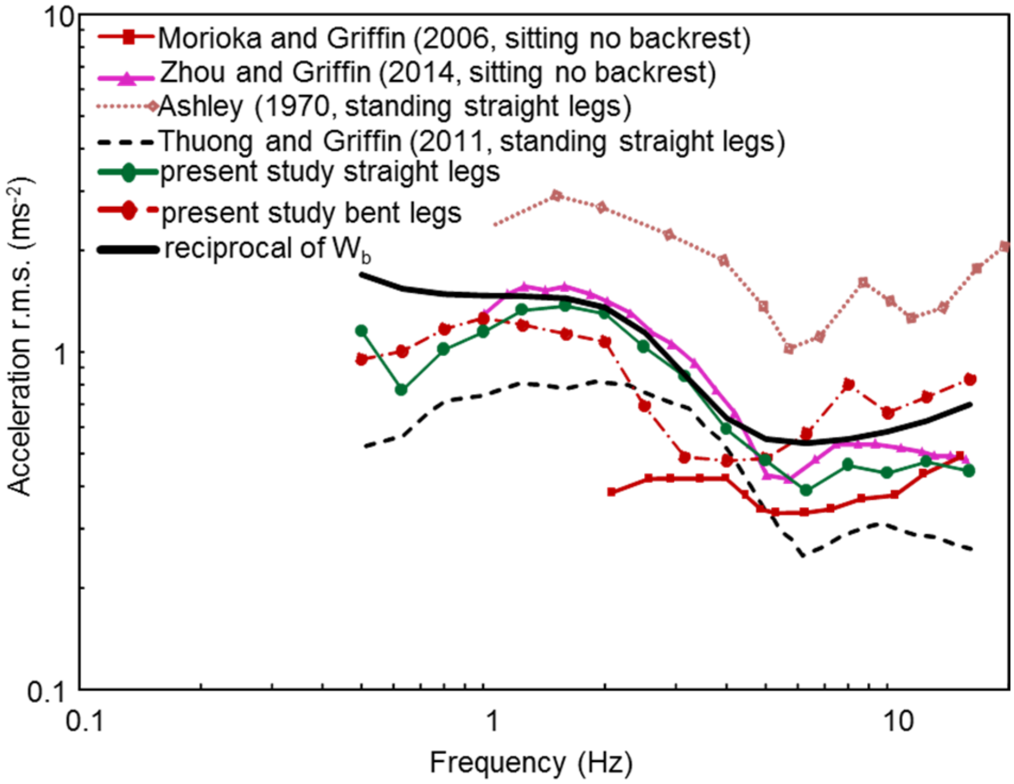

Figure 4 Equivalent comfort contours from the present and past studies with similar and different postures at a subjective magnitude of ψ = 100.

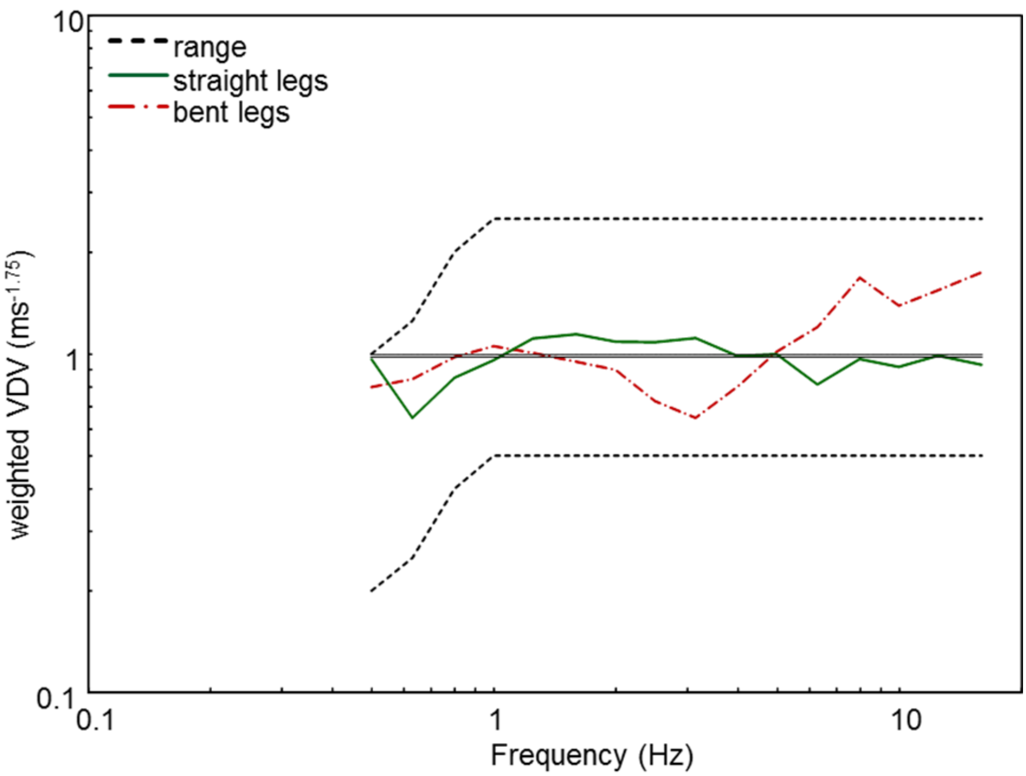

Figure 5 Equivalent comfort contours in terms of W_b frequency-weighted VDV with 'straight legs' (▬▬) and 'bent legs' (▬ ▪) for a subjective magnitude ψ=100. Median values for 14 subjects. Range (- - -) shows the lowest and highest magnitudes presented to subjects.

The variability of the 16 weighted values in each of the two lines in Figure 5 relative to the median value of each line was estimated separately. When standing with ‘straight legs’, relative to the median value of 0.98 $ms^{-1.75}$, the weighted VDV varies between a maximum of +1.39 dB (at 1.6 Hz) and a minimum of -3.6 dB (at 0.63 Hz), with an average error of -0.11 dB. When standing with ‘bent legs’, relative to the median value of 0.99 $ms^{-1.75}$, the weighted VDV varies between a maximum of +4.89 dB (at 16 Hz) and a minimum of -3.72 dB (at 3.15 Hz), with an average error of +0.35 dB. In BS 6841:1987 it is noted that the frequency weighting W_b is applicable to erect standing postures and that it may not always be appropriate when the knees are bent. This study shows that if the legs are bent, the application of frequency weighting W_b will tend to underestimate discomfort at frequencies around 2 to 3 Hz and overestimate discomfort at frequencies greater than about 5 Hz.

5. Conclusion

Bending the legs increases the discomfort caused by vertical vibration in the frequency range 2 to 3 Hz but reduces the discomfort caused by frequencies greater than 5 Hz. Frequency weighting W_b is reasonable for evaluating vertical vibration when people stand with straight legs but underestimates the discomfort at frequencies between 2 to 3 Hz and overestimates the discomfort at frequencies greater than 5 Hz when standing with legs bent at the knees. In both postures, the frequency-dependence of vibration discomfort depends on the magnitude of vibration.

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