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Original Article

Frequency Weightings for Fore-and-aft Vibration at the Back: Effect of Contact Location, Contact Area, and Body Posture

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Abstract: Fore-and-aft vibration of a backrest can influence discomfort and the risk of injury associated with whole-body vibration. Relevant standards (BS 6841:1987 and ISO2631-1:1997) recommend the W_c frequency weighting for evaluating fore-and-aft vibration of backrests, but do not specify the precise location for measuring vibration. This study determined equivalent comfort contours for fore-and-aft vibration of the backs of seated persons from 2 to 80 Hz using the method of magnitude estimation, examining the effect of input location, contact area, and body posture. The equivalent comfort contours indicate decreased sensitivity to vibration acceleration at frequencies greater than 8 Hz. Equivalent comfort contours with a full backrest were similar to those with contact at only the highest location on the back. The derived frequency weightings are broadly consistent with frequency weighting W_c but suggest somewhat greater sensitivity at frequencies greater than 30 Hz and vary in shape with changes in vibration magnitude. It is concluded that with low and moderate magnitudes of vibration the severity of fore-and-aft vibration of a backrest can be assessed from the frequency-weighted fore-and-aft acceleration measured at the highest point of contact between the backrest and the body if the frequency weighting W_c is employed in the evaluation.

Key words: Whole-body vibration, Backrest, Equivalent comfort contour, Contact area, Contact location, Body posture

Introduction

Vibration can be transmitted to the body of a seated person via the seat, a support for the feet, and a backrest. In some environments, fore-and-aft vibration of the backrest can be a principal source of discomfort and may influence the risk of injury associated with whole-body vibration. The fore-and-aft vibration of the backrest of a car seat can be caused by a combination of the fore-and-aft, vertical, and pitch vibration of the floor[1)], often with a principal peak in the transmissibility of the backrest around 5 Hz[2, 3)].

For the evaluation of whole-body vibration with respect to health, British Standard 6841[4)] requires consideration of fore-and-aft vibration at the backrest in addition to vibration in the three orthogonal axes on the supporting seat surface. International Standard 2631-1[5)] requires consideration of all three translational axes on the supporting seat surface and encourages measurements of fore-and-aft vibration on the backrest. The EU Physical Agents (vibration) Directive[6)] only requires consideration of vibration on the supporting seat surface in the direction having the greatest weighted magnitude, and does not require consideration of vibration on the backrest. The relevant standards[4, 5)] advocate the use of the W_c frequency weighting for evaluating fore-and-aft vibration at a backrest, but do not specify the precise location for measuring vibration. Whereas BS 6841 says "*Measurements on the seat-back should be made at the position with the greatest effective vibration in contact with the body*", ISO 2631 says "*Measurements on the seat-back should be made in the area of principal support of the body*".

The W_c frequency weighting was based on an equivalent comfort contour for fore-and-aft vibration of a vertical backrest determined over the frequency range 2 to 63 Hz at vibration magnitudes causing discomfort equivalent to that caused by 0.8 ms^{-2} r.m.s. 10-Hz vertical seat vibration[7)]. Equivalent comfort contours show the vibration magnitudes required to produce the same strength of sensation across a range of frequencies of vibration and indicate, for example, the frequencies producing the greatest discomfort (where the least acceleration is required to cause discomfort). Equivalent comfort contours for fore-and-aft vibration of the back have also been determined, over the frequency range 2 to 80 Hz with backrest inclinations of 0, 20 and 40 degrees using vibration magnitudes producing discomfort equivalent to that caused by 0.25 ms^{-2} r.m.s. 10-Hz vertical seat vibration[8)]. The equivalent comfort contour obtained with a 0 degree (vertical) backrest was similar to the W_c frequency weighting, whereas contours obtained with inclined backrests showed differences.

With vertical whole-body vibration, the posture of the body can alter both seat-to-head transmissibility and vibration discomfort. When asked to change their posture from relaxed

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(i.e. slouched) to erect (i.e. upright) during exposure to vertical vibration, subjects sitting without a backrest had increased transmission of vibration to the head and lower equivalent comfort contours (i.e. increased sensitivity to vibration) at frequencies greater than 10 Hz[7]. However, in contrast, Oborne and Boarer[9] reported similar comfort contours for vertical whole-body vibration with subjects sitting in 'slouched' and 'upright' postures. There are no known studies of the effects of body posture on equivalent comfort contours for fore-and-aft vibration at the back.

The contact location and contact area may influence discomfort caused by vibration of a backrest. At very low frequencies, contact with a backrest over the full height of the back might be beneficial in providing stability to the body (i.e. reducing back motion), depending on the phase between the motions of the seat and the backrest. At high frequencies, contact with a backrest may increase vibration in the body if the vibration at the supporting seat surface would otherwise be attenuated by the dynamics of the body. It has been found that in a seat where the backrest provided only lumbar support, the backrest increased discomfort caused by fore-and-aft vibration at frequencies between 3 and 5 Hz[10]. Any beneficial or detrimental effects of backrest vibration may be expected to vary with the height of backrest contact and the area of backrest contact, in addition to the frequency of the vibration.

The transmission of fore-and-aft vibration to the backrest of a car seat has been shown to vary with height up the backrest, with greatest transmissibility at the middle of backrest, possibly due to variations in the dynamic stiffness of the backrest and regional differences in the apparent mass of the back[11]. The fore-and-aft apparent mass of the back has been shown to vary with the location of application of vibration to the back, with varying resonance frequencies[12]. It seems reasonable to expect that differences between the dynamic responses of the back at different heights will result in differences in the discomfort caused by fore-and-aft vibration applied at different positions on the back.

Equivalent comfort contours for fore-and-aft, lateral, and vertical vibration depend on the magnitude of vibration at the seat[13], at the hand[14] and at the foot[15]. The magnitude-dependence of equivalent comfort contours for the hand and the foot has been partly explained by mediation via different psychophysical channels at different vibration magnitudes[14, 15]. With whole-body vibration, the frequencies at which the equivalent comfort contours for vertical vibration show greatest discomfort appear to correspond to resonance frequencies[13]. A combined study of discomfort and apparent mass at frequencies of horizontal vibration between 1.6 and 10 Hz at magnitudes in the range 0.125 to 1.0 ms^{-2} r.m.s. found that discomfort and apparent mass were similarly affected by both the frequency and the magnitude of vibration, suggesting the non-linear subjective response may partly be attributed to the non-linear biodynamic responses[16]. Similar findings have been reported for continuous and transient whole-body vertical vibration[17]. The only known equivalent comfort contours for backrest vibration[7, 8] were obtained at a single level of discomfort. Since the mechanisms involved in the perception of vibration at a backrest are not well understood, it is not known whether equivalent comfort contours for the back exhibit a magnitude-dependence.

This study was designed to determine equivalent comfort contours for fore-and-aft vibration of the backs of seated persons over a range of vibration frequencies (2 to 80 Hz) and over a range of vibration magnitudes (from close to the threshold of perception to magnitudes associated with discomfort and risks to health), examining the effects of input location, contact area, and body posture.

Methods

Subjects

Twelve male subjects with a mean age of 24.2 yr (standard deviation, SD=1.9), a mean height of 180.3 cm (SD=6.7) and a mean weight of 74.0 kg (SD=10.0) participated in the study. All subjects were students or office workers with no history of occupational exposure to whole-body vibration.

Prior to vibration exposure, each subject completed a health questionnaire and an exposure consent form. Subjects were provided with written instructions and given the opportunity to ask questions prior to commencement.

The experiment was approved by the Human Experimentation Safety and Ethics Committee of the ISVR, University of Southampton. Informed consent to participate in the experiments was given by all subjects.

Backrest conditions

Equivalent comfort contours were determined with 10 backrest conditions, with input locations, contact areas, and body postures as described in Table 1 and shown in Fig. 1. A supplementary experiment was also performed to determine the relative discomfort between the 10 backrest conditions.

Apparatus

In the main experiment, fore-and-aft vibration of a wooden full backrest (650 × 680 mm) was generated by a Derritron VP85 vibrator that had a three link-arm suspension system capable of supporting a static load of 350 kg. The vibrator was mounted in a rigid trunnion and powered by a 1,000 w amplifier (Derritron), supplied with a cooling fan. Two shorter wooden backrests (125 mm and 250 mm in height), with rounded edges at the top and bottom, and were rigidly secured to the full backrest at required positions so that a total of 10 different backrest contact conditions could be investigated. Subjects sat on a stationary horizontal flat wooden seat 15 cm below the bottom of the full backrest and supported their feet on a stationary footrest, with the height of the footrest adjusted so that with their lower legs vertical the upper surfaces of their upper legs were approximately horizontal.

In a supplementary experiment to determine the relative discomfort between the 10 different backrest conditions, a Derritron VP30 vibrator with a full wooden backrest (650 × 680 mm) was employed with an identical stationary wooden seat. In this experiment, subjects moved between a backrest secured to the VP85 vibrator and the full backrest secured to the VP30 vibrator while their feet remained on the same stationary footrest.

Sinusoidal vibration was generated and acquired using *HVLab* Data Acquisition and Analysis Software (version 3.81) via a personal computer with anti-aliasing filters (TechFilter)

Table 1. Ten backrest conditions (see Fig. 1 for schematic presentation of the conditions)

Condition	Backrest height	Backrest position	Body posture
Condition 1	12.5 cm	Top	Upright
Condition 2	12.5 cm	Upper-middle	Upright
Condition 3	12.5 cm	Middle	Upright
Condition 4	12.5 cm	Lower-middle	Upright
Condition 5	12.5 cm	Bottom	Upright
Condition 6	25.0 cm	Top and upper-middle	Upright
Condition 7	25.0 cm	Bottom and lower-middle	Upright
Condition 8	65.0 cm	Full back	Upright
Condition 9	12.5 cm	Middle	Relaxed
Condition 10	65.0 cm	Full Back	Relaxed

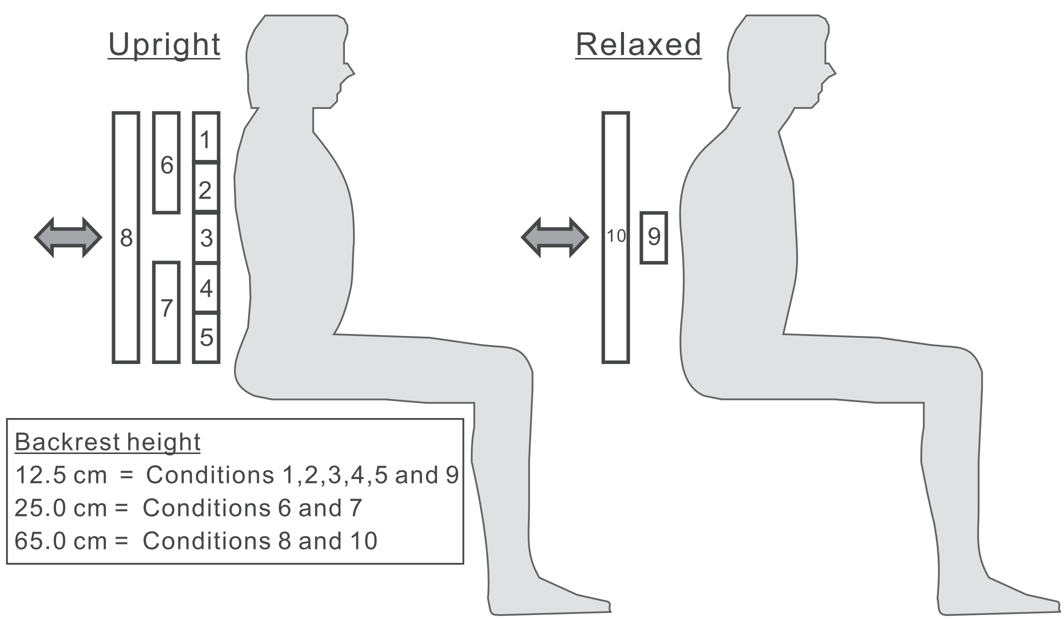

Fig. 1. Ten backrest conditions employed in the experiment. The subjects sat on a stationary rigid seat with their feet resting on a stationary rigid footrest.

and analogue-to-digital and digital-to-analogue converters (PCL-818). The signals were generated at 1,000 samples per second and passed through 150-Hz low-pass filters. The stimulus parameters and the psychophysical measurement procedures were computer-controlled. A piezoresistive accelerometer (Entran EGCSY-240D*-10) was attached near to the centre of each wooden backrest. The background vibration, mostly electrical noise at 50 Hz, was less than 0.005 ms^{-2} r.m.s. and was not perceptible to subjects.

Stimuli

Sinusoidal vibratory stimuli, 6 s in duration, with rise and fall times of 0.5 s were created with cosine-tapered ends. Test stimuli were presented at each of the 17 preferred 1/3rd-octave centre frequencies from 2 to 80 Hz at each of eight acceleration magnitudes (0.08, 0.125, 0.20, 0.315, 0.50, 0.80, 1.25 and 2.0 ms^{-2} r.m.s.) (Table 2). For Conditions 1 to 7 and Condition 9, vibration stimuli at 20, 25, 40, 50, and 80 Hz were omitted.

Procedure

Each subject attended a total of seven sessions to complete the main experiment and the supplementary experiment. Each session lasted about an hour including breaks.

In the main experiment, the psychophysical method of magnitude estimation (Stevens, 1975) was employed to obtain ratings of the discomfort caused by fore-and-aft vibration within each of the 10 backrest conditions. Pairs of motions, a 6-s reference motion and a 6-s test motion, were presented with a 1.0-s interval. The reference motion was fixed with a frequency of 10 Hz and a magnitude of 0.315 ms^{-2} r.m.s. The test motion was randomly presented from the range of frequencies and magnitudes shown in Table 2. Both the reference motion and the test motion were presented with the same backrest condition. Subjects were asked to assign a number representing the discomfort of the test motion relative to the discomfort of the reference motion, assuming the discomfort of the reference motion corresponded to ‘100’. Subjects were able to ask for a pair of stimuli to be repeated if they were

Table 2. Test stimuli employed in the main experiment. A reference stimulus (10 Hz at 0.315 ms^{-2} r.m.s.) was used throughout the experiment

	Magnitude (ms^{-2} r.m.s.)							
Frequency (Hz)	0.08	0.125	0.20	0.315	0.50	0.80	1.25	2.0
2	+	+	+	+	+			
2.5								
3.15								
4								
5								
6.3								
8								
10								
12.5								
16								
20		+	+	+	+	+	+	+
25		+	+	+	+	+	+	+
31.5								
40			+	+	+	+	+	+
50			+	+	+	+	+	+
63								
80			+	+	+	+	+	+

= Stimuli used for all 10 backrest conditions.

+ = Additional stimuli used for Conditions 8 and 10 (full backrest).

unsure of their judgment. They were instructed to indicate ‘no sensation’ if the test stimulus was not perceived. A small cue light was illuminated during the presentation of the reference and the test stimuli.

Prior to commencing the experiment, subjects practiced magnitude estimation by judging the lengths of lines drawn on a paper and then by judging a few selected vibration stimuli. This provided an opportunity to check that subjects understood the procedure and also familiarised them with the type of vibration stimuli.

The supplementary experiment was performed with the same subjects to determine the relative discomfort caused by 10-Hz fore-and-aft backrest vibration between the 10 backrest conditions. This experiment also employed the method of magnitude estimation with the reference stimulus (at 0.315 ms^{-2} r.m.s.) presented in Condition 8 (full back, upright posture) and the test stimulus (randomly presented from seven magnitudes: 0.08, 0.125, 0.2, 0.315, 0.5, 0.8, and 1.25 ms^{-2} r.m.s.) in each of the 10 backrest conditions. The interval between the reference and test stimuli was not fixed, allowing the experimenter to trigger the reference stimulus when a subject completed the change of backrest condition. The duration between the reference stimulus and the test stimulus varied between subjects and backrest conditions, but was no more than 5 s.

A few stimuli at low magnitudes were not perceived by all subjects and were not included in the analysis of judgements. Magnitude estimates lower than 10 were also excluded.

During the tests, subjects were exposed to white noise at approximately 70 dB(A) via a pair of headphones to prevent them hearing the vibration and to assist their concentration on the vibration by masking any distracting sounds.

Data analysis

The determination of the growth in sensation with increasing vibration magnitude was made using Steven’s Power Law[18]:

$$\psi = k\varphi^n \tag{1}$$

This suggests a linear relationship, with a slope, n, between the logarithm of the psychophysical magnitude, ψ, (i.e. the subjective magnitude of a stimulus) and the logarithm of the physical magnitude, φ, (i.e. objectively measured vibration acceleration of a stimulus).

For each subject, linear regressions between the logarithms of the subjective magnitudes and the logarithms of the physical magnitudes were performed to determine the exponent, n, and the regression constant, k, at each frequency for each backrest condition. Individual values of k and n were thereby determined for each subject for all frequencies with each backrest condition.

Vibration magnitudes required to produce a particular sensation magnitude across the frequency range (i.e. an equivalent comfort contour) were determined by transforming Eq. (1) to:

$$\log_{10}\psi = n \log_{10}\varphi + \log_{10}k \tag{2}$$

Equivalent comfort contours for sensation magnitudes ranging from 25 to 300 were produced for each of the 10 backrest conditions, based on the median values of the exponent, n, and the constant, k, over the 12 subjects.

The equivalent comfort contours were adjusted to reflect the relative discomfort between the 10 backrest conditions with the 10-Hz reference stimulus of Condition 8 (full backrest with upright posture). Firstly, the equivalent comfort contours for all 10 backrest conditions were normalised so that within each condition the acceleration magnitude at 10 Hz equivalent to a sensation magnitude of 100 was produced by 0.315 ms^{-2} r.m.s. (i.e. the reference stimulus used within each condition). This required only very minor adjustment. Secondly, using the data from the supplementary experiment, the subjective magnitude produced by 0.315 ms^{-2} r.m.s. at 10 Hz with each of the 10 backrest conditions was determined relative to the subjective magnitude of the same stimulus with Condition 8 (full backrest with upright posture), using Stevens power law as shown in Eq. (1). For each backrest condition, the equivalent comfort contours were then adjusted by multiplying the sensation magnitudes by the median percentage difference between the subjective magnitude obtained with that condition and that obtained with Condition 8 (full backrest with upright posture).

Data were analysed using the Statistical Package for the Social Sciences (SPSS) version 17.0. Non-parametrical statistical techniques were employed: Friedman two-way analysis of variance and Wilcoxon matched-pairs signed ranks tests for repeated measures and the Spearman rank correlation to test for an association between variables.

Results

Growth of sensation

The median rates of growth of sensation (exponent n) at each frequency are compared between backrest conditions in Fig. 2, comparing the effects of contact location, contact area and body posture. A unity value for the exponent (i.e. n=1.0) means that as the magnitude of vibration doubles the rating of discomfort doubles. The greater the exponent the greater the rate of increase in discomfort as vibration magnitude increases. The median rates of growth of sensation (exponent n) and constant values (k) for each frequency of selected backrest conditions (Conditions 1, 3, 5, 8 and 9) are shown in Table 3.

There were statistically significant effects of vibration frequency on the rate of growth of sensation with increasing magnitude of vibration, with a similar frequency-dependence in all backrest conditions (Friedman, p<0.01). However, there were no statistically differences in the rate of growth between 8 and 80 Hz in any backrest condition (Friedman, p>0.05). The frequency-dependence of the rate of growth of sensation in Condition 1 and Condition 8 illustrate the trends in other conditions. In Condition 1, the rate of growth of sensation at 2.5 Hz was significantly greater than any other frequency (Wilcoxon, p<0.05), whereas the rate of growth at 8 Hz was significantly less than at 10, 12.5 and 16 Hz (Wilcoxon, p<0.05). In Condition 8, the rate of growth at 3.15 Hz was significantly greater than at 4, 5, 6, and 8 Hz (Wilcoxon, p<0.05) and the rate of growth at 6 Hz was significantly less than at 25, 40, 50 and 63 Hz (Wilcoxon, p<0.05).

Effect of contact location

There were no significant differences in the rates of growth of sensation between the five conditions that explored the effect of the location of backrest contact (Conditions 1 to 5) at any frequency except at 2.5 Hz (Friedman, p=0.019) and 63 Hz (Friedman, p=0.014). At 2.5 Hz, Condition 5 (bottom back) gave a lower exponent than the other four locations (Wilcoxon, p<0.05). At 63 Hz, Condition 1 (top back) gave a lower exponent than both Condition 2 (Wilcoxon, p=0.05) and Condition 4 (Wilcoxon, p=0.028) (Fig. 2(a)). The 25-cm backrest at the lower contact location (Condition 7: lower-middle and bottom back) gave a significantly lower rate of growth than at the higher contact location (Condition 6; top and upper-middle back) at 2.5 and 4 Hz (Wilcoxon, p<0.05).

Table 3. Median exponents (n), and constants (k) in Stevens' Power Law for Conditions 1, 3, 5, 8, and 9

	Exponent (n)					Constant (k)				
Frequency	*C1*	*C3*	*C5*	*C8*	*C9*	*C1*	*C3*	*C5*	*C8*	*C9*
2	-	-	-	0.696	-	-	-	-	242.80	-
2.5	1.000	0.881	0.719	0.816	0.792	268.99	241.69	233.61	283.28	285.38
3.15	0.871	0.740	0.695	0.807	0.603	200.26	179.16	193.19	195.19	193.44
4	0.765	0.635	0.595	0.660	0.595	196.20	159.48	162.14	191.36	165.56
5	0.685	0.592	0.610	0.538	0.562	208.60	159.58	152.37	182.71	169.38
6.3	0.627	0.727	0.541	0.713	0.631	199.11	161.96	166.37	229.04	163.48
8	0.569	0.726	0.506	0.647	0.703	164.88	168.46	150.34	220.00	196.69
10	0.666	0.859	0.751	0.810	0.764	171.07	180.84	156.29	198.23	158.22
12.5	0.937	0.815	0.799	0.853	0.871	150.83	140.29	133.40	186.84	163.91
16	0.847	0.772	0.711	0.749	0.934	148.76	124.57	111.99	157.76	147.64
20	-	-	-	0.733	-	-	-	-	130.67	-
25	-	-	-	0.752	-	-	-	-	110.05	-
31.5	0.673	0.764	0.610	0.675	0.856	87.84	84.95	90.73	104.92	95.28
40	-	-	-	0.975	-	-	-	-	98.12	-
50	-	-	-	0.740	-	-	-	-	96.15	-
63	0.555	0.712	0.847	0.808	0.621	72.32	71.01	106.75	84.10	74.33
80	-	-	-	0.676	-	-	-	-	79.59	-

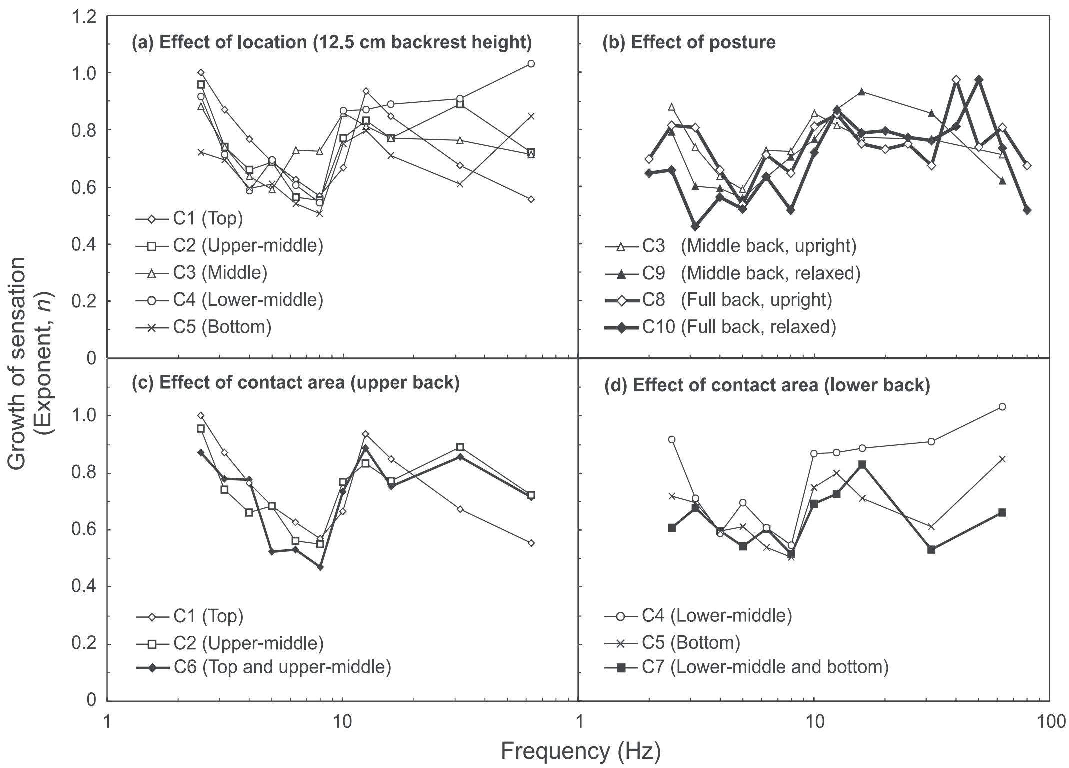

Fig. 2. Rates of growth of sensation (median exponent, n, from 12 subjects) as a function of vibration frequency from 2 to 80 Hz for 10 backrest conditions: (a) effect of contact location, (b) effect of back posture, (c) effect of contact area at upper back, (d) effect of contact area at lower back.

Effect of back posture

A change of back posture, from upright to relaxed, did not significantly alter the rate of growth of sensation (Fig. 2(b)). With the 12.5-cm backrest applied to the middle back, there were no significant differences in the rate of growth between the upright posture (Condition 3) and the relaxed posture (Condition 9) at any frequency investigated. With the full backrest, the upright posture (Condition 8) gave a greater rate of growth than the relaxed posture (Condition 10) but only at 3.15 and 4 Hz (Wilcoxon, $p<0.05$).

Effect of contact area

For the upper back, the rate of growth of sensation differed between Conditions 1, 2 and 6 at 4, 5, 31.5 and 63 Hz (Friedman, $p<0.05$). Although there was increased area of contact in Condition 6 (top and upper-middle back) there was a similar rate of growth of sensation to the smaller area of contact in Condition 2 (upper-middle back). However there was a significant difference between Condition 1 (top back) and Condition 6 (top and upper-middle back) at 4, 31.5 and 63 Hz (Wilcoxon, $p<0.05$) (Fig. 2(c)).

For the lower back, there were differences in the rates of growth of sensation between Conditions 4, 5, and 7 at 12.5 Hz (Friedman, $p=0.028$), where Condition 7 (lower-middle and bottom back) was similar to Condition 5 (bottom back) but significantly different from Condition 4 (lower-middle back) (Wilcoxon, $p=0.005$) (see Fig. 2(d)).

Correlation with body dimensions

There were only a few (11 of 122 cases) statistically significant positive correlations between the rate of growth of sensation and body stature or shoulder height (Spearman, $p<0.05$). However, the correlations were systematic and suggested that taller subjects had greater rates of growth of sensation. There were no significant correlations with other body dimensions, including shoulder breadth and body weight.

Relative discomfort between backrest conditions

Before comparing equivalent comfort contours across the 10 backrest conditions, they were adjusted for the relative sensitivity between conditions as determined in the supplementary experiment.

Ratios between the median discomfort ratings with each of the 10 backrest conditions and the median rating obtained with Condition 8 (full backrest, upright posture) with the 0.315 ms^{-2} r.m.s. 10-Hz reference vibration are shown in Fig. 3. There was a significant overall difference between conditions (Friedman, $p=0.001$). The findings from statistical tests between specific backrest conditions are presented below.

Equivalent comfort contours

Figure 4 shows equivalent comfort contours for all 10 backrest conditions calculated for sensation magnitudes of 50, 100, 200, and 300 (where 100 is equivalent to the discomfort produced by 0.315 ms^{-2} r.m.s. at 10 Hz with a full backrest and an upright posture (i.e. Condition 8).

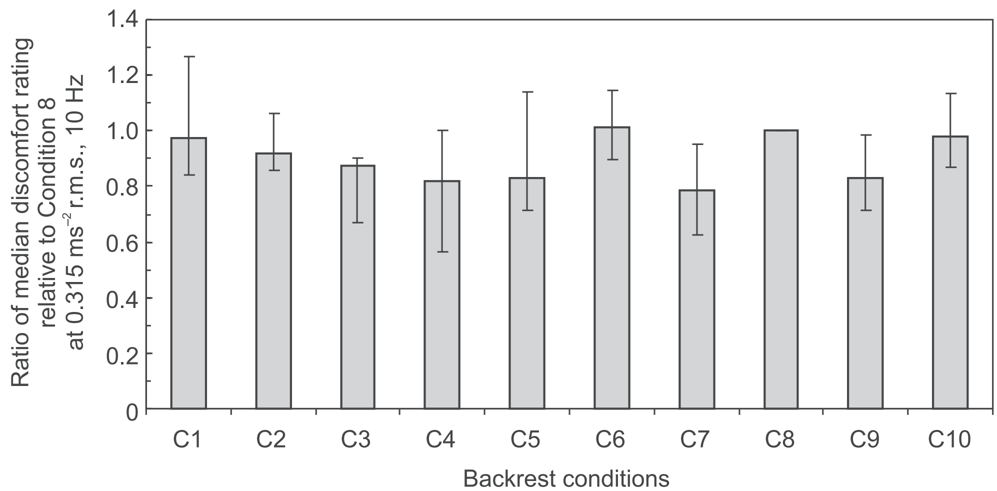

Fig. 3. Ratio of median discomfort rating for each of 10 backrest conditions relative to a vibration magnitude of 0.315 ms^{-2} r.m.s. at 10 Hz with a full backrest and an upright back posture (Condition 8). Error bars indicate inter-quartile ranges.

Effect of vibration frequency

All equivalent contours increase approximately in proportion to frequency (i.e. they are equivalent to constant velocity) between about 8 and 25 Hz. Between 2 and 8 Hz, and between 25 and 80 Hz, the equivalent comfort contours depend on the backrest condition, but tend to approximately constant acceleration as the input location on the back becomes lower.

Effect of vibration magnitude

All equivalent comfort contours are magnitude-dependent, particularly at frequencies between 3 and 8 Hz where the contours show increased sensitivity with decreasing magnitude of vibration (see Fig. 4). The contours reflect the frequency dependence in the rates of growth of sensation found between 3 and 8 Hz. No significant changes in the rates of growth of sensation were found at frequencies greater than 8 Hz, reflected in the less-pronounced magnitude-dependence in this frequency range.

Effect of contact location

With 10-Hz vibration at a magnitude of 0.315 ms^{-2} r.m.s., the discomfort ratings with Condition 4 (lower-middle back) were significantly less than those with Condition 3 (middle back) (Wilcoxon, p=0.006) (see Fig. 3). Similarly, discomfort ratings with Condition 3 (middle back) were significantly less than those with Condition 2 (upper-middle back) (Wilcoxon, p=0.012). Also, discomfort ratings obtained with Condition 7 (lower-middle and bottom back) were significantly less than those with Condition 6 (top and upper-middle back) (Wilcoxon, p=0.034).The effect of contact location on the contours equivalent to a sensation magnitude of 100 is shown in Fig. 5(a). It appears that vibration applied to the lower back tended to cause less discomfort than vibration applied to the upper back.

At frequencies between 3 and 8 Hz, vibration of the upper back (Conditions 1, 2 and 6) seems to cause greater discomfort (lower comfort contours) than vibration of the lower back (Conditions, 3, 4, and 7). At frequencies greater than 25 Hz, vibration applied to the lower back caused greater discomfort than vibration applied to the upper back.

Effect of posture

With 10-Hz vibration at a magnitude of 0.315 ms^{-2} r.m.s., there was no significant difference in discomfort ratings between Conditions 3 and 9 or between Conditions 8 and 10 (Wilcoxon, p=0.875; Fig. 3). In Fig. 5b, it can be seen that with vibration applied to the middle of the back (Conditions 3 and 9), there was little difference in discomfort between the two body postures (upright and relaxed), although a slight increase in median discomfort with the relaxed posture at frequencies less than 10 Hz. Similarly, with a full backrest (Conditions 8 and 10), the relaxed posture tended to show greater sensitivity to vibration than the upright posture at frequencies between 3.15 and 5 Hz.

Effect of contact area

With 10-Hz vibration at 0.315 ms^{-2} r.m.s., discomfort ratings for Condition 6 (top and upper-middle back) were significantly greater than those for Condition 2 (upper-middle back) (Wilcoxon, p=0.034), but not greater than those for Condition 1 (top back) (p=0.937; Fig. 3). Similarly, there was no significant difference in discomfort ratings when comparing Condition 1, Condition 2, or Condition 6 with Condition 8 (full back, upright posture) (Friedman, p=0.423). Increasing the contact area (i.e. Condition 6, the summation of the areas of Conditions 1 and 2) gave similar discomfort to that with vibration applied only to the upper area of the back (i.e. Condition 1) (Fig. 5(c)).

With vibration applied to the lower back, there were no significant differences in comfort ratings between Conditions 4, 5, and 7 with 10-Hz vibration at a magnitude of 0.315 ms^{-2} r.m.s. (Friedman, p=0.558). An increase in contact area in the lower back did not greatly change the discomfort caused by fore-and-aft backrest vibration (Fig. 5(d)).

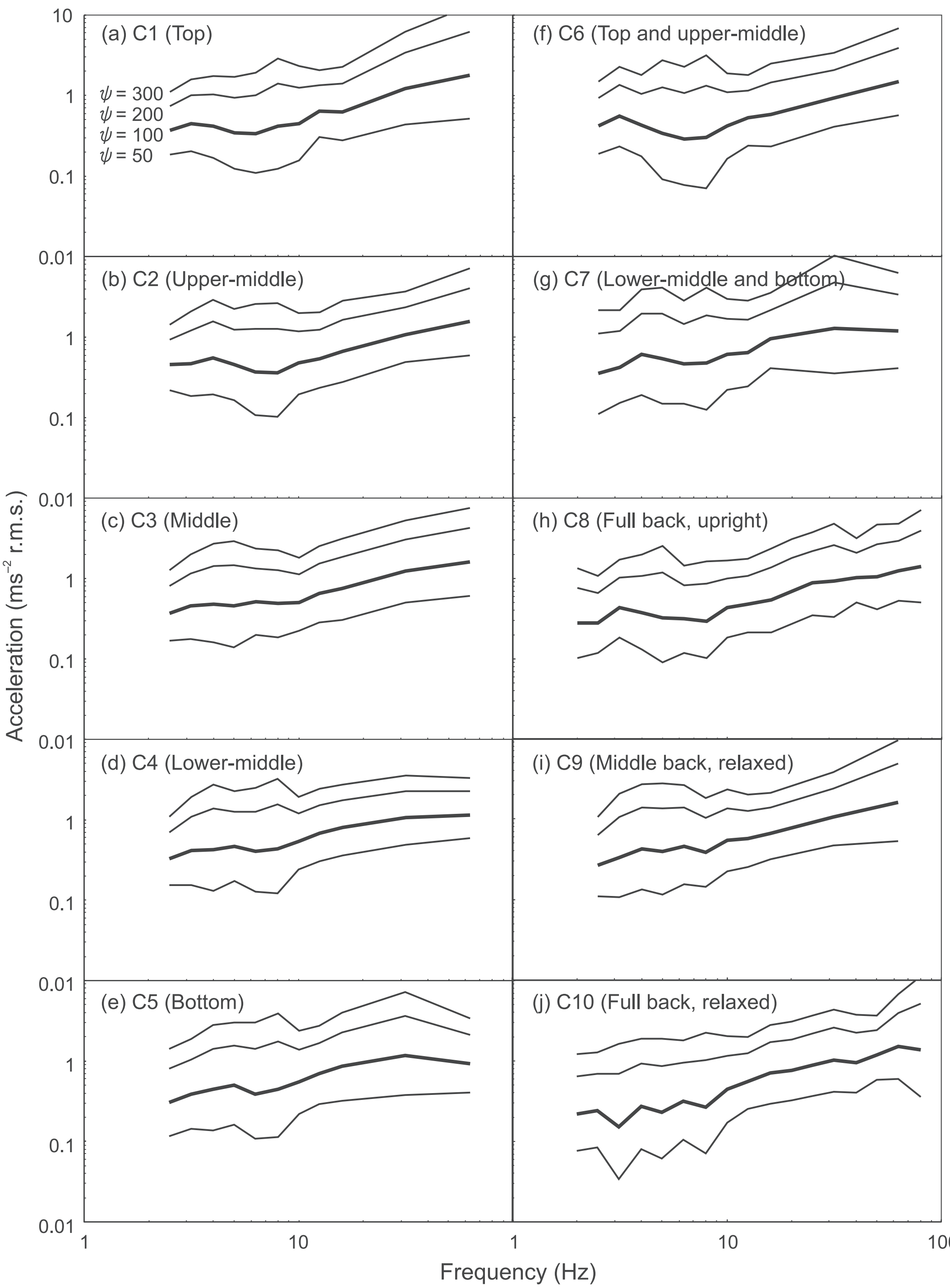

Fig. 4. Equivalent comfort contours for sensation magnitudes from 50 to 300 for each of the 10 backrest conditions relative to a vibration magnitude of 0.315 ms^{-2} r.m.s. at 10 Hz with a full backrest and an upright back posture (Condition 8).

Discussion

Effect of frequency

The equivalent comfort contours for fore-and-aft backrest vibration are frequency-dependent, with sensitivity to acceleration generally greater at lower frequencies (below about 10 Hz) than at higher frequencies, presenting a progressive decrease in sensitivity to acceleration as the frequency increased to 80 Hz. This overall trend was consistent for all backrest conditions (Fig. 4).

Figure 6 compares the equivalent comfort contours determined with a full backrest and an upright posture (Condition 8) with the contours determined by Parsons *et al*.[7] and Kato and Hanai[8] for similar backrest conditions. The shapes of equiva-

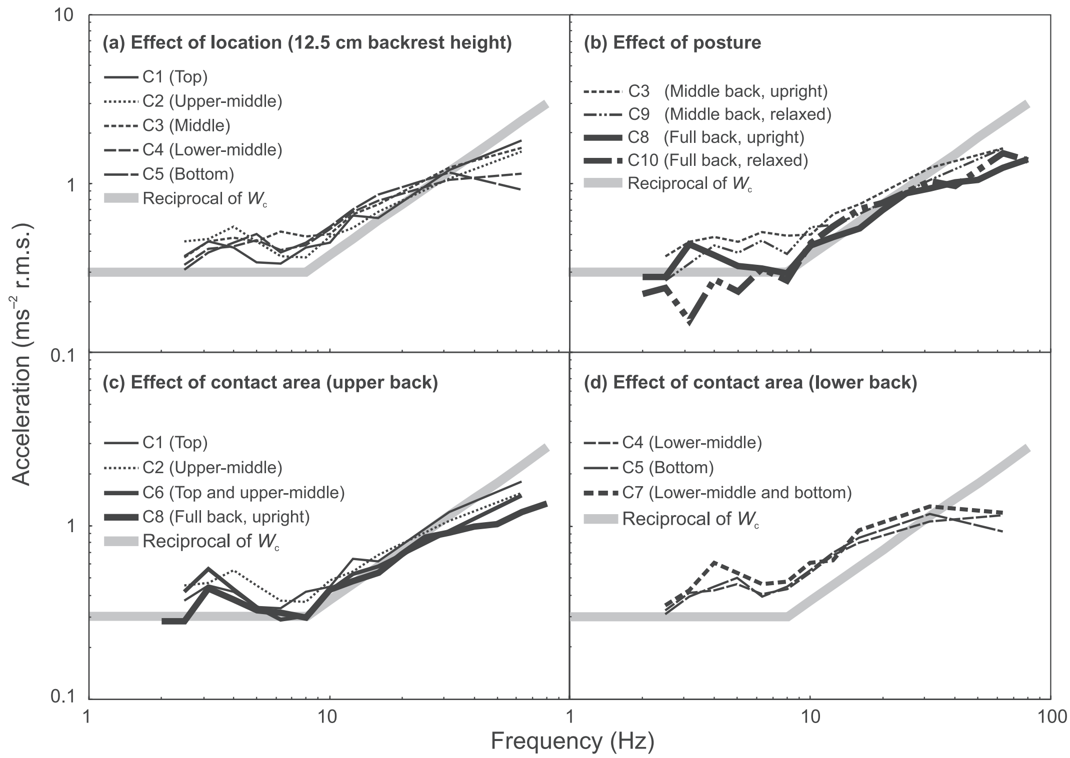

Fig. 5. Equivalent comfort contours for sensation magnitudes of 100 (equivalent to the discomfort produced by 0.315 ms^{-2} r.m.s. at 10 Hz with a full backrest in an upright back posture (Condition 8)): (a) effect of contact location, (b) effect of back posture, (c) effect of contact area at upper back, (d) effect of contact area at lower back. The reciprocal of the W_c frequency weighting normalised to 0.3 ms^{-2} r.m.s. is overlaid for comparison.

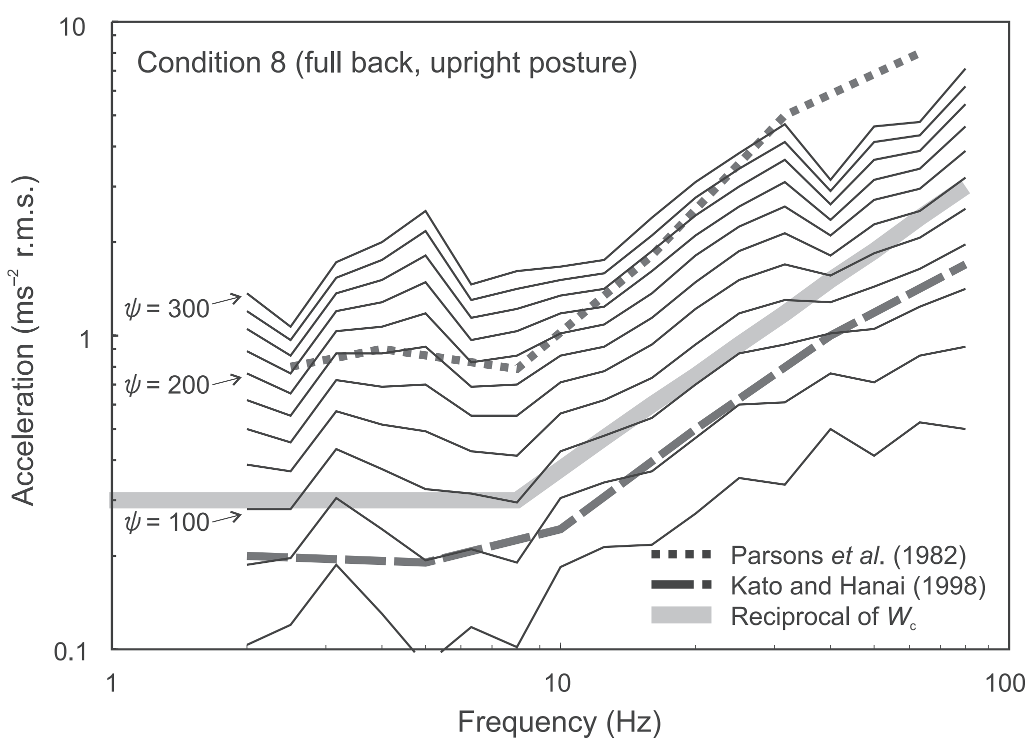

Fig. 6. Comparison of equivalent comfort contours for sensation magnitudes from 25 to 300 (in steps of 25) for Condition 8 (full back, upright posture) with equivalent comfort contours of the back determined by Parsons *et al.* (1982) and Kato and Hanai (1998).
The reciprocal of the W_c frequency weighting normalised to 0.3 ms^{-2} r.m.s. is overlaid for comparison.

lent comfort contours show reasonable agreement, except at frequencies greater than about 30 Hz where the present study shows greater sensitivity. Comfort contours at vibration magnitudes greater than 2.0 ms^{-2} r.m.s. were determined by extrapolation of regressions in the current experiment, so comparisons with the comfort contour of Parsons *et al.*[7] at frequencies greater than 20 Hz are tentative.

Effect of vibration magnitude

Most backrest conditions showed increased sensitivity (decreased level of the comfort contours) at frequencies between 3 and 8 Hz, particularly evident at low sensation magnitudes (e.g. ψ=50). With increasing sensation magnitudes, the equivalent comfort contours at frequencies less than 10 Hz altered to approximately constant acceleration. At frequencies less than 10 Hz, the rate of growth of sensation with increasing vibration magnitude depended on vibration frequency (Fig. 2), which is reflected in the different magnitude-dependence of the comfort contours in this frequency range. At frequencies greater than 8 Hz, the rate of growth of sensation with increasing magnitude of vibration did not differ significantly, so the magnitude-dependence of the comfort contours was less pronounced.

The change in sensitivity with vibration magnitude at frequencies between 3 and 8 Hz may be associated with a change in the transmission of fore-and-aft vibration to the back. When exposed to fore-and-aft vibration from a rigid seat with a rigid backrest at low magnitudes (less than 0.25 ms^{-2} r.m.s.), the apparent mass of the entire back showed resonances in the range 3 to 6 Hz (median around 4 Hz), but the resonances shifted to a lower frequency and became less distinct with increasing magnitude of vibration up to about 1 ms^{-2} r.m.s.[19, 20].

A similar trend in the magnitude-dependence of the fore-and-aft apparent mass of the entire back has been found in a study with only backrest vibration, with major resonances in the range 4 to 8 Hz (median 6 Hz) with the lowest magnitude of vibration (i.e. 0.1 ms^{-2} r.m.s.)[12], consistent with the present results with the full backrest (Condition 8; Fig. 6).

Subashi *et al.*[16] examined the effect of the magnitude of fore-and-aft and lateral vibration on subjective and biodynamic responses of seated subjects (without a backrest) exposed to sinusoidal vibration in the magnitude range 0.125 to 1.0 ms^{-2} r.m.s. and the frequency range 1.6 to 10 Hz. With increasing magnitude of vibration, they found significant correlations between increased discomfort and normalised apparent mass at 2.0, 2.5, 3.15, and 5.0 Hz. The results indicate that the magnitude-dependence of comfort contours is associated with, and possibly caused by, the nonlinear dynamic response of the body in this frequency range. Since similar findings have been obtained with vertical vibration of seated subjects[17], it seems likely that the nonlinear equivalent comfort contours found here with fore-and-aft backrest vibration may be explained by the same phenomenon.

Effect of contact location

The frequency dependence of the comfort contours showed systematic changes with height of contact with the back: at low sensation magnitudes, the frequency of greatest sensitivity (lowest point in the comfort contours) increased from about 4 to 8 Hz as the contact location became lower (Fig. 4). These trends in the comfort contours are similar to trends in the in the fore-and-aft apparent mass of the back. Jalil and Griffin[12] determined the fore-and-aft apparent mass of the back at five locations similar to those in the present study and found a resonance between 4 and 5 Hz at the upper back and between 5 and 8 Hz at the middle and lower back.

Vibration of the upper back produced greater discomfort than vibration of the lower back at frequencies between 3 and 31.5 Hz (Fig. 5(a)). Vibration of the upper back probably caused greater head motion than vibration of the lower back, and this may have increased discomfort. During fore-and-aft whole-body vibration, the transmission of fore-and-aft vibration to the head has been found to be increased between 1 and 2 Hz and between 6 and 10 Hz if a backrest is present[21]. A relationship between equivalent comfort contours for vertical seat vibration and vertical seat-to-head transmissibility was demonstrated with various seating conditions (both with and without backrest) by Parsons *et al.*[7].

Vibration of the lower back (Conditions 4, 5 and 7) produced greater discomfort than vibration of the upper back (Conditions 1, 2 and 6) at frequencies between 31.5 and 63 Hz (Fig. 5). The increased sensitivity of the lower back at high frequencies may have been due to increased contact force when the contact location changed from the upper back to the lower back. It has previously been suggested that increased sensitivity to fore-and-aft vibration at 20 and 40 Hz with an inclined backrest (compared to a vertical backrest) may also be due to increased pressure at the back when a seat is inclined[8].

Effect of posture

Posture had a small effect on discomfort caused by fore-and-aft backrest vibration, with a trend towards greater discomfort with a relaxed posture than with an upright posture at frequencies less than 10 Hz. If the contact location shifted towards the middle back with a relaxed posture, the opposite trend in comfort would have been expected. Instead, the change in posture from upright to relaxed may have altered dynamic response of the back, increasing the transmission of vibration to the body.

Effect of contact area

Increasing the contact area (e.g. doubling the size of the backrest in contact with the back) did not increase discomfort, at either the upper back or the lower back. Instead, the discomfort tended to correspond to that associated with the higher area of contact with the back. This suggests discomfort was more influenced by input position (i.e. upper or lower back) than by the size of the contact area. Since the equivalent comfort contours obtained with Condition 1 (top back) showed similar equivalent comfort to those obtained with Condition 8 (full back, upright posture), the discomfort caused by fore-and-aft vibration of a full backrest could be predicted from the fore-and-aft vibration measured at the highest point of contact with a backrest. This will also often be the position with the greatest magnitude of vibration.

Frequency weightings for the back

For Conditions 1, 3, 5, 8 and 9, the equivalent comfort contours corresponding to a sensation magnitude of 100 (i.e. vibration causing the same discomfort as 10 Hz with 0.315 ms^{-2} r.m.s. in Condition 8) were inverted and normalised (so as to have a value of unity at 8 Hz) and then overlaid with the W_c frequency weighting used in current standards[4, 5] (Fig. 7(a)). The frequency weightings derived from the present results are in reasonable agreement with the frequency weighting, W_c, except at frequencies greater than 30 Hz where the present results suggest greater sensitivity, implying the W_c frequency weighting underestimates sensitivity to backrest vibration at frequencies greater than about 30 Hz.

Frequency weightings derived from Condition 8 (full back, upright posture) for sensation magnitudes of 50, 100, 200, and 300 are shown in Fig. 7(b). It may be seen that the variation in the frequency weightings with different sensation magnitudes is similar or greater than the variation with different backrest conditions (see Fig. 7(a) and 7(b)). The non-linear effect of vibration magnitude on discomfort caused by fore-and-aft backrest vibration indicates a need for caution when applying a single frequency weighting over a wide range of vibration magnitudes.

Frequency weightings for the top back (Condition 1) and the full back (Condition 8) had similar shapes (Fig. 7(a)). In practical situations the vibration is likely to be greatest at the top of the backrest. It therefore seems reasonable to conclude that the discomfort caused by fore-and-aft backrest vibration may be estimated from the frequency-weighted fore-and-aft acceleration at the highest point of contact between the backrest and the body using frequency weighting W_c.

Conclusions

Over the frequency range 2 to 80 Hz, equivalent comfort contours for fore-and-aft vibration at the back depend on input location, with greater sensitivity at higher contact locations. Discomfort was not directly affected by increases in the area of contact with the vibration input (within either the upper back or the lower back), but corresponded to discomfort associated with the upper area of contact. Posture of the back had only a small effect on vibration discomfort: at frequencies less than 8 Hz, a relaxed posture produced more discomfort than an upright posture. It is concluded that the vibration input position (i.e. upper, middle, or lower back), rather than the contact area or sitting posture, is the greater determinant of discomfort caused by fore-and-aft vibration of the back over the frequency range 2.5 to 80 Hz.

Frequency weightings derived from the comfort contours are reasonably consistent with the W_c frequency weighting used in current standards, but suggest greater sensitivity at frequencies higher than 30 Hz. Fore-and-aft backrest vibration may be assessed from the frequency-weighted fore-and-aft acceleration measured at the highest point of contact between the backrest and the body if the frequency weighting W_c is employed in the evaluation. However, the magnitude-dependence of equivalent comfort contours indicates the need for caution when applying a single frequency weighting over a wide range of vibration magnitudes.

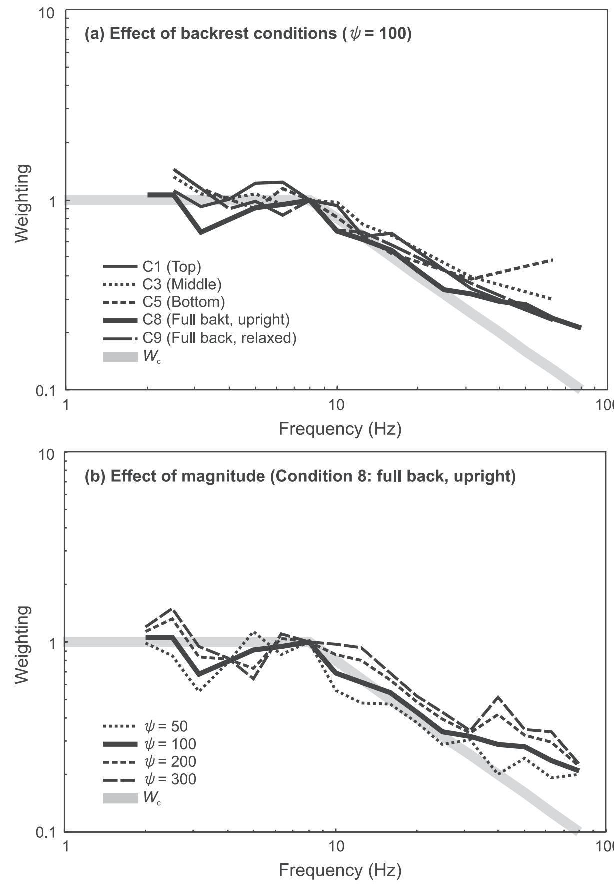

Fig. 7. Derived frequency weightings (inverted equivalent of comfort contours normalised at 8 Hz).
A sensation magnitude of 100 is equivalent to the discomfort produced by 0.315 ms^{-2} r.m.s. at 10 Hz with a full backrest and an upright back posture (Condition 8). The results are compared with the W_c frequency weighting. (a) Effect of backrest condition for sensation magnitudes of 100, (b) Effect of vibration magnitude for sensation magnitudes of 50, 100, 200, and 300.

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