EQUIVALENT COMFORT CONTOURS FOR WHOLE-BODY VERTICAL VIBRATION: EFFECT OF BACKREST INCLINATION

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Abstract

The inclination of a backrest may be expected to alter the vibration transmitted to the body and the associated vibration discomfort. This study examined the influence of backrest inclination on the discomfort arising from whole-body vertical vibration when sitting in a rigid seat with a backrest inclined at 0° (upright), 30°, 60° and 90° (recumbent). Equivalent comfort contours were determined over the frequency range from 1 to 20 Hz and over the magnitude range from 0.2 to 2.0 ms^{-2} r.m.s. relative to the discomfort caused by 8-Hz vertical vibration at 0.4 ms^{-2} r.m.s. When sitting with the backrest inclined to 60° or 90°, there was less discomfort around 5 and 6.3 Hz than when sitting with the upright backrest. Around 16 and 20 Hz there was greater discomfort when sitting with the backrest inclined to 30°, 60°, and 90° than when sitting with the upright backrest. The reductions in discomfort at the lower frequencies may be associated with increased postural support and changes in the biodynamic responses of the body when reclined. Increased transmission of vibration to the head may explain the greater discomfort at high frequencies when sitting reclined. It is concluded that different methods of vibration evaluation are appropriate when evaluating vibration with upright and inclined backrests.

1. Introduction

When travelling in transport, seated people are exposed to vibration from the seat and the backrest. Laboratory experimental studies of vibration discomfort have mostly been conducted without a backrest or with a rigid vertical backrest. In static environments a backrest provides more support and more comfort when it is inclined, but backrest inclination may be expected to influence the vibration transmitted to the body and the discomfort caused by vibration during travel. Procedures for predicting the discomfort associated with different backrest inclinations and different characteristics of vibration are needed so that seat design can be optimised for comfort.

Current standards (BS 6841:1987; ISO 2631-1:1997) suggest vibration discomfort can be predicted from an evaluation of the vibration at the interfaces between the body and the support surfaces (e.g., the seat pan, backrest, and footrest for a seated person) using appropriate frequency weightings. However, there is no clear provision in the standards for any adjustment of the frequency weightings to allow for variations in the inclination of backrests.

It has been reported that backrest inclination changes the frequency-dependence of discomfort caused by *x*-axis vibration of backrests (Kato and Hanai, 1998; Basri and Griffin, 2011a) and the relative sensitivity to vertical seat vibration (Basri and Griffin, 2011b). The W_c frequency weighting developed from equivalent comfort contours for *x*-axis vibration of an upright backrest (Parsons *et al.*,

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1982) has been shown to be less suitable for evaluating the *x*-axis vibration of inclined backrests. The W_c weighting tends to overestimate the discomfort caused by *x*-axis vibration of inclined backrest at low frequencies (less than 8 Hz) but underestimate the discomfort at high frequencies (Kato and Hanai, 1998; Basri and Griffin, 2011a). Recently, equivalent comfort contours for vertical vibration at the seat pan have been determined while sitting with stationary inclined backrests (0°, 30°, 60° and 90° from vertical) and a stationary footrest (Basri and Griffin; 2011b). With increasing inclination of the backrest, the proportion of body weight supported by the vibrating seat pan decreased and vibration discomfort was reduced at all frequencies. The reduction in discomfort was more prominent (by about 6 dB) with greater inclinations of the backrest (60° and 90°) and at frequencies less than 8 Hz. The findings imply that sensitivity to vertical seat vibration reduced relative to sensitivity to *x*-axis vibration of the backrest as the backrest inclination increased.

The study reported here investigated the influence of backrest inclination on the discomfort of seated people exposed to whole-body vertical vibration. It was hypothesised that there would be a change in the frequency-dependence of discomfort arising from whole-body vertical vibration with backrest inclination. It was expected that current frequency weightings would not provide optimum predictions of variations in vibration discomfort when sitting with different inclinations of the backrest.

2. Method

2.1. Apparatus

An extruded aluminium frame with plywood surfaces provided a rigid support at the seat pan, backrest, footrest, and calves. The seat was securely mounted to the platform of a vertical vibrator. The seat pan surface was horizontal, the backrest was adjustable to inclinations of 0°, 30°, 60°, or 90° (fully recumbent), and the footrest was inclined 60° from the vertical. The dimensions of the rig were chosen to provide a comfortable sitting posture for a 50th percentile British male aged 19 to 45 years (Pheasant, 1990). The positions were achieved using an H-point manikin with knee and ankle angles set to 120° and 100°, respectively. With the backrest inclined at 90°, subjects lay horizontally with their backs, heads, and calves supported on a flat surface. A rigid headrest was used with all backrest conditions except with the upright backrest. The supporting surfaces at the seat pan, the backrest, the headrest, and the calves were covered with 1-mm thick neoprene rubber to provide some friction between the support and the body.

The vibration stimuli were produced using a hydraulic vibrator capable of 1-meter peak-to-peak displacement in the vertical direction. The stimuli were generated and sampled using *HVLab* Signal Processing Toolbox in Matlab (version R2009) and output via a digital-to-analogue converter (NI 6211) at 512 samples per second.

The acceleration of the platform was monitored using single-axis piezo-resistive accelerometers (Entran Model EGCSY-240D-10) attached to the platform. Signals from the accelerometers were low-pass filtered at 50 Hz and then sampled at 512 samples per second.

2.2. Stimuli

All vibration stimuli were sinusoidal and in the vertical direction with a total duration of 5 s including 1-s of cosine-tapering at the start and end. Test stimuli were generated in an array of 14 frequencies (the preferred one-third octave centre frequencies from 1 to 20 Hz) and seven magnitudes (separated by 3 dB steps). The range of magnitudes was such that the same W_b frequency-weighted acceleration was used at all frequencies (e.g. 0.5 to 2 ms^{-2} r.m.s. at 1 Hz, and 0.2 to 0.8 ms^{-2} r.m.s. at 20 Hz). Subjects judged the discomfort caused by each of the test stimuli relative to the discomfort caused by a 8-Hz reference stimulus of 0.4 ms^{-2} r.m.s.

2.3. Procedure

The experiment was conducted in five sessions with five different backrest conditions (i.e., sitting upright with no backrest and sitting with the backrest inclined at 0°, 30°, 60°, and 90°). All five sessions with each subject were completed within three days, with one session on the first day followed by two sessions on the second day and the remaining two sessions on the final day. The findings obtained without a backrest are not presented in this paper. Each session lasted less than 45 minutes. The order of the sessions was balanced across subjects. On the first day, subjects had a short exercise judging the apparent length of lines relative to the length of a reference line. To confirm further their understanding of the magnitude estimation method used in the experiment, they also practiced judging vibration before commencing the experiment. On the second and final day, subjects were provided with a rest of 5 or 10 minutes between sessions.

Each session included two psychophysical tests: (i) equivalent comfort contours within the backrest inclination, and (ii) relative discomfort between the backrest inclination and the condition with no backrest.

2.3.1. Equivalent comfort contours within backrest inclination

Subjects sat on the seat pan with their backs leaning comfortably against the backrest. Their hands rested on their laps or were folded together and rested on their stomach when the backrest was inclined to 60° or 90° (recumbent). In the upright backrest (0°) condition, there was no support for the head and subjects were requested to sit with a comfortable upright posture. For backrest inclinations of 0° (upright), 30°, and 60°, the feet were supported, whereas when recumbent (at 90°), the calves were supported.

Subjects were requested to provide a magnitude estimate for the discomfort caused by the test stimulus assuming the magnitude estimate of the discomfort caused by the reference stimulus was 100. There were 98 pairs of reference and test stimuli (14 frequencies at 7 magnitudes) presented in random order with subjects sitting with the same backrest inclination. This part of the session was completed in approximately 30 minutes.

2.3.2. Relative discomfort between backrest inclinations

Subjects sat upright with no backrest (the common reference condition for comparing all backrest inclinations) to receive the reference stimulus and then sat with their backs leaning comfortably against the backrest (sitting as when determining equivalent comfort contours within backrest inclination) to experience the test stimulus. They were requested to provide a magnitude estimate for the discomfort caused by the test stimulus assuming the magnitude estimate for the discomfort caused by the reference stimulus was 100. There were seven pairs with the same seven magnitudes of the 8-Hz test stimulus presented when determining equivalent comfort contours within backrest inclination. The stimuli were presented in a different random order for each subject over a period of 3 to 5 minutes.

2.4. Subjects

Twelve healthy male subjects participated in all five sessions of the experiment. Subjects were aged between 23 and 31 years, with median (minimum and maximum) stature 1.74 m (1.65 and 1.94 m), and median weight 66 kg (48 and 107 kg). Subjects were students and staff of the University of Southampton with no history of any serious illness, injury, or disability.

Subjects were required to close their eyes during presentations of the stimuli to avoid seeing their body movement. They wore headphones presenting a masking white noise at 65 dBA. The experimenter and subjects were provided with separate emergency stop buttons.

The experiment was approved by the Human Experimentation Safety Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton. All subjects gave their voluntary consent prior to the start of their first session on each day.

3. Results

3.1. Rate of growth of discomfort

The magnitude estimate of vibration discomfort, ψ, caused by the vibration magnitude, φ, at each frequency is assumed to be related by a power law (Stevens, 1975):

$$\Psi = k\,\varphi^{n} \qquad \text{Equation 1.}$$

Individual values for the rate of growth of discomfort, n, and the constant, k, were determined from the slopes and intercepts of linear least squares regressions between $\log_{10}\psi$ and $\log_{10}\varphi$ at each frequency.

The rate of growth of discomfort, n, within each of the four backrest inclinations was strongly dependent on the frequency of vibration ($p<0.001$, Friedman; Figure 1). However, the rate of growth of discomfort did not differ across backrest inclinations at any frequency ($p=0.086$, Friedman).

3.2. Equivalent comfort contours within backrest inclination

Individual equivalent comfort contours were calculated at seven sensation magnitudes (from ψ = 50 to 200, relative to 100 with 0.40 ms^{-2} r.m.s. of 8-Hz vibration with the same backrest condition) using Equation 1 and individual n and k values at each frequency within each backrest inclination. Median equivalent comfort contours were constructed from the 12 individual equivalent comfort contours at each of these seven sensation magnitudes (Figure 2).

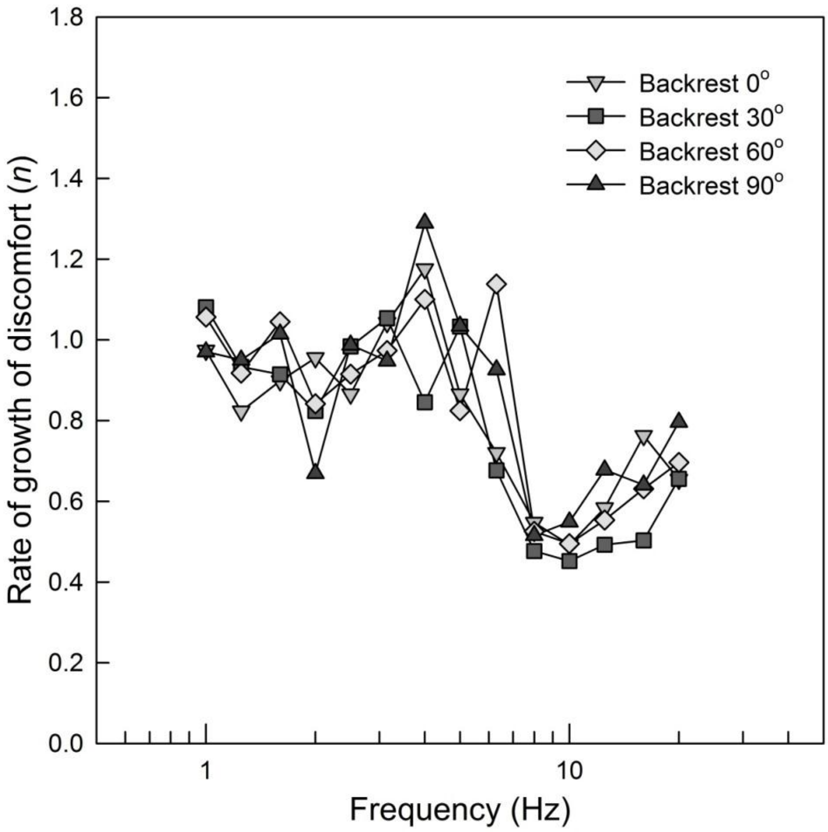

Figure 1 Median rates of growth of discomfort (values of the exponent, *n*) with the four backrest inclinations.

3.3. Relative discomfort between backrest inclinations

The equivalent comfort contours for each backrest inclination for each subject were rescaled to the sensation magnitude of the common reference (i.e. the discomfort caused by 0.4 ms^{-2} r.m.s. at 8 Hz when sitting with no backrest), using individual *n* and *k* values obtained with the respective backrest inclinations. The medians of these twelve individual 'rescaled' equivalent comfort contours were determined for each backrest inclination to show the relative discomfort between backrest conditions (Figure 3). The equivalent comfort contours show the r.m.s. acceleration required at the platform (or the seat pan) at each frequency for each backrest condition to cause similar discomfort to that caused by the common reference vibration.

The vibration magnitude required at any frequency for the discomfort to be equivalent to that caused by the common reference vibration depended on the backrest inclination (p=0.003, Friedman). However, there were no significant differences in the vibration magnitudes required between sitting with the backrest inclined at 60° and with the backrest fully reclined at any frequency (p>0.008, Wilcoxon after Bonferroni correction for six multiple pairwise comparisons). With the backrest inclined to 30°, the required vibration magnitude was significantly less than with the upright backrest at 20 Hz (p=0.002; Wilcoxon). With the backrest inclined to 60°, the required vibration magnitude was significantly less at 16 and 20 Hz, and significantly greater at 5 and 6.3 Hz than with the upright backrest (p<0.008, Wilcoxon). With the fully reclined backrest, the vibration magnitude required was significantly less at 16 and 20 Hz and significantly greater at 5 Hz than with the upright backrest (p<0.008, Wilcoxon).

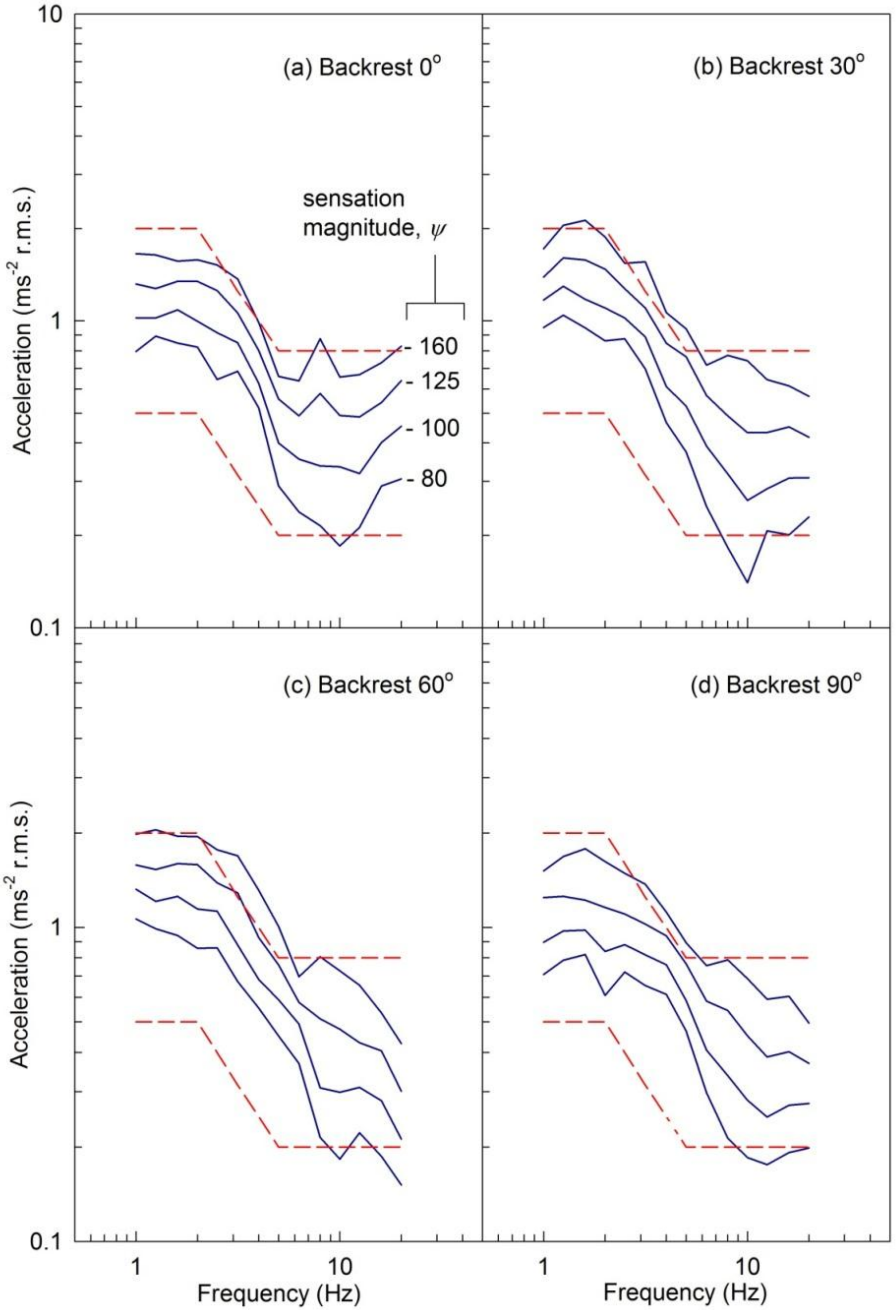

Figure 2 Median equivalent comfort contours at seven sensation magnitudes (Ψ = 80 to 160) for each backrest inclination, where 100 corresponds to the discomfort associated with the reference vibration (0.4 ms^{-2} r.m.s. at 8 Hz, with the same backrest inclination). Dotted lines indicate the range of stimuli used in the study.

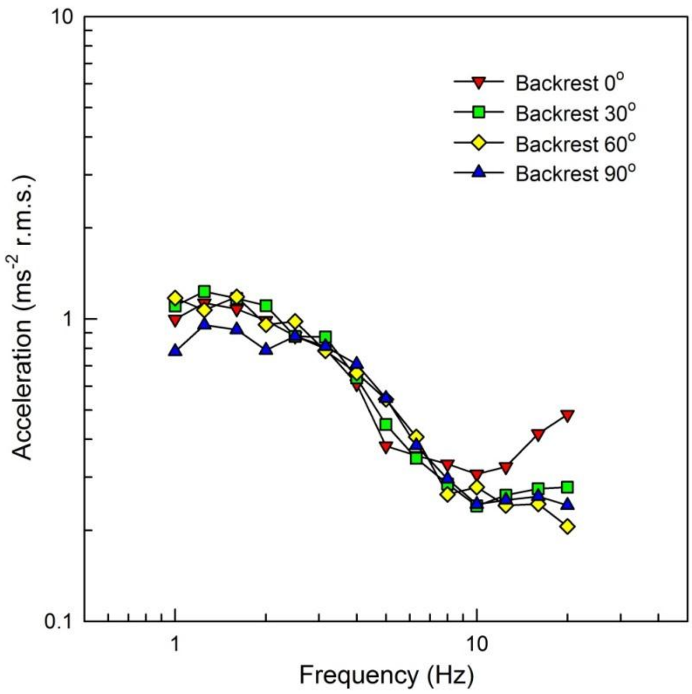

Figure 3 Relative discomfort between backrest inclinations. Contours show the vibration acceleration at the platform (or the seat pan) required when sitting with each backrest inclination to produce discomfort equivalent to the common reference (0.4 ms^{-2} r.m.s. at 8 Hz when sitting upright with no backrest contact).

4. Discussion

4.1. Effect of backrest inclination

Compared with the upright backrest, the inclined backrests (30°, 60° and 90°) show a clear trend for increased discomfort at frequencies greater than 8 Hz and reduced discomfort at 5 Hz and 6.3 Hz, although the difference is small with the 30°-backrest (Figure 3). In addition to experiencing vibration at the seat surface, subjects were exposed to increasing vibration in the *x*-axis of the back as the inclination of the backrest increased. The frequencies of *x*-axis acceleration of the back that cause greatest discomfort have been found to shift from less than 8 Hz to around 10 or 12.5 Hz as the inclination of a backrest increases: the discomfort caused by backrest vibration is reduced at the lower frequencies when the backrest is inclined (at 30°, 60° or 90°) and 30 to 40% greater accelerations are required in the *x*-axis of the back at frequencies between 4 to 8 Hz to cause discomfort similar to that with an upright backrest (Basri and Griffin, 2011a). This may explain the increased discomfort at frequencies greater than 8 Hz and the reduced discomfort at 5 and 6.3 Hz with inclined backrests.

Reductions in discomfort around 5 and 6.3 Hz when a backrest is inclined may be associated with increased postural support with inclined backrests. The support may have provided stability and reduced the tendency for the upper-body to pitch or sway. Reductions in discomfort at 5 and 6.3 Hz might alternatively be explained by the increase in the resonance frequency evident in the vertical apparent mass as the inclination of a backrest increases. The resonance in the vertical apparent mass measured at the seat surface increased from 5 or 5.5 Hz with an upright backrest to 6.5 or 7.5

Hz with a 30°-inclined backrest (Shibata and Maeda, 2009; Toward and Griffin, 2009). An increase in the resonance frequency of the vertical apparent mass measured on the seat as a backrest inclines is consistent with a greater percentage of the body mass being supported by the inclined backrest, and the backrest becoming a more dominant source of vibration. This may explain why the region of greatest sensitivity to acceleration increased from 5 Hz with an upright backrest to a greater frequency with the inclined backrests.

Increased discomfort with inclined backrests at frequencies greater than 10 Hz (Figure 3) might also have arisen from increased discomfort in the head or neck. The addition of a vertical backrest increases the vibration of the head in several directions during vertical excitation of a seat (Paddan and Griffin, 1988).

With the fully reclined backrest (recumbent), increased discomfort at frequencies greater than 8 Hz may also be associated with resonance frequencies in the vertical apparent mass of the semi-supine body (at 7 or 9.4 Hz) when lying with maximum contact on a horizontal flat backrest (Huang and Griffin, 2008) and resonances in the transmission of vertical vibration from a back support to the sternum (between 6 and 12 Hz) in the same posture (Huang and Griffin, 2009).

4.2. Effect of vibration magnitude

Within all backrest inclinations, the dependence of the rate of growth of discomfort on the frequency of vibration of the platform resulted in a strong dependence of the equivalent comfort contours on the magnitude of the vibration. There is a clear trend for a decrease in the frequency at which the discomfort tends to be greatest as the magnitude of vibration increases, particularly with no backrest and with the upright backrest. As the sensation magnitude increased, the frequencies of greatest discomfort decreased from 8 Hz, consistent with the nonlinearity in the apparent mass where resonance frequencies decrease with increases in vibration magnitude. A similar trend has been reported previously with equivalent comfort contours for vertical seat vibration (Morioka and Griffin, 2006; Basri and Griffin, 2011b).

With the fully reclined backrest (i.e., recumbent), there is a tendency for the frequency-dependence of the equivalent comfort contours to change from approximately constant acceleration at frequencies greater than 8 Hz to constant jerk (-6 dB per octave) as the magnitude of excitation increased. A similar trend is apparent with inclined backrests (30° and 60°). Discomfort in the head or neck seems to have been increasing discomfort with increasing magnitude at high frequencies.

4.3. Effect of frequency of vibration

With inclined backrests (30°, 60° and 90°), the frequency-dependence of the equivalent comfort contours are approximately similar to each other, although significantly different from that with the upright backrest (Figure 3). The magnitude of vibration of the platform (or the seat pan) required to cause similar discomfort was significantly greater when sitting with an inclined backrest than when sitting with an upright backrest at frequencies greater than 8 Hz, but significantly lower at frequencies around 5 or 6.3 Hz. With the fully reclined backrest (90°), the frequency-dependence of the equivalent comfort contours obtained in the present study are broadly similar to thresholds and equivalent sensation contours reported in previous studies (Miwa and Yonekawa, 1969; Szameitat and Dupuis, 1976; Miwa *et al*., 1984; Yonekawa *et al*., 1999; Gibson, 1978; Figure 4b). The contours reported by Gibson (1978) differ at high frequencies, possibly because, unlike the rigid supports used in the other studies, he used a stretcher that may have reduced the transmission of high-frequency vibration to the body.

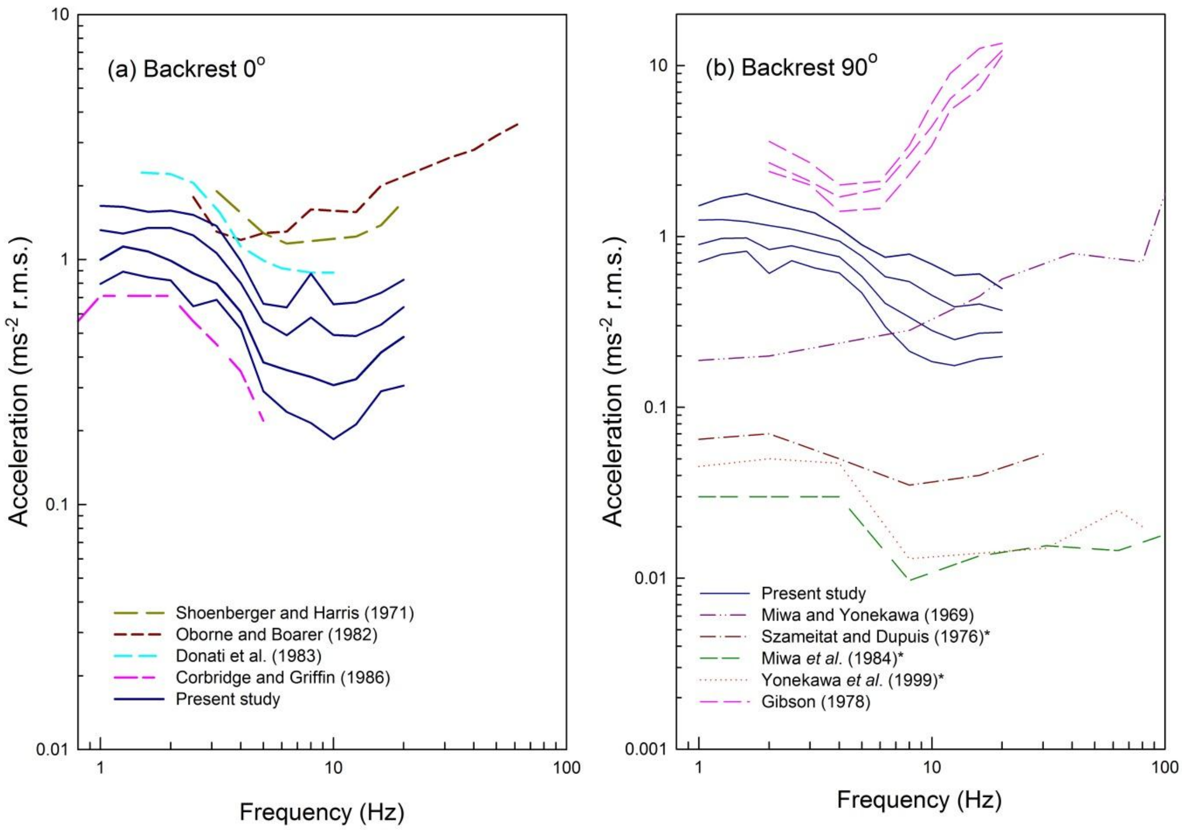

Figure 4 Comparison of median equivalent comfort contours obtained with an upright backrest (0°) and a fully reclined backrest (90°) in the present study with thresholds (marked with asterisks) and equivalent sensation contours reported previously.

With the upright backrest (0°), the frequency-dependence of the equivalent comfort contours for vertical vibration of the platform (or the seat pan) seem consistent with that reported in earlier studies (Shoenberger and Harris, 1971; Oborne and Boarer, 1982; Donati *et al*., 1983; Corbridge and Griffin, 1986; Figure 4a). The vibration discomfort caused by vertical vibration can be predicted sufficiently from vertical seat vibration using the W_b frequency weighting (Figure 5a). However, the prediction of vibration discomfort caused by vertical vibration from an evaluation of vertical seat vibration alone is inadequate with inclined backrests (30°, 60°; Figures 5b and 5c) and when recumbent with a fully reclined backrest (Figure 5d). Inclined backrests reduce overall discomfort around 5 and 6.3 Hz but increase discomfort at frequencies greater than 8 Hz.

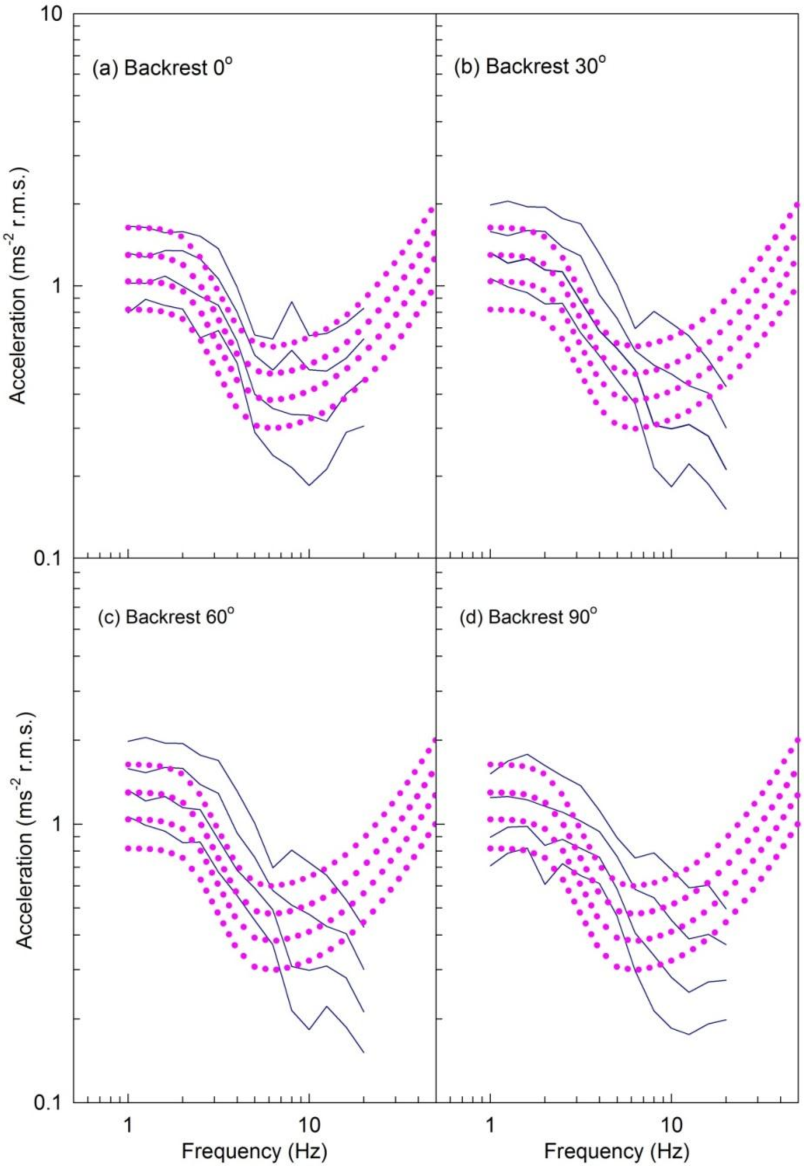

Figure 5 Median equivalent comfort contours (ψ = 80 to 160, relative to 100 with 0.40 ms^{-2} r.m.s. of 8-Hz vibration with the same backrest condition) for four backrest inclinations overlaid with the frequency-dependence of the W_b frequency weighting.

5. Conclusions

The inclination of a backrest affects the discomfort caused by vertical whole-body vibration. When sitting with a backrest inclined to 60° or 90° there is less discomfort around 5 and 6.3 Hz than with an upright backrest. Around 16 and 20 Hz there is greater discomfort when sitting with a backrest inclined to 30°, 60°, and 90° than when sitting with an upright backrest. Reductions in discomfort at the lower frequencies may be associated with increased postural support and changes in the biodynamic responses of the body when reclined. Increased transmission of vibration to the head may explain the greater discomfort at high frequencies when sitting reclined. It is concluded that different methods of vibration evaluation are appropriate when evaluating vibration with upright and inclined backrests.

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