THRESHOLDS FOR THE PERCEPTION OF VIBRATION OF THE BACK: EFFECT OF BACKREST INCLINATION

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Abstract

Drivers, passengers, and patients in various forms of transport are supported by backrests at angles between the vertical and the horizontal. The effect of backrest inclination on the perception of vibration has not been previously reported, and there are no standardised guidelines that can be used to optimise the design of vehicles or seats so as to minimise the probability of perceiving vibration in these postures. This study was designed to determine the effect of backrest inclination on absolute thresholds for the perception of vibration applied normal to the back (i.e. fore-and-aft vibration with an upright backrest, and vertical vibration with a fully reclined backrest). Thresholds were determined using an up-and-down transformed response (UDTR) method at frequencies from 2.5 to 25 Hz at four backrest angles: 0° (upright), 30°, 60° and 90° (recumbent). Inclining the backrest raised thresholds at frequencies between 4 and 8 Hz. It is concluded that the frequency weighting W_c provides a useful prediction of the perception of fore-and-aft vibration with an upright backrest. Frequency weightings W_b or W_k might be used to predict the frequency-dependence of vibration perception with inclined backrests, but only at frequencies greater than about 8 Hz.

1. Introduction

Although vibration is generally unwanted by car drivers and passengers it can provide useful feedback of road contact conditions and the state of the car. Understanding human perception of vibration, and the factors that influence perception, can assist the optimisation of the design of vehicles and seats.

For a seated person, vibration can be transmitted to the body via the main supporting seat surface, the seat backrest, and the support for the feet. The apparent mass and the transmissibility of the body, the absolute threshold of perception, and the discomfort at supra-threshold levels differ between these locations. Thresholds for the perception of whole-body vibration when sitting, standing or lying vary with the frequency and direction of vibration, with sensitivity generally greater when lying than when sitting or standing (Miwa, 1967; Miwa and Yonekawa, 1969; Parsons and Griffin, 1988). Such findings have influenced standardised frequency weightings for evaluating vibration with respect to the probability of perception (BS 6841: 1987; ISO2631-1: 1997).

Perception thresholds may be compared with the apparent mass of the body, because greatest sensitivity can be expected at the resonance frequencies of the body. For persons exposed to vertical vibration when sitting with no backrest, there is a resonance in the vicinity of 4 Hz (Fairley and Griffin, 1989) and thresholds for the perception of vibration acceleration tend to be lowest at frequencies between 2 and 7 Hz (Miwa, 1967; Parsons and Griffin, 1988). With fore-and-aft vibration, there are

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resonances around 0.7 and 2.5 Hz (Fairley and Griffin, 1990) and acceleration thresholds are least at frequencies less than 4 Hz (Miwa, 1967; Parsons and Griffin, 1988). The fore-and-aft apparent mass of the entire back, determined from the ratio of the force to the acceleration at a backrest during fore-and-aft whole-body vibration, exhibits three resonances: at frequencies less than 2 Hz, between 3 and 5 Hz, and in the range of 4 to 7 Hz (Nawayseh and Griffin, 2005).

The effects of backrests and backrest inclination on perception thresholds have received little attention. Parsons *et al.* (1982) determined equivalent comfort contours for vibration of a vertical flat backrest and found that sensitivity to vertical and lateral acceleration was less than sensitivity to fore-and-aft acceleration. Discomfort caused by vertical acceleration of the backrest was greatest at frequencies less than 4 Hz whereas discomfort caused by fore-and-aft acceleration was greatest at frequencies less than 8 Hz. Similar findings with a flat vertical backrest have been reported by Morioka and Griffin (2009). Kato and Hanai (1998) found that the discomfort caused by backrest vibration applied normal to the back increased with increasing backrest inclination.

The effects of contact with differing parts of the back on both discomfort and apparent mass have also been investigated. Morioka and Griffin (2009) found that the frequency at which acceleration caused greatest discomfort increased from 4 to 8 Hz as the contact location was lowered from the upper back to the lower back, broadly consistent with the resonance frequencies in the apparent mass of the upper back (4 to 5 Hz) and the middle and lower back (5 to 8 Hz) (Abdul Jalil and Griffin, 2008).

The influence of backest vibration on thresholds for the perception of whole-body fore-and-aft vibration has been studied by Gallais *et al.* (upublished). They found that, at some frequencies, the thresholds were determined by vibration at the back (as opposed to the seat or the feet) and that they were influenced by the dynamic response of the seat backrest. However, the mechanisms involved in the perception of vibration of the back are not well understood (Morioka and Griffin, 2009) and the effect of backrest inclination on the absolute threshold for perception of vibration at the back have not been investigated.

This study was undertaken to improve understanding of absolute thresholds for the perception of backrest vibration applied normal to the back at frequencies between 2.5 and 25 Hz, and to examine the effects of backrest inclination from fully upright to fully recumbent. It was hypothesised that the thresholds would depend on the frequency of vibration, and that they would broadly reflect the resonance frequencies in the apparent mass of the back at frequencies less than 8 Hz. It was also hypothesised that with increasing backrest inclination (i.e. a more reclined backrest), the thresholds would increase due to changes in the dynamic response of the body, such as a stiffening arising from greater compression of the tissues of the back supporting the weight of the torso on the backrest.

2. Method

2.1 Apparatus

Vibration of the back was produced by a Derritron VP85 electrodynamic vibrator powered by 1500 watt amplifier. The vibration was applied normal to the back via a flat wooden backrest attached to the table of the vibrator (Table 1). The backrest was rotated on its trunnion so as to oscillate at 0, 30, 60, or 90 degrees to the vertical.

The test rig comprised an adjustable seat-pan and footrest (Figure 1). The rig was adjusted to provide a comfortable sitting posture for the 50th percentile British male aged 19 to 45 years, with the knee angle at 120° and the ankle angle at 100° (Pheasant, 1990) The backrest was positioned such that its lower end was above the pelvis, so that it did not push on the pelvis.

Table 1 Apparatus

Accelerometer	Piezo-resistive accelerometer (Entran Model EGCSY-240D-10)
Signal conditioning	*HVLab* Data Acquisition and Analysis Software (version 3.81)
	Techfilter anti-aliasing filter
	PCL-818 analogue-to-digital converter
Derritron VP85	Electrodynamic vibrator with three link-arm suspension restricting motion to one translational direction
	powered by a 1500 W Derritron amplifier
	supported by a trunnion (allowing vibrator to be inclined)
Backrest	Attached to the vibrator table
	wooden plate covered with 1-mm rubber
	length 500 mm, width 310 mm, thickness 40 mm
Headrest	Stationary; attached to the trunnion, supported by aluminium structure
	wooden plate covered with 1-mm rubber
	length 180 mm, width 240 mm, thickness 40 mm
Test rig	Comprised of seat-pan and footrest
	seat-pan: height-adjustable, wooden plate covered with 1-mm rubber, 500x400x25 mm
	footrest; height and angle-adjustable, wooden plate, 500x300x15 mm.

The vibration was generated and acquired using *HVLab* Data Acquisition and Analysis Software v3.81 via a personal computer with anti-aliasing filters (Techfilter) and analogue-to-digital and digital-to-analogue converters (PCL-818). The vibration stimuli were generated at 1000 samples per second. The vibration was measured using a piezo-resistive accelerometer mounted within the backrest and the signal acquired at 1000 samples per second via low-pass filters at 40 Hz. The background vibration, which was about 0.004 ms^{-2} r.m.s. and predominantly at 50 Hz, was not perceptible.

2.2 <u>Vibration stimuli</u>

The vibration stimuli were 2-second sinusoidal waveforms with 0.5-second cosine tapers at both ends. They were presented at the eleven preferred one-third octave centre frequencies from 2.5 to 25 Hz. For each subject, the frequencies were tested in an independent random order.

2.3 Psychophysical method

Absolute thresholds for the perception of vibration of the back were determined using the 'up-and-down transformed response' (UDTR) method proposed by Wetherill and Levitt (1965). After each presentation of a stimulus, a subject was requested to indicate whether it was felt by saying 'yes' or 'no'. At each frequency, the initial stimulus was presented at the absolute threshold for the perception of vibration at that frequency estimated from preliminary tests. The magnitude of vibration was increased by 2 dB after each 'no' response (i.e. the subject did not feel the vibration) and decreased by 2 dB after two consecutive 'yes' responses (i.e. the subject did feel the vibration). The method determines the vibration perceived on 70.7% of presentations (Levitt, 1971). The procedure was terminated after six reversals (3 peaks and 3 valleys). The thresholds were calculated from the average acceleration at the last two peaks and last two valleys.

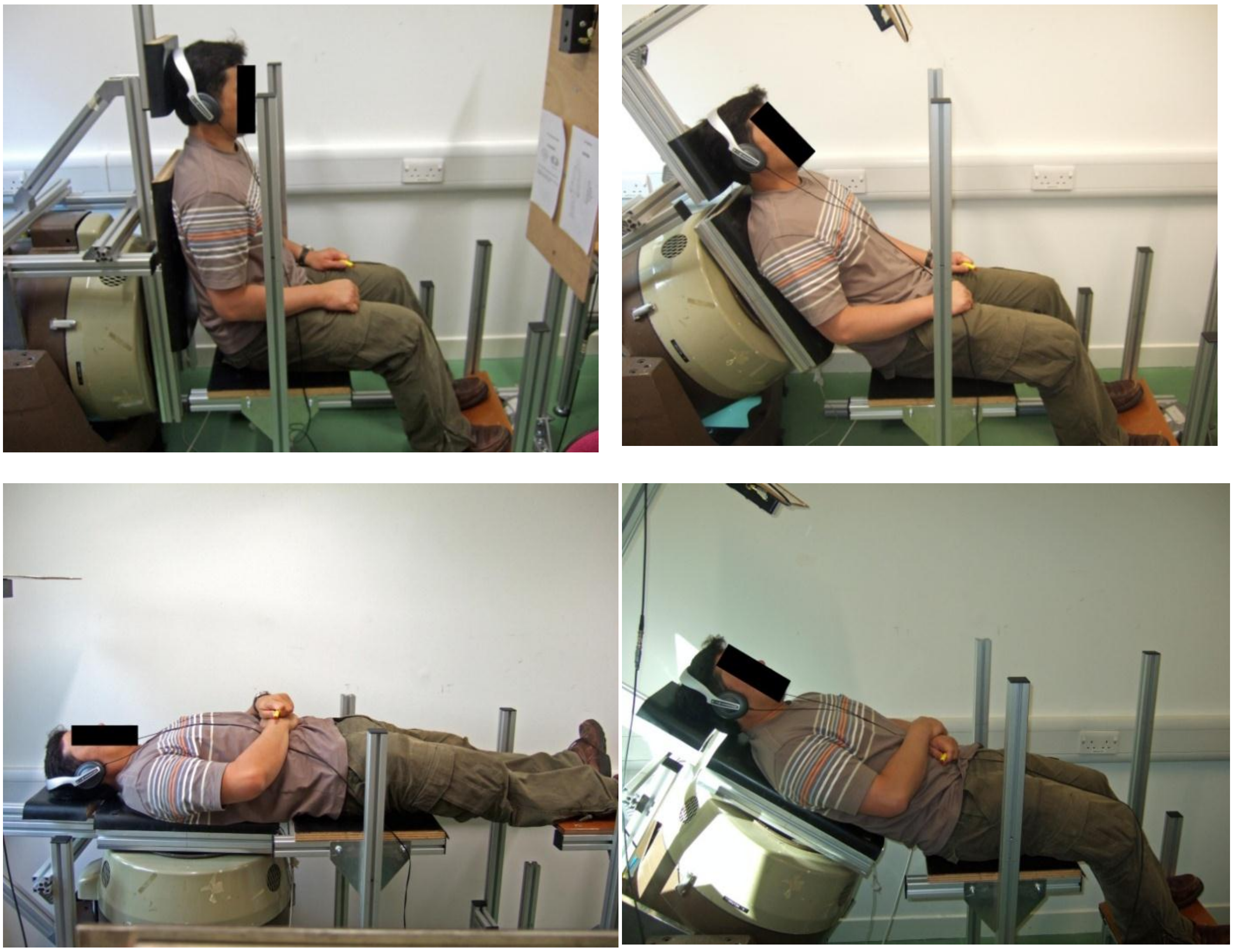

Figure 1 Test rig at 0, 30, 60, and 90 degree inclinations.

2.4 Procedure

Subjects attended four sessions corresponding to the four backrest inclinations (i.e. 0°, 30°, 60° and 90°) on four different days. In each session, subjects sat on the seat with their backs and heads leaning comfortably against the backrest and the stationary headrest. With the backrest at 0°, 30°, and 60°, the feet were supported, whereas in the 90° position (lying), only the calves were supported.

Subjects wore headphones that presented 75 dB white noise, so as to mask any distracting sounds, and held an emergency stop button.

A cue light was used to indicate when a stimulus was being presented. After each presentation of a stimulus (i.e. when the light was off), subjects indicated whether they had felt the vibration. Subjects were given written instructions and participated in preliminary trials to familiarise them with the procedure. Each session lasted about 20 to 30 minutes.

2.5 Subjects

Using a within-subject experimental design (related samples), the same twelve male subjects with mean age 27.8 years (range: 21 to 40), height of 171.8 cm (165 to185), and weight 66.7 kg (53 to 90) participated in all four sessions. The subjects were students and staff of the University of Southampton and were healthy with no history of serious illness, injury, or disability expected to influence their perception of vibration.

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

3. Results

At each backrest inclination, the absolute thresholds for perception of vibration varied with the frequency of vibration (Figure 2; *p*<0.001, Friedman).

Backrest inclination had a significant effect on perception thresholds at all frequencies from 4 to 8 Hz, but not at other frequencies (Figure 3; *p*<0.05, Friedman).

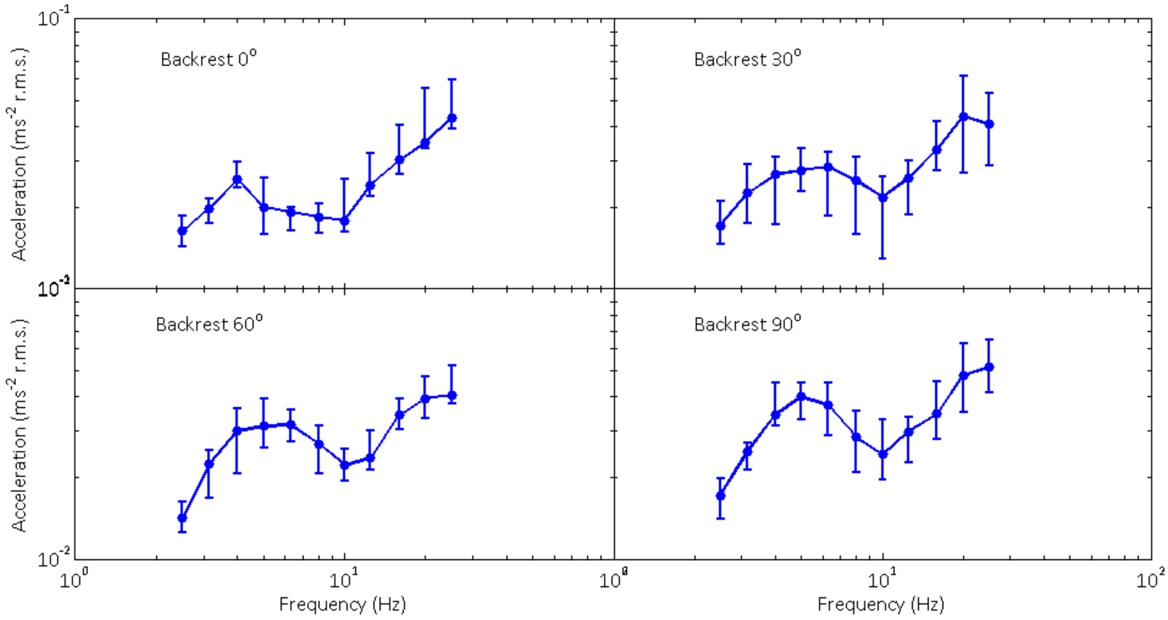

Figure 2 Medians and inter-quartile ranges of absolute perception thresholds with four backrest inclinations.

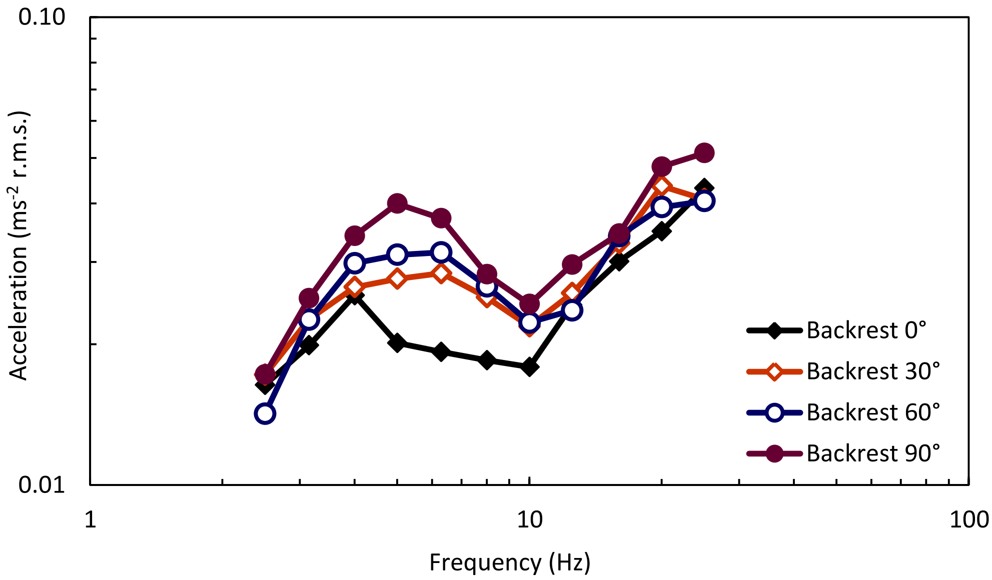

Figure 3 Median absolute thresholds for perception of vibration of the back at four backrest inclinations: 0° (upright), 30°, 60° and 90° (recumbent).

There were significant differences between 90° (recumbent) and 0° (upright) at 4.0, 5.0, 6.3 and 8.0 Hz (p<0.008; Wilcoxon). The difference was about 6 dB at 5 and 6.3 Hz. With vibration at 6.3 Hz, there were also significant differences between 60° and 0° (p=0.006; Wilcoxon) and between 90° and 30° (p=0.009; Wilcoxon; Table 3). With vibration at 5 Hz there was a significant difference between 90° and 30° (p=0.003; Wilcoxon).

Table 2 Wilcoxon matched-pairs signed ranks test of the differences in absolute thresholds between backrest angles.

Frequency	Difference in absolute thresholds for perception between backrest angles					
(Hz)	90° - 0°	60° - 0°	30° - 0°	90° - 30°	90° - 60°	60° - 30°
2.5	-	-	-	-	-	-
3.15	++	-	-	-	-	-
4	++	-	-	++	+	-
5	++	+	+	++	+	-
6.3	++	++	+	++	-	-
8	++	+	+	-	-	-
10	+	-	-	+	-	-
12.5	-	-	-	-	-	-
16	-	-	-	-	-	-
20	-	-	-	-	-	-
25	-	-	-	+	-	-

++ p<0.01, + p<0.05, - p>0.05; Wilcoxon matched-pairs signed ranks tests.

4. Discussion

4.1 Effect of frequency

The high sensitivity to vibration acceleration at low frequencies apparent in Figures 2 and 3 was possibly due to relative motion between the moving back and the stationary pelvis. A similar phenomenon has been found where the discomfort caused by vertical vibration depends on the relative motion between the seat and the feet (Jang and Griffin, 1999).

The rate of decrease in acceleration thresholds with increasing frequency is about 6 dB per octave between 10 and 25 Hz, corresponding to approximately constant velocity over this range. Between 2.5 and 4 Hz, the rate of increase is about 6 dB per octave or greater: thresholds at 60° and 90° tend to 12 dB per octave, corresponding to constant displacement and consistent with perception arising from relative displacement between the vibrating backrest and the stationary supports for the pelvis or head. At frequencies between 4 and 10 Hz, there is increased sensitivity, possibly due to one or more resonances in the body.

4.2 Effect of backrest inclination

The inclination of the backrest influenced thresholds at frequencies between 4 and 8 Hz, where sensitivity was greatest with the vertical backrest (i.e. at 0°) (Figure 3). As the backrest reclined, thresholds in this frequency range increased systematically. With increasing inclination, the force on the backrest arising from the mass of the upper body will have increased approximately in proportion to the sine of the angle of inclination. This may have tended to increase the area of contact with vibration and the compression of tissues within the area of contact. This frequency range broadly coincides with resonance frequencies evident in the fore-and-aft apparent mass of the back in the region of 4 to 6 Hz (Abdul Jalil and Griffin, 2008; Nawayseh and Griffin, 2005), and in the vertical apparent mass of the back when fully recumbent (Huang and Griffin, 2008). The ratio of apparent mass at resonance to the apparent mass at low frequencies (i.e. static mass) was greater with subjects sitting with a vertical backrest than with subjects lying supine on a back support, by a ratio of approximately 3 compared to 1.5. The greater amplification of forces when sitting with the vertical backrest may have increased sensitivity more than when lying supine. Additionally, muscle activity may have been necessary to maintain posture when sitting with a vertical backrest but not when supine.

4.3 Comparison with previous studies

With the vertical backrest (i.e. at 0°), the absolute thresholds obtained in this study can be compared with thresholds and equivalent comfort contours obtained with fore-and-aft vibration of the back. The frequency-dependence of the acceleration thresholds in the present study is similar to that obtained for fore-and-aft vibration of the back by Gallais *et al.* (unpublished) but the thresholds are slightly higher (Figure 4). Gallais *et al.* used the method of limits with longer duration stimuli (3 seconds) and detected thresholds at 50% probability. Morioka and Griffin (2002) have shown that different psychophysical methods can result in considerable differences in the threshold (e.g. by 3 to 6 dB). A full height backrest used by Gallais *et al.* may have also resulted in greater sensitivity if the pelvis was vibrated. The stationary headrest in the present study may have reduced curvature of the back in the

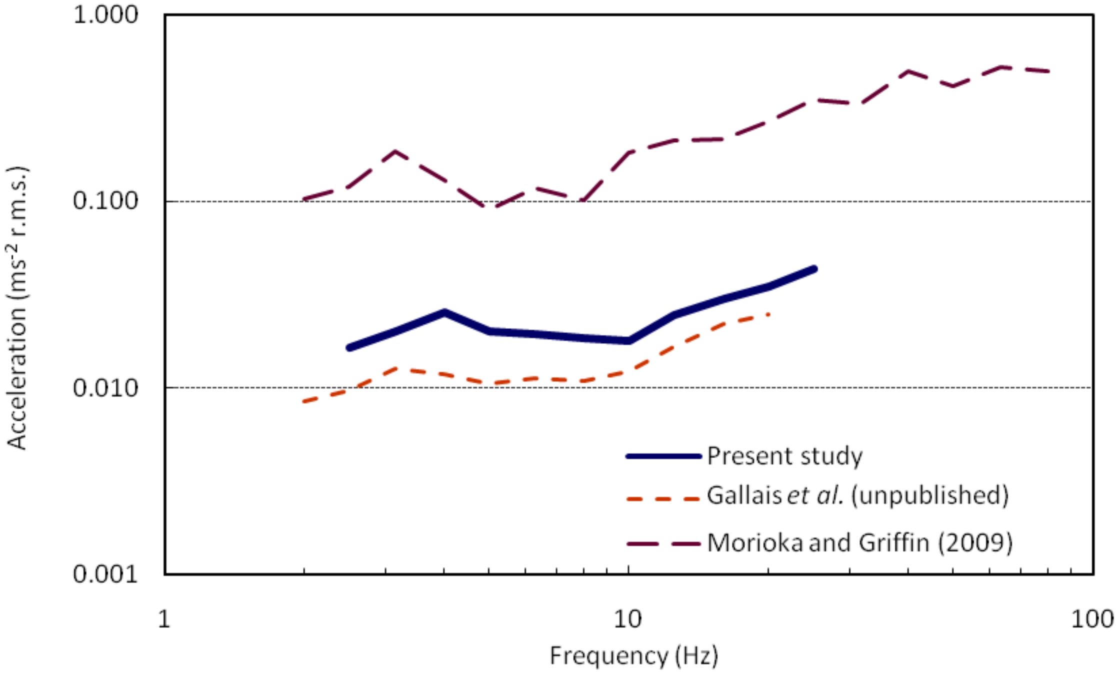

Figure 4 Median absolute thresholds for the perception of fore-and-aft back vibration (upright) in the current study compared to absolute perception thresholds of Gallais *et al.* (unpublished), and an equivalent comfort contour at 50% of the discomfort caused by 10-Hz sinusoidal vibration at 0.315 ms^{-2} r.m.s. (Morioka and Griffin, 2009).

thoracic region (subjects were instructed to rest their head on the headrest), increasing the area of contact at this location and reducing pressure lower in the back.

Morioka and Griffin (2009) obtained equivalent comfort contours for fore-and-aft vibration of a vertical flat backrest. In Figure 4, the current absolute thresholds are compared with the comfort contours obtained by Morioka and Griffin for vibration considered to cause 50% of the discomfort caused by 10 Hz sinusoidal vibration at 0.315 ms^{-2} r.m.s. It can be seen that the equivalent comfort contour has broadly the same frequency-dependence as the absolute thresholds.

With the backrest at 90° (recumbent) the thresholds can be compared with those from studies of the perception of vertical (i.e. *x*-axis) whole-body vibration by supine recumbent subjects (Parsons and Griffin, 1988; Miwa *et al.*,1984; Yonekawa *et al.,* 1999) (Figure 5).

At high frequencies (greater than 5 Hz), the shape of the median perception threshold with 90° inclination of the backrest is broadly consistent with thresholds for supine subjects, but the thresholds are about 6 dB higher than those reported by Miwa *et al.* (1984) and Yonekawa *et al*.(1999) and about 3 dB higher than those reported by Parsons and Griffin (1988). In the studies with supine subjects, the vibration was presented to the whole body, and thresholds would reflect the body part with the greatest sensitivity. At different frequencies, the vibration may be first detected by supine subjects in different parts of the body: the head, heels, ischial tuberosities, feet, chest trunk, or the back (Parsons and Griffin, 1988). Miwa and Yonekawa (1969) showed that different parts of the recumbent body

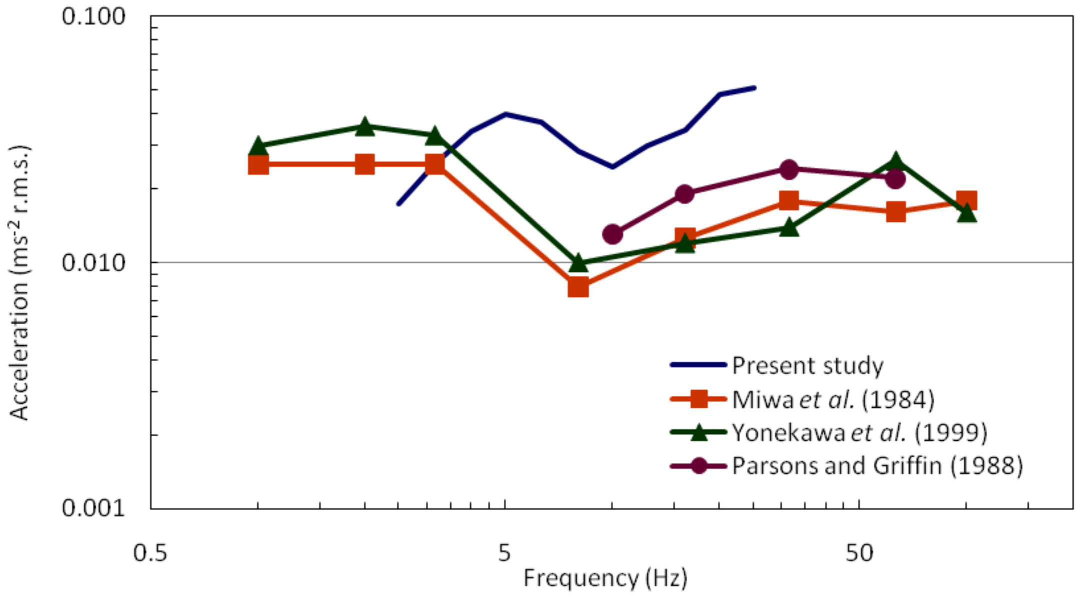

Figure 5 Median perception thresholds for back vibration (with 90° inclination) in the present study compared to perception thresholds for vertical whole-body vibration in recumbent subjects.

have different sensitivity to vertical whole-body vibration. Differences in the psychophysical methods may also have contributed to the differences in thresholds. Miwa *et al.* used the method of limits with longer continuous stimuli (10 seconds) than used in the present study. Yonekawa *et al.* and Parsons and Griffin used the method of adjustment that required the subjects to actively participate in adjusting the level of the stimuli.

At low frequencies, thresholds obtained with vibration of only the back in the present study are lower than those obtained with vibration of the entire supine body, consistent with increased sensitivity at low frequencies arising from relative motion between the backrest and the stationary seat-pan or stationary headrest.

4.4 Frequency weightings

British Standard 6841 (1987) and International Standard 2631 (1997) do not advocate any frequency weighting for predicting thresholds for the perception of fore-and-aft vibration at the back of a seated person but advocate the use of W_b or W_k for predicting the perception of vertical vibration by a recumbent person when there is no vibration at the head (e.g. the vibration is attenuated by a pillow).

The results suggest that thresholds for the perception of the fore-and-aft vibration of vertical backrests (i.e. 0° inclination) could be predicted with reasonable accuracy using the weighting W_c (see Figure 6). The frequency-dependence of thresholds for the perception of vibration with inclined and horizontal backrests (i.e. 30°, 60° and 90° inclination) could be roughly predicted using either weighting W_b or weighting W_k (see Figure 7), but only at frequencies greater than about 8 Hz. The absolute thresholds obtained with inclined and horizontal backrests were higher than suggested by W_b and W_k: they were greater than the root-mean-square of the weighted acceleration corresponding to sinusoidal vibration

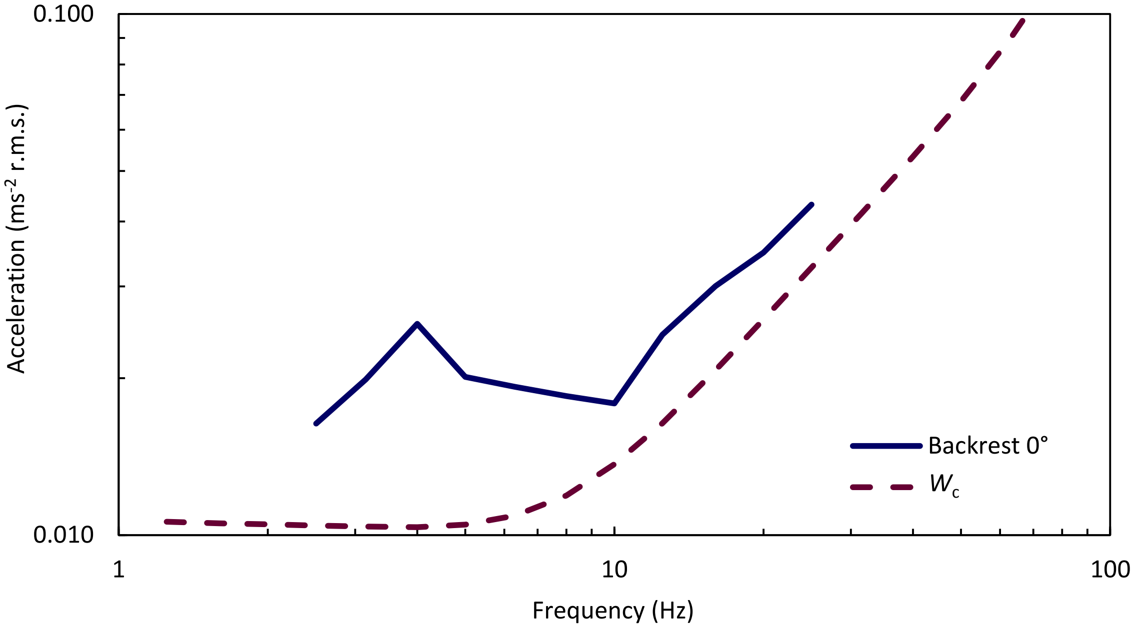

Figure 6 Thresholds for the perception of fore-and-aft vibration of the back with a vertical backrest (0° inclination) compared with the reciprocal of realisable frequency weighting W_c (drawn at the root-mean-square of the frequency weighted sinusoidal acceleration corresponding to ±0.015 ms^{-2}).

with a magnitude of ±0.015 ms^{-2}, which is said to be detectable by 50% of alert fit persons. The prediction of thresholds at low frequencies requires further study.

In transport, vibration of the back occurs together with vibration of other points of contact with the body, especially the seat and the feet. To predict the probability of perception of low frequency

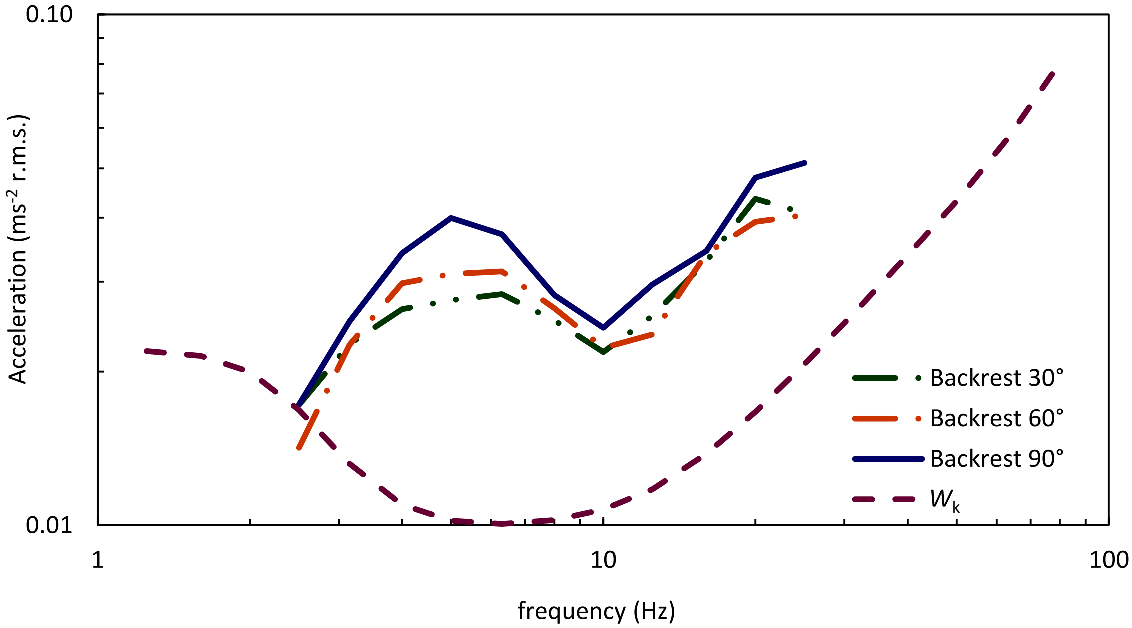

Figure 7 Thresholds for the perception of vibration of the back with inclined backrests compared with the reciprocal of realisable frequency weighting, W_k, for recumbent vertical whole-body vibration (drawn at the root-mean-square of the frequency weighted sinusoidal acceleration corresponding to ±0.015 ms^{-2}).

vibration of the back in a real condition it is necessary to identify which part of the body is most sensitive. It appears that with all backrest inclinations investigated here, sensitivity was high at low frequencies (i.e. 2.5 to 4 Hz), probably due to relative motion between the moving backrest and the non-moving seat or headrest. The influence of seat back inclination on sensitivity at low frequencies without the influence of relative motion merits further attention.

5. Conclusions

Thresholds for the perception of vibration of a backrest depend on the backrest inclination at frequencies between 4 and 8 Hz, where there is a systematic reduction in sensitivity with increasing backrest inclination. At frequencies less than about 4 Hz, relative motion between the backrest and other body supports seems to increase the perception of vibration.

The frequency-dependence of the perception of vibration at the back may be predicted approximately using frequency weighting W_c for vertical backrests and, at frequencies greater than about 8 Hz, using either W_b or W_k for inclined backrests.

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