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Abstract

National and International Standards (e.g. BS 6841 and ISO 2631-1) provide methodologies for the measurement and assessment of whole-body vibration in terms of comfort and health. The EU Physical Agents (Vibration) Directive (PAVD) provides criteria by which vibration magnitudes can be assessed. However, these standards only consider upright seated (90°) and recumbent (0°) backrest angles, and do not provide guidance for semi-recumbent postures. This paper reports an experimental programme that investigated the effects of backrest angle on comfort during vertical whole-body vibration. The series of experiments showed that a relationship exists between seat backrest angle, whole-body vibration frequency and perceived levels of discomfort. The recumbent position (0°) was the most uncomfortable and the semi-recumbent positions of 67.5° and 45° were the least uncomfortable. A new set of frequency weighting curves are proposed which use the same topology as the existing BS and ISO standards. These curves could be applied to those exposed to whole-body vibration in semi-recumbent postures to augment the existing standardised methods.

Keywords: whole-body vibration, human comfort, backrest angle

Running header: “Backrest angle and whole-body vibration”

Relevance statement

Current vibration standards provide guidance for assessing exposures for seated, standing and recumbent positions, but not for semi-recumbent postures. This paper reports new experimental data systematically investigating the effect of backrest angle on discomfort experienced. It demonstrates that most discomfort is caused in a recumbent posture and that least was caused in a semi-recumbent posture.

1. Introduction

The majority of whole-body vibration exposures occur in transport environments where the dominant motion is often in the vertical direction with vibration occurring in a frequency range of 0.2 to 20 Hz (e.g. passenger transport, earth-moving and industrial machinery, agricultural and forestry machines, military vehicles). The vertical biomechanical response of the human body shows a resonance at about 4 to 5 Hz which coincides with the frequencies where people are most sensitive in psychophysical tests. The exposure of the seated or standing human to whole-body vibration, especially at frequencies in the human resonance range can have a variety of detrimental effects on perceived comfort and health (BS 6841, 1987; ISO 2631-1, 1997).

Currently, two standards BS 6841 (1987) and ISO 2631-1 (1997), provide methodologies for the measurement and assessment of human response to whole-body vibration in terms of health, comfort, vision and manual control. The standards define frequency weightings for application to vibration at the seat, floor and backrest in the translational and rotational axes. For assessments of health or comfort, the standards provide different methods of dealing with complex multi-axis vibration (Mansfield, 2005), based on calculations of the vibration dose value (VDV) or the root-mean-square (r.m.s.) of the frequency weighted acceleration and suggest criteria by which the quantities can be evaluated. Although the standards provide specific guidance for assessing those in seated, standing and recumbent positions, there is no suggested strategy to take into account semi-recumbent postures that are experienced by drivers of, for example, military vehicles, patients being transported by ambulance, some long-reach excavators used in demolition, race-car drivers, and passenger transportation where seats recline to facilitate sleep (e.g. long-haul air travel, some trains, some ships).

The effect of whole-body vibration exposure on comfort and health is dependent on a number of factors: the frequency, duration and magnitude of vibration, the position at which contact between the body and vibration occurs, vibration waveform and the posture and orientation of the body (Mansfield, 2005). Changes in posture result in changes in the transmission of vibration from the seat to the head and body (Griffin *et al.*, 1979; Paddan and Griffin, 1988). In many environments postures are dictated by seating, workspace configuration or specialised tasks, although seating can also be used for vibration isolation (Corbridge *et al.*, 1989).

Short term exposure to whole-body vibration can result in physiological changes. Researchers have reported cardiovascular responses (heart rate, respiration rate, blood pressure, and oxygen intake) during exposure to moderate vibration 2-20 Hz (Guignard, 1985). High magnitudes of vertical vibration (amplitudes of 1.5g), in the frequency range of 1-15 Hz for 15 minutes have been shown to result in the subjects experiencing symptoms of chest pain (Magid *et al.*, 1960). Long term whole-body vibration has been proposed as a causal factor in the development of the lumbar spine disorders and back pain in general (Ozkaya *et al.*, 1996; Zerlett, 1986; Bovenzi and Zadini, 1992). Studies by Magnusson and Pope (1998) on the epidemiology and biomechanics of working postures, reported that no single posture could be maintained for a long period of time without considerable discomfort. Lack of body movement leads to accumulation of metabolites, which leads to an acceleration of the degeneration of the discs and increases the risks of disk herniation. Most importantly the authors concluded that an inclined backrest reduces the effects of vibration, as it reduces the disc pressure.

There are no known studies that have made a specific link between health effects, vibration and posture. Stayner (2001) highlighted that although it is possible to associate back pain with an occupation, it is far more difficult to identify which aspect of the occupation is the cause of the pain. It is unlikely, therefore, that epidemiological data can provide a basis for establishing relative health risks between any pathogen that might be present for those working in reclined postures. Nevertheless, epidemiological studies show that those employed in sectors with high magnitudes of vibration tend to have higher prevalence of back pain (Bovenzi and Betta, 1994; Bovenzi and Hulshof, 1998; Mehta and Tewari, 2000; Mansfield and Marshall, 2001) although it is not necessarily the vibration that causes the pain.

There is a large individual variability in subjective assessments of discomfort during exposure to whole-body vibration. Studies have shown that the variation in subjective assessment may be due to the physical size of the participants, in that large males and female participants tend to be less sensitive to low frequencies (less than 6.3 Hz) and more sensitive to higher frequencies of vertical vibration (Griffin *et al.*, 1982). Other sources of individual variation include expectation, experience and context.

It has been suggested that by reclining the crew in military armoured vehicles, the effects of vibration will reduce, and the resulting reduction of the physical profile of the vehicle could make the vehicle less detectable to the enemy. The implications of this are that crew will be required to perform a number of tasks in a reclined posture and stay in that posture for prolonged periods of time. However, as typical tasks undertaken by crew require extended periods of sustained vigilance, the human cost of discomfort should not be overlooked. Previous studies have shown that discomfort ratings and fatigue significantly increase with reclination (towards the recumbent) for long duration tasks (80 to 240 minutes), even with no vibration exposure (Thody *et al.*, 1993; Edwards *et al.*, 1994; Edmonds, 1994). Causes of discomfort can be attributed to secondary biomechanical considerations rather than directly to the posture: lifting the head whilst reclined to view a display or working with upper limbs above shoulder level were both considered to generate unacceptable postural loads. If these postures are combined with vibration exposure, then discomfort might develop more rapidly.

The EU Physical Agents (Vibration) Directive (PAVD) (European Commission 2002 Directive 2002/44/EC) is implemented in all Member States in Europe and, for the first time, introduced limits on the vibration exposures for workers. Central to the Directive is the requirement to assess and minimise risks with vibration exposure. If vibration exposure is considered to constitute a risk, or if it exceeds the 'daily exposure action value' of 0.5 ms^{-2} $A(8)$ measured according to ISO 2631-1 (1997), then some form of action must be taken to minimise those risks. The Directive is clear that a holistic approach is required such that, for example, the design and layout of workspaces is optimised. As ISO 2631-1 (1997) does not provide guidance for assessment of those exposed to whole-body vibration in semi-reclined postures, it is possible that the assessment may generate results that do not reflect the true risk for the operator exposed to vibration when seated in such a posture. Risk assessments that are too conservative may result in an unnecessary reduction in individual exposure times, and impact adversely on worker productivity; assessments that underestimate the risk may result in an unnecessary increase in risk of whole-body vibration injury.

This paper reports a research programme that was designed to identify the relative sensitivity of the human body to vibration of different frequencies and at different backrest angles, with a view to proposing new frequency weightings that could be used to augment comfort or risk assessments of those exposed to vibration in reclined postures. This study represents the second part of a 2-part experiment looking at the effects of vibration on performance (Paddan *et al.*, 2012) and discomfort.

2. Method

2.1 Design

The study comprised two main experimental phases. Phase I investigated the effects of sinusoidal, vertical whole-body vibration at frequencies of 2 Hz, 4 Hz, 8 Hz, 16 Hz, 32 Hz and 64 Hz, on perceived comfort at each of 5 backrest angles: 0° (recumbent), 22.5°, 45°, 67.5° and 90° (upright), see Figure 1. Phase II investigated the effects of changes in backrest angle on perceived comfort during exposure to 8 Hz of vertical whole-body vibration. Phase II followed Phase I. The overall aim of the study was to establish whether seat backrest angle had any effect on perceived comfort, and to use the data to generate new frequency weighting curves. The design of the experiment was approved by the QinetiQ Ethics Committee under a generic laboratory whole-body vibration exposure protocol.

Figure 1 about here

2.2 Participants

Twenty participants (10 male, 10 female) took part in the experiment and participated in both experimental phases. The mean age of the male participants was 30.3 years (stdev = 9.7 years, range 21–53 years), mean weight was 78.0 kg (stdev = 10.5 kg, range 61–93 kg), and mean height was 1.78 m (stdev = 0.07 m, range 1.67–1.85 m). The mean age of the female participants was 32.1 years (stdev = 9.0 years, range 22–47 years), mean weight was 64.8 kg (stdev = 8.6 kg, range 53–83 kg), and mean height was 1.69 m (stdev = 0.07 m, range 1.63–1.87 m).

2.3 Apparatus

A man-rated vertical vibration simulator with a capacity of displacements up to ±0.9 m was used to generate the vibration stimuli. It can be programmed to accept vertical vibrations generated by laboratory instruments or derived from recorded vehicle data. The vibration simulator has a velocity limit of 1.5 ms^{-1}, an acceleration limit of 30 ms^{-2}, and a frequency range of 0 to 50 Hz.

An adjustable seat was mounted on the platform of the vertical vibration simulator (see Figure 2). The main frame for the adjustable seat used for the trial was of a rigid wooden construction. The seat measured 2.0 x 0.8 x 1.5 m high with backrest fully upright and incorporated an adjustable footrest, a 3-point safety harness, a chest strap and a motorised backrest that could be driven remotely to any angle between 0° (recumbent) and 90° (upright) (see Figure 2). The seat surface was covered in high friction 1 mm thick foam rubber and the participants had the use of a small head cushion measuring 0.22 x 0.15 x 0.35 m. The acceleration at the base of the seat was measured using an Endevco Q-Flex QA-116-15 servo accelerometer. Additional orthogonal acceleration measurements were also taken from the mid-point on the rear of the backrest using Endevco 7265-10 piezo-resistive accelerometers. Participant intercom and emergency stop controls were also provided.

Figure 2 about here

2.4 Procedure

The participants attended the laboratory on a total of eight occasions. The first visit comprised a calibration and familiarisation session. The nature of the trial was explained and informed, written consent obtained. The participants were exposed to all of the sinusoidal stimuli to be used in the trial, that had frequencies of 2 Hz, 4 Hz, 8 Hz, 16 Hz, 32 Hz and 64 Hz, a magnitude of 2 ms^{-2} r.m.s. and a duration 10 seconds. Each stimulus had a 500 ms linear taper at the start and end. Exposure of the participants to these stimuli allowed the output of the vertical oscillator to be calibrated to each individual. In addition, this allowed the participants to ascertain the range of whole-body vibration that they would be exposed to. This exposure was repeated at the start of each experimental session to help re-familiarise participants with their assessment criteria. In addition, on the first visit a short dummy run was undertaken. The participants were exposed to two randomly selected pairs of stimuli, presented to the participant in the same manner used in the main experiment to familiarise the participant with the trial methodology and subjective comfort rating criteria.

Immediately after the presentation of each pair of whole-body vibration stimuli, the participants were asked to give a subjective comfort rating for the comparator stimulus relative to the reference stimulus, where the reference stimulus was always equal to 100%. If the participants believed the comparator stimulus was more uncomfortable than the reference, they gave a rating above 100%. If they believed it was more comfortable than the reference, they gave a rating below 100%. Participants were allowed to determine their own upper and lower limits.

Between one and five days following the familiarisation session the participants attended the laboratory for the first of five sessions comprising Phase I of the trial. For each session the participants were exposed to whole-body vibration stimuli whilst seated in one of five backrest angles: 0° (recumbent), 22.5°, 45°, 67.5° and 90° (upright). The order of backrest seating angle for each participant was determined by a

Latin square design. Participants completed the main Phase I trials over five sequential days at the same time of day for each individual.

On arrival at the laboratory, participants sat on the seat at the appropriate backrest angle. The footrest and the participant's feet were positioned so that the leg angle at the knee was fixed at 120° for all conditions. The participants were then secured to the seat by the 3-point harness, and headphones placed on the head and the headrest adjusted. The headphones allowed 2-way communication with the experimenter and also conveyed pink noise (65 dB(A) at the ear) to mask the noise of the vertical vibration simulator in operation.

The tests comprised twelve pairs of stimuli that were each repeated three times: a reference and a comparator stimulus. Frequency combinations used were 2 Hz (reference) & 2 Hz (comparator), 2 & 4 Hz, 2 & 8 Hz, 2 & 16 Hz, 2 & 32 Hz, 2 & 64 Hz and 16 Hz (reference) & 2 Hz (comparator), 16 & 4 Hz, 16 & 8 Hz, 16 & 16 Hz, 16 & 32 Hz, and 16 & 64 Hz. There was a 1-second gap between the reference and comparator. An auditory tone, to indicate the start of each pair was sounded immediately prior to the onset of the reference stimulus. There was a 20-second gap between each pair of stimuli, during which time the participant was asked to provide their comfort rating. There was a 2-minute rest period between each of the three sets of twelve stimulus pairs. The randomisations of the pairs and timing of the onset of stimuli were controlled by custom-written control software.

It took approximately 40 minutes to complete each experimental session for each participant for Phase I. The total VDV for all the stimulus pairs used in this part of the trial was 10.6 $ms^{-1.75}$.

Following the completion of Phase I, the participants attended the laboratory for Phase II of the study. During this Phase, the participants attended the laboratory for two sessions. The first session comprised calibration and familiarisation, during which the participants were exposed to the 8 Hz stimulus and a dummy run of one of the trials. For the experimental session of Phase II, the participants were exposed to a stimulus comprising a frequency of 8 Hz at a vibration magnitude of 2 ms^{-2} r.m.s for three repeats of four pairs of reference-comparator seat positions: 45° & 0°, 45° & 22.5°, 45° & 67.5°, and 45° & 90°. A similar test protocol was used for Phase I and Phase II.

It took approximately 40 minutes to complete each experimental session for each participant for Phase II. The total VDV for all the stimulus pairs used in this part of the trial was 11.3 $ms^{-1.75}$.

3. Results

As described above, participants were asked to express their perceived level of discomfort for a given test stimulus with respect to the reference stimulus, using a comparative scale where 100% represented the two stimuli being equal. As no upper bounds or resolution were set, participants were free to map their subjective impression of the whole-body vibration to the objective scale in any way that they felt appropriate. For example, one participant used the range from 80% to 140% and another subject used the range from 50% to 500%. The results from Phase I are summarised in Figure 3: the graphs show the median of six repeats for each participant (three repeats with a 2 Hz reference and three repeats with a 16 Hz reference). Each graph represents one participant's response to each of the five backrest angles, and the differing ranges used by the participants can be clearly seen.

Figure 3 about here

To directly compare the results from all participants could produce misleading results due to differences between their subjective mapping, and therefore all of the results were normalised using Equation (1) (Mansfield *et al.*, 2000). The normalised results for each participant have zero mean and unity standard deviation, enabling a direct comparison to be made of the relative ratings. Higher values indicate greater ratings of discomfort.

$$R_N = \frac{R_R - \bar{x}_P}{\sigma_P} \qquad (1)$$

Where R_N = Normalised Score

R_R = Raw Score

$\bar{x}_P$ = Mean of participant’s raw scores

σ_P = Standard deviation of participant’s raw scores

The results from Phase I are shown in Figure 4, with the normalised response against test stimulus frequency (the second of the pair of frequencies presented to each participant). In this figure, the results for both of the reference frequencies (2 Hz and 16 Hz) have been combined for each of the test stimulus frequencies. Participants were most sensitive to whole-body vibration in the 4 to 16 Hz frequency range. For the 0°, 22.5°, 45° and 67.5° backrest angles, the greatest ratings occurred at 8 Hz; for the 90° backrest angle, the greatest ratings occurred at 4 Hz.

Figure 4 about here

The normalised results from Phase II are shown in Figure 5. During Phase II, the stimulus frequency was kept constant at 8 Hz and the backrest angle varied. A backrest angle of 45° was chosen as the reference position and therefore has a value of zero in Figure 5. At 8 Hz (the frequency where participants were most sensitive to vibration), the recumbent position of 0° was considered to be the most uncomfortable and the backrest angle of 67.5° was the least uncomfortable. Generally the effect of backrest angle on perceived comfort at 8 Hz was significant ($p<0.05$, paired-samples t-test; Table 1). The only exceptions occurred for comparison of results obtained at 22.5° and 90° and results obtained at 45° and 90°. For each of the practical backrest angle transitions (0º↔22.5º, 22.5º↔45º, 45º↔67.5º and 67.5º↔90º) significant differences were observed.

Figure 5 about here

Table 1 about here

If Figure 4 was to be plotted on a 3-dimensional graph (*x*-axis = frequency, *y*-axis = backrest angle, *z*-axis = normalised perceived discomfort), then Figure 5 would be a perpendicular slice through the frequency axis at 8 Hz. The result of normalising the values of the results of Phase I at 8 Hz (Figure 4) according to the results from Phase II (Figure 5) is shown in Figure 6, which describes the relationship between backrest angle and perceived comfort. These combined results show that the extreme postures (0° and 90°) were the most uncomfortable.

Figure 6 about here

4. Weighting Filters

4.1 Weighting filters defined by ISO 2631-1 and BS 6841

Both ISO 2631-1 (1997) and BS 6841 (1987) describe methods of calculating vibration exposure from acceleration data. The two standards differ in the calculations used (Griffin, 1998; Rimell and Mansfield, 2007), but both have similar methods of weighting the data prior to calculation. This paper only considers vertical vibration, and therefore horizontal or rotational vibration, and the application of the standards to upright standing operators will not be considered.

The standards provide frequency weighting curves dependent on the posture of the operator, the direction of the vibration, and whether the measurement is required for an indication of health risk, comfort, perception threshold or motion sickness. For operators using a recumbent or upright sitting posture and for vertical motion, ISO 2631-1 (1997) recommends the use of its Wk curve and BS 6481 (1987) recommends the use of its Wb curve. These two curves are shown in Figure 7, and it can be seen that there are slight differences in the magnitude response, although they have similar general shapes (Mansfield, 2005).

Figure 7 about here

The frequency weighting curves are defined by a set of *s*-domain (Laplace operator) equations and by tabulated third-octave values. ISO 2631-1 weighting curves are defined by the following equations:

High-pass
$$H_h(s) = \frac{s^2}{s^2 + \frac{\omega_1}{Q_1}s + \omega_1^{\ 2}} \quad (2)$$

Low-pass
$$H_l(s) = \frac{\omega_2^{\ 2}}{s^2 + \frac{\omega_2}{Q_2}s + \omega_2^{\ 2}} \quad (3)$$

Accel-vel transition
$$H_t(s) = \frac{(Q_4 \cdot \omega_4^{\ 2})s + (Q_4 \cdot \omega_4^{\ 2} \cdot \omega_3)}{(Q_4 \cdot \omega_3)s^2 + (\omega_3 \cdot \omega_4)s + (Q_4 \cdot \omega_4^{\ 2} \cdot \omega_3)} \quad (4)$$

Step
$$H_s(s) = \frac{s^2 + \frac{\omega_5}{Q_5}s + \omega_5^{\ 2}}{s^2 + \frac{\omega_6}{Q_6}s + \omega_6^{\ 2}} \quad (5)$$

where: $\omega_n = 2\pi f_n$ and f_n = corner frequency

The total weighting function is defined as:

$$H_{ISO}(s) = G \cdot H_h(s) \cdot H_l(s) \cdot H_t(s) \cdot H_s(s) \quad (6)$$

where G is a scalar gain value.

The coefficient values for Wk are given in Table 2. By replacing s with $j\omega$, and then separating the real and imaginary parts, the complex frequency response can be obtained. The magnitude and phase response can be obtained by use of a rectangular-to-polar conversion.

Table 2 about here

The BS 6841 weighting curves for Wb are defined by the following equations:

Band-limiting
$$H_b(s) = \frac{s^2}{s^2 + \frac{\omega_1}{Q_1}s + \omega_1^2} \cdot \frac{\omega_2^2}{s^2 + \frac{\omega_2}{Q_1}s + \omega_2^2} \tag{7}$$

Weighting
$$H_w(s) = \frac{s^2 + \frac{\omega_5}{Q_3}s + \omega_5^2}{s^2 + \frac{\omega_6}{Q_4}s + \omega_6^2} \cdot \frac{s + \omega_3}{s^2 + \frac{\omega_4}{Q_2}s + \omega_4^2} \cdot \frac{2\pi K f_4^2 f_6^2}{f_3 f_5^2} \tag{8}$$

where: $\omega_n = 2\pi f_n$ and f_n = corner frequency

The total weighting function is defined as:

$$H_{BS}(s) = H_b(s) \cdot H_w(s) \tag{9}$$

It can be shown that Equation 6 is algebraically equivalent to Equation 9 when the substitutions shown in Table 3 are used and when Q1 = Q2. Therefore, the weighting filters described in Table 2 can also be implemented using the *s*-domain equations of BS 6841 (Equation 7 to Equation 9).

Table 3 about here

Rimell and Mansfield (2007) have proposed a general method for implementing vibration weighting filters as infinite impulse response (IIR) filters for inclusion in analysis software, the methods presented are applicable to the filters described here.

Alternatively, the filters can be converted to linear-phase finite impulse response (FIR) digital filters as described by Notini and Mansfield (2004).

4.2 Weighting filter design for a wide range of postures

Using the *s*-domain equations for Wk (Equation 2 to Equation 6), the parameters were selected such that the calculated transfer function was an optimum fit with the measured data. A minimum least-squares metric was used to fit the data. Figure 8 shows an example where the measured data points and the transfer function are shown for the 90º posture. As the experimental data only covered the frequency range from 2 Hz to 64 Hz, the response outside of this range is unknown and therefore the new filters include low- and high-pass filtering to limit the influence of the out-of-band frequencies (a similar band-limiting function is also included in the current standards). The complete set of weighting filters is shown in Figure 9 and their coefficients are presented in Table 2. These filters may be implemented by inserting the coefficients into Equations 2 to 6 or into an existing digital implementation.

Figure 8 about here

Figure 9 about here

The experiment, and hence the resulting weighting filters, are defined only at discrete backrest angles; however, through the use of an interpolation strategy, it is possible to calculate a weighting filter for any angle between 0º (recumbent) and 90º (upright). The interpolation enables any weighting filter coefficients to be calculated for any backrest angle and is based on a 4th order polynomial fit of the form:

$$y = \sum_{j=0}^{4} a_j \cdot x^j \qquad (10)$$

where a is the coefficient and x is the backrest angle. The coefficients shown in Table 4 were calculated using a Singular Value Decomposition (SVD) polynomial-fitting algorithm, and the correlation coefficient, r, is equal to unity for every one of interpolated filter coefficients. Because r = 1, the interpolated frequency responses are an exact match to those found experimentally for the backrest angles of 0º, 22.5º, 45º, 67.5º and 90º. For example, consider the equation for f_5 as a function of backrest angle, x:

$$f_5 = 3.13 + 0.608x - 0.022176x^2 + 3.4283\times10^{-4}x^3 - 1.9054\times10^{-6}x^4 \qquad (11)$$

It is advisable to exercise caution when interpolating between 90º and 67.5º, as the response between these angles is uncertain. Figure 10 shows the interpolated filter for a backrest angle of 10º, and also the two nearest filters based on the experimental results for 0º and 22.5º.

Table 4 about here

Figure 10 about here

5. Discussion

The aim of this study was to investigate whether seat backrest angle influenced perceived comfort during vertical whole-body vibration. This study has showed that, in general, the level of perceived discomfort increases with decreasing backrest angle (i.e. more reclined). At 8 Hz (the frequency of most sensitivity in this study) it was monotonic from 67.5° to 0°. Also noteworthy is that the participants are most sensitive to whole-body vibration over the frequency range of 4 Hz to 8 Hz, which corresponds to the region of the resonance frequency of the human body (Mansfield *et al.*, 2000; Paddan and Griffin, 1988).

Previous research into biomechanics of humans on stationary chairs (Magnusson *et al.*, 1994; Magnusson and Pope, 1998; Goel *et al.*, 1999; Kayis and Hoang, 1999; Wilke *et al.*, 1999; Lengsfeld *et al.*, 2000) has shown that chairs with armrests, a tilting seat-pan and a lumbar support reduce intradiscal pressure in the spine, and also that intradiscal pressure decreases as the backrest angle decreases (becomes more recumbent). A decrease in spinal intradiscal pressure results in a reduction in the perceived discomfort of the user. The research, which only considered a limited range of postures with backrest angles from -10° (anterior lean) to 50° (posterior lean) and recumbent, also recommended a backrest angle of 70°. The findings from the experiment described in this paper suggest that such earlier research may also be applicable to chairs mounted to vibrating surfaces for backrest angles of between 90° and 45°.

The upright 90° posture is considered to be the most uncomfortable at all frequencies except 8 Hz, which is to be expected as, for postural support, a reclined sitting position is desirable for maximum comfort, allowing the muscles to relax. It is also possible that, in the 90° position, the back was not pressed hard against the backrest, effectively resulting in an unsupported back, which, according to Nachemson (1985), applies about twice the intradiscal pressure to the spine compared with the relaxed sitting position. The recommended backrest angle for an office chair is 70° to

75°, with a seat-pan tilt of 5° to 10° (Pheasant, 1990). The 67.5° and 45° postures produced less discomfort than the 90° posture whilst exposed to vibration at all frequencies investigated in this study. In this experiment, participants' hands were by their sides. If, however, the participants were engaged in a task where their arms were above shoulder height, it is expected that they would find the recumbent positions increasingly uncomfortable after a short period of time (Magnusson and Pope, 1998).

Figures 11 and 12 compare the results from this study with the results published by Maeda *et al.*, (2001). The posture used in the experiment described in this paper for the recumbent (0°) position is slightly different (the legs were bent to represent a possible driving position) to that used in the experiment reported by Maeda. The disparity in the curves at higher frequencies (see Figure 11) may be due to the use of different head supports (this experiment used a padded head-rest whereas Maeda used no head support). ISO 2631-1 suggests the use of Wj frequency weighting for supine vibration exposures without padded head support; this shows greater sensitivity to high frequency vibration, similar to the results reported by Maeda. The posture for the upright position (90°) in this experiment corresponded to that used by Maeda and the measured response below 16 Hz is very similar to the results published by Maeda (see Figure 12).

Figure 11 about here

Figure 12 about here

If it is required to control risk from whole-body vibration, then the new set of frequency weighting filters presented here could be used to augment assessments according to ISO 2631-1. The standard format enables users to apply the filters using their existing filter topologies (either analogue or digital) simply by inserting the new coefficient values. In most cases this would result in backrest angles of 67.5° being shown to be preferable, and fully reclined to be worst. Other ergonomic considerations, such as static postural loading and fatigue, should also be considered.

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Figures

Figure 1. The five postures used in the experiments illustrating the changes in backrest angle (‘0° supine’, ‘90° upright’).

Figure 2. Apparatus used in the experiment, showing the 67.5° backrest angle condition.

Figure 3. Raw (non-normalised) results from Phase I for each of the twenty participants (one graph for each participant). Each line shows the mean of six repeats at each backrest angle (three repeats with a 2 Hz reference and three with a 16 Hz reference).

Figure 4. Effects of vibration frequency on mean normalised discomfort ratings for 20 participants in five postures. Greater ratings correspond to more discomfort (0° = recumbent, 90° = upright).

Figure 5. Effects of backrest angle on mean normalised discomfort ratings for 20 participants tested at 8 Hz. Greater ratings correspond to more discomfort. (0° = recumbent, 90° = upright). Error bars show ± 1 Standard Deviation.

Figure 6. Combined effects of backrest angle and frequency of vibration on mean normalised discomfort ratings for 20 participants. Greater ratings correspond to more discomfort. (0° = recumbent, 90° = upright).

Figure 7. Published frequency weighting curves: Wk from ISO 2631-1, Wb from BS 6841.

Figure 8. Filter approximation to measured data for 90º backrest angle. The dots represent the experimental data and the solid line represents the new weighting filter transfer function.

Figure 9. New weighting curves for different backrest angles and the existing ISO 2631-1 Wk curve.

Figure 10. Interpolated frequency weighting response for a 10º backrest angle. The responses at 0º and 22.5º are also shown for comparison.

Figure 11. Comparison of subject responses from this study with published data for the 0° posture (recumbent). Data from Maeda *et al.*’s study have been scaled for clarity.

Figure 12. Comparison of subject responses from this study with published data for the 90° posture (upright). Data from Maeda *et al.*’s study have been scaled for clarity.

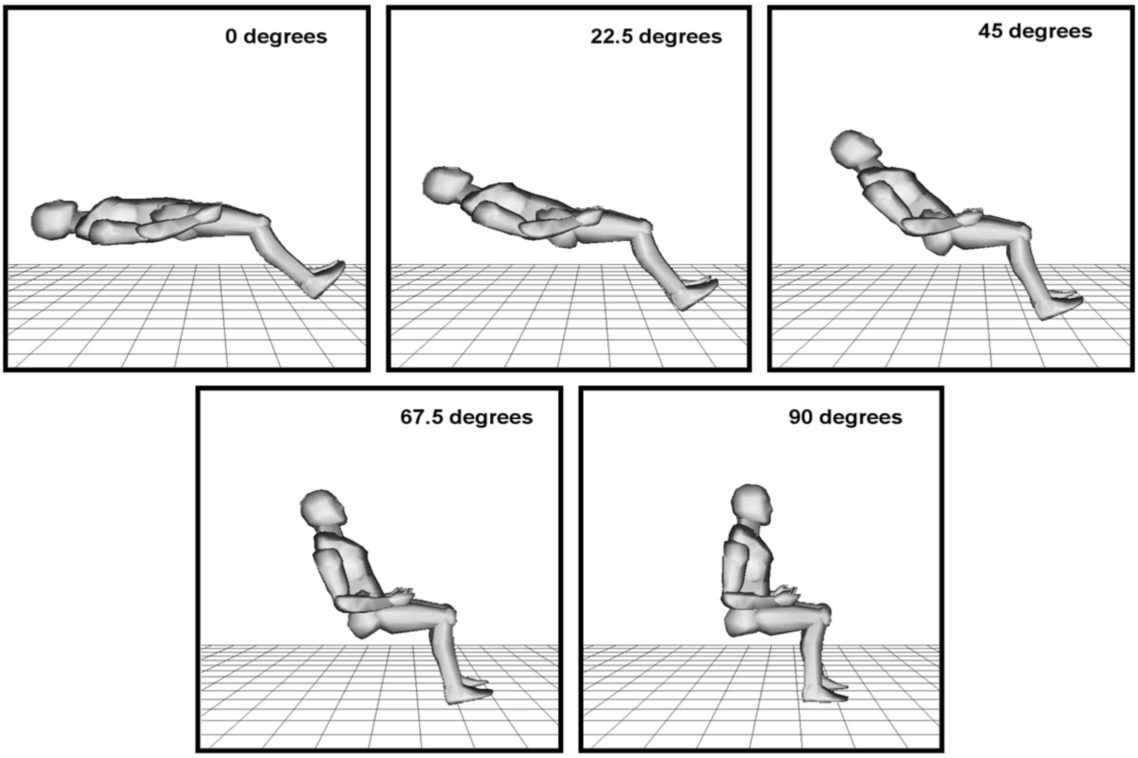
Tables

Table 1. Results from a paired-Samples t-test for Phase II to examine the significance of an effect of backrest angle at a frequency of 8 Hz. Values below 0.05 are considered to be significant.

Table 2. Coefficients for the new frequency weighting curves and for ISO 2631-1 Wk.

Table 3. Equivalence between the BS and ISO s-domain weighting curve definitions.

Table 4. Interpolation coefficients.



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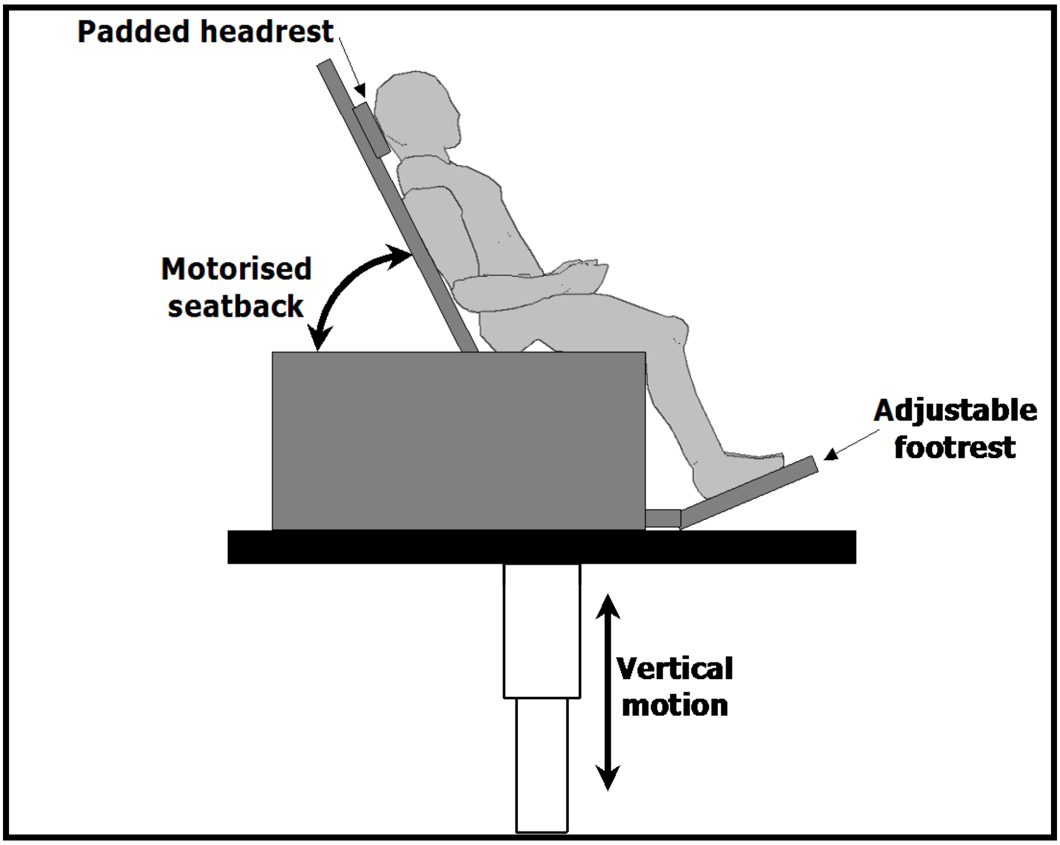

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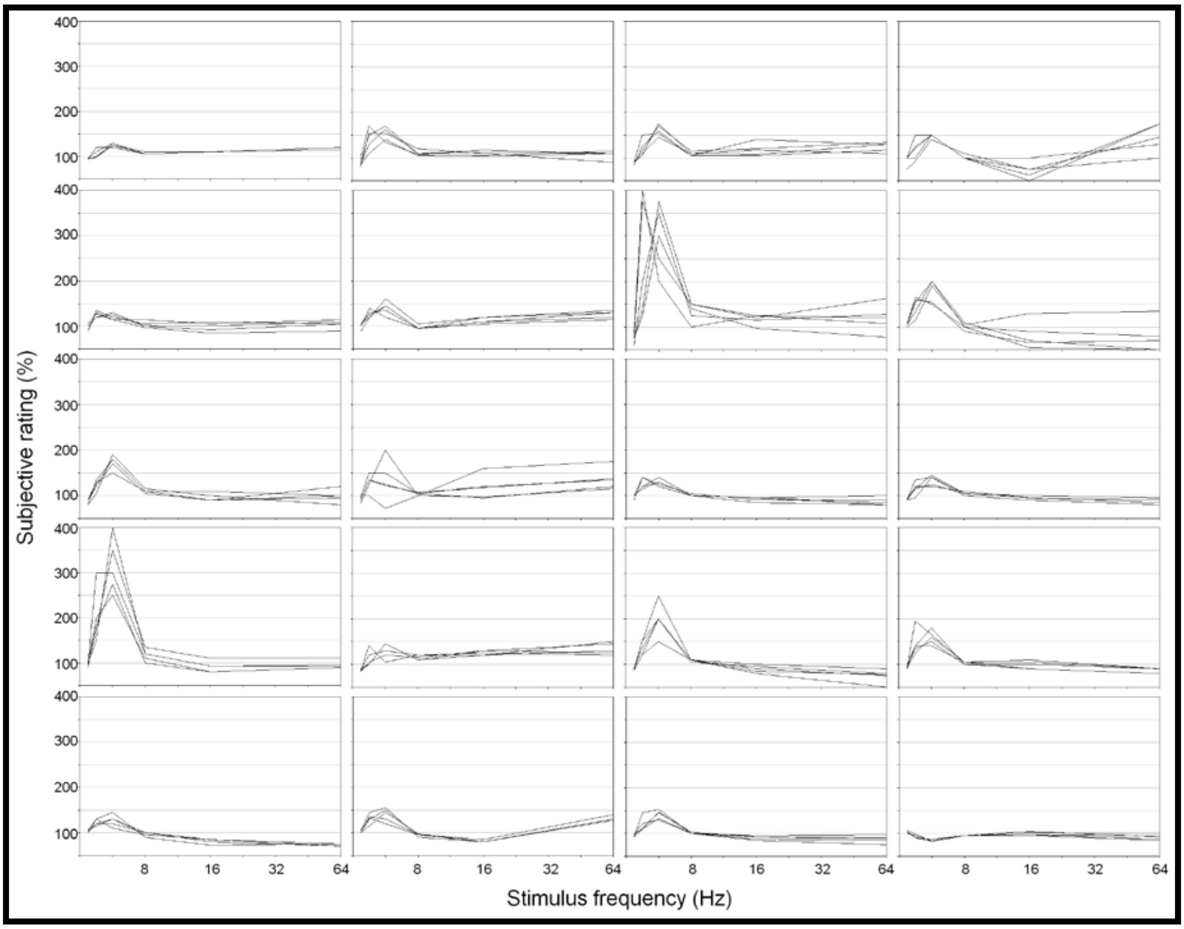

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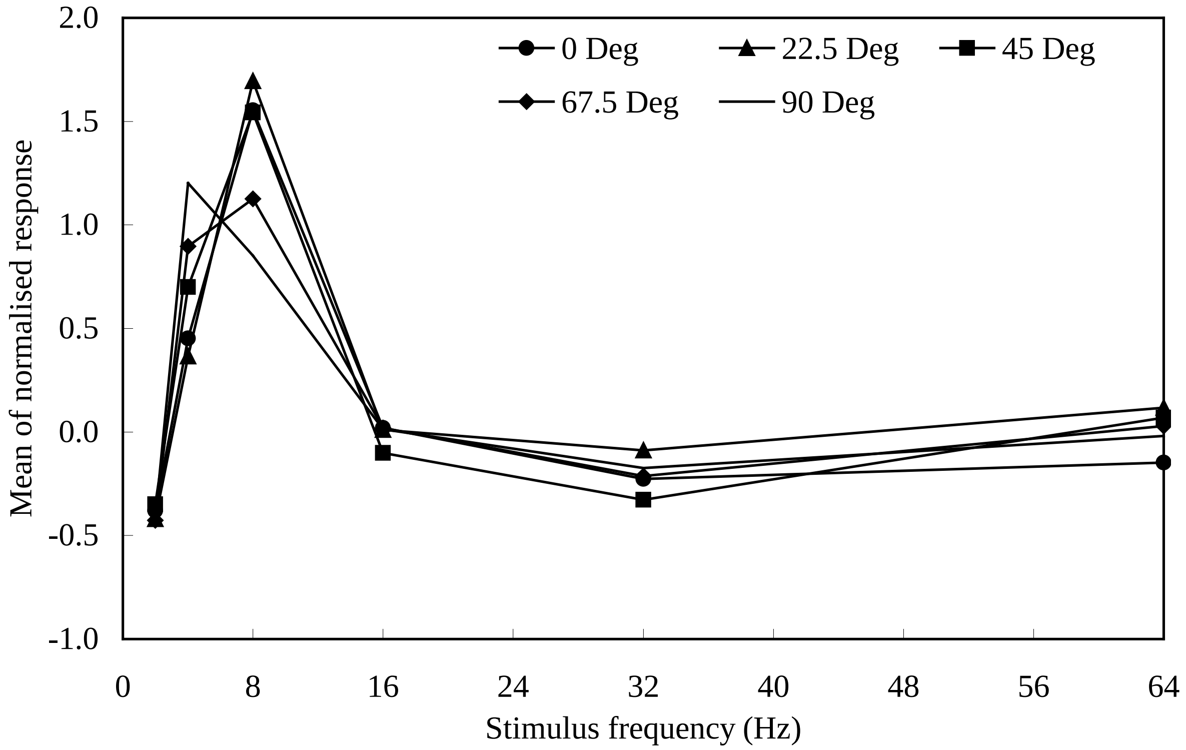

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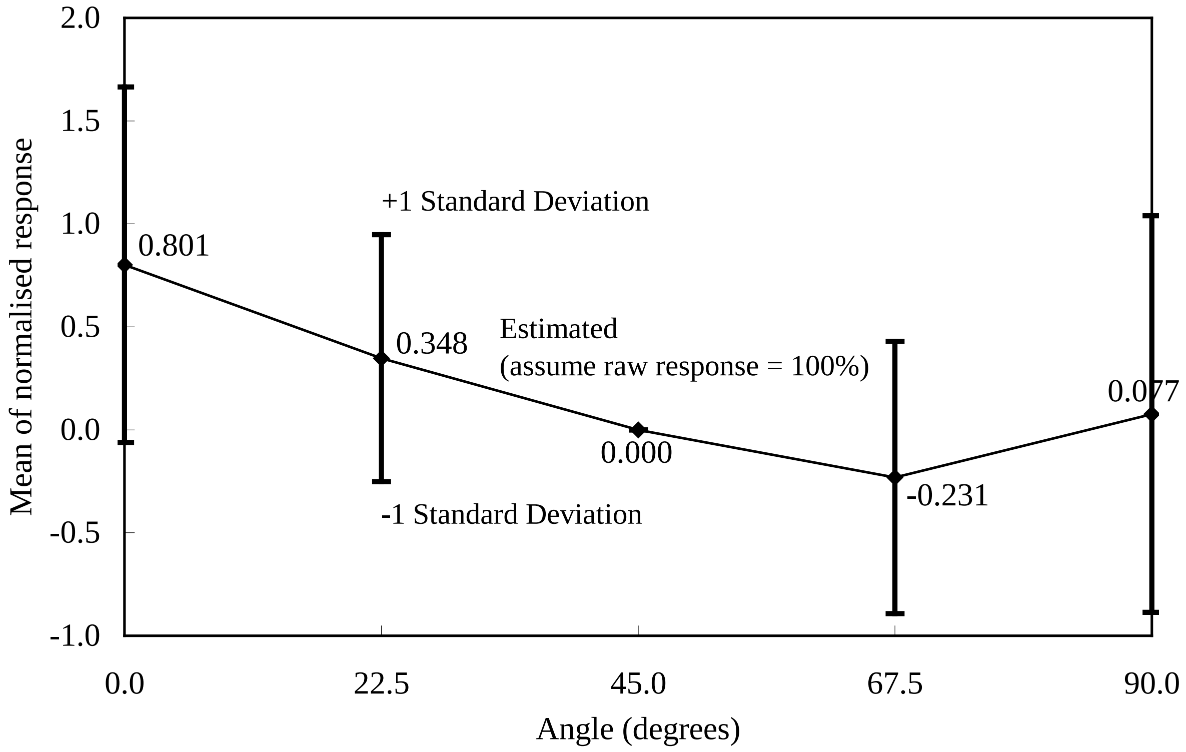

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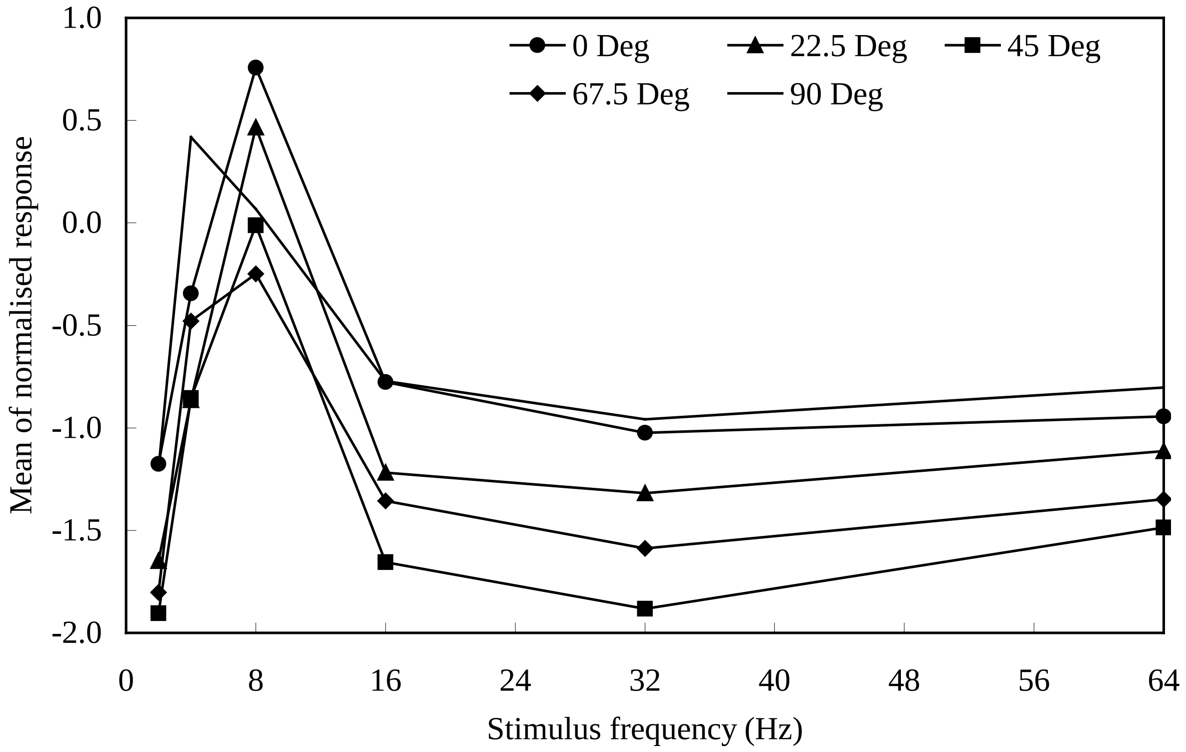

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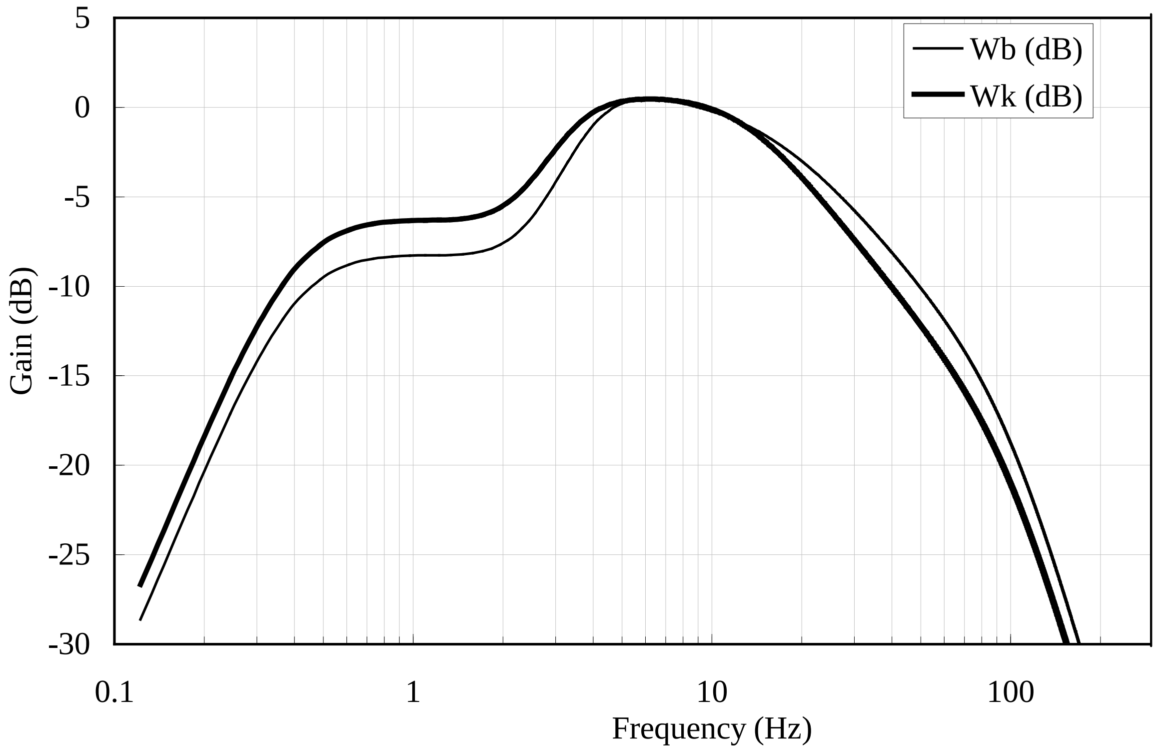

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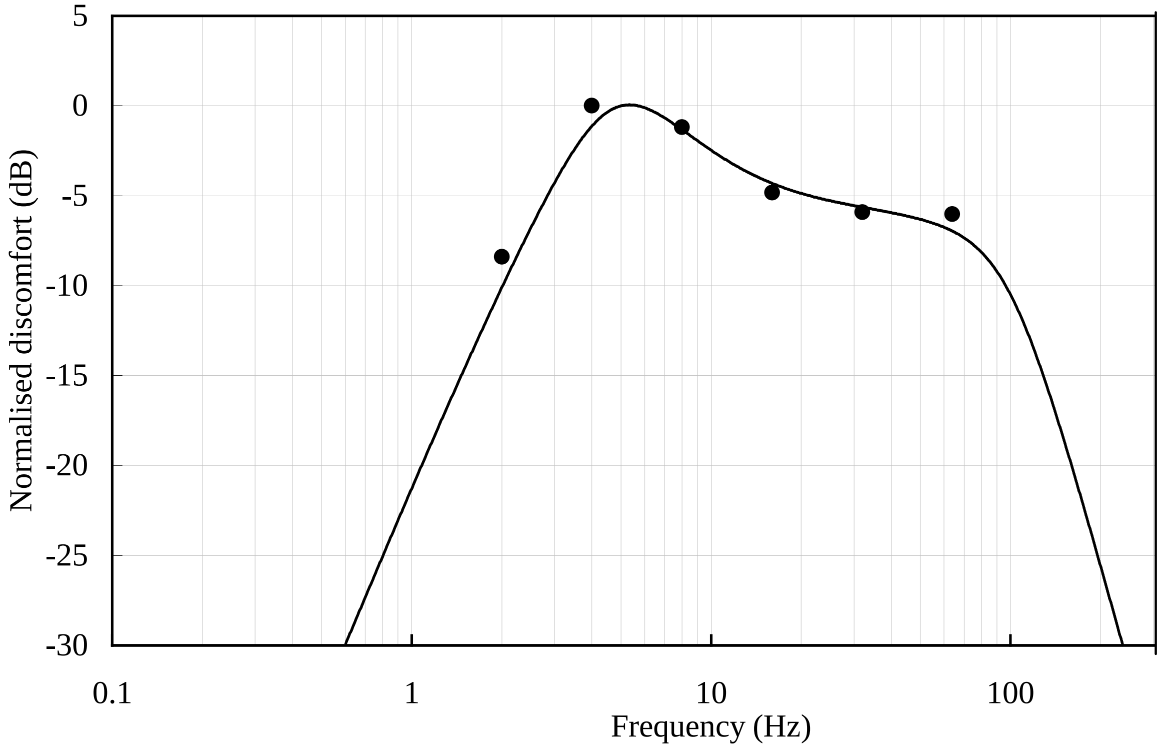

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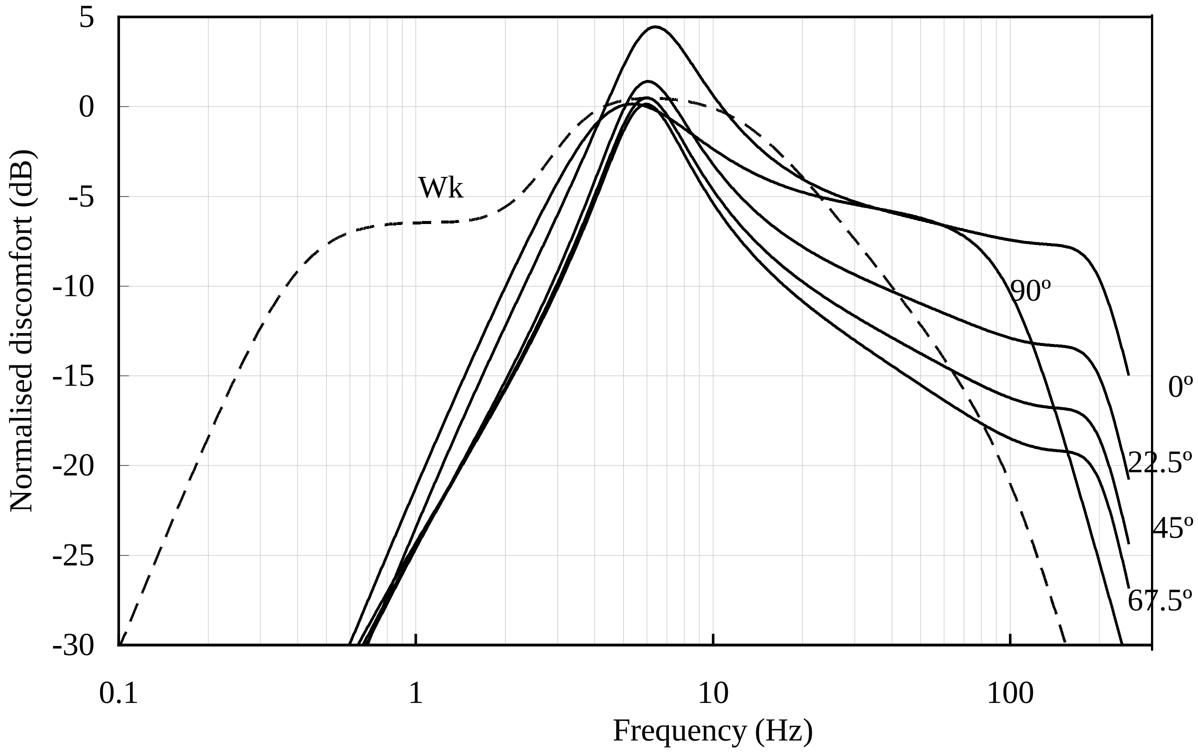
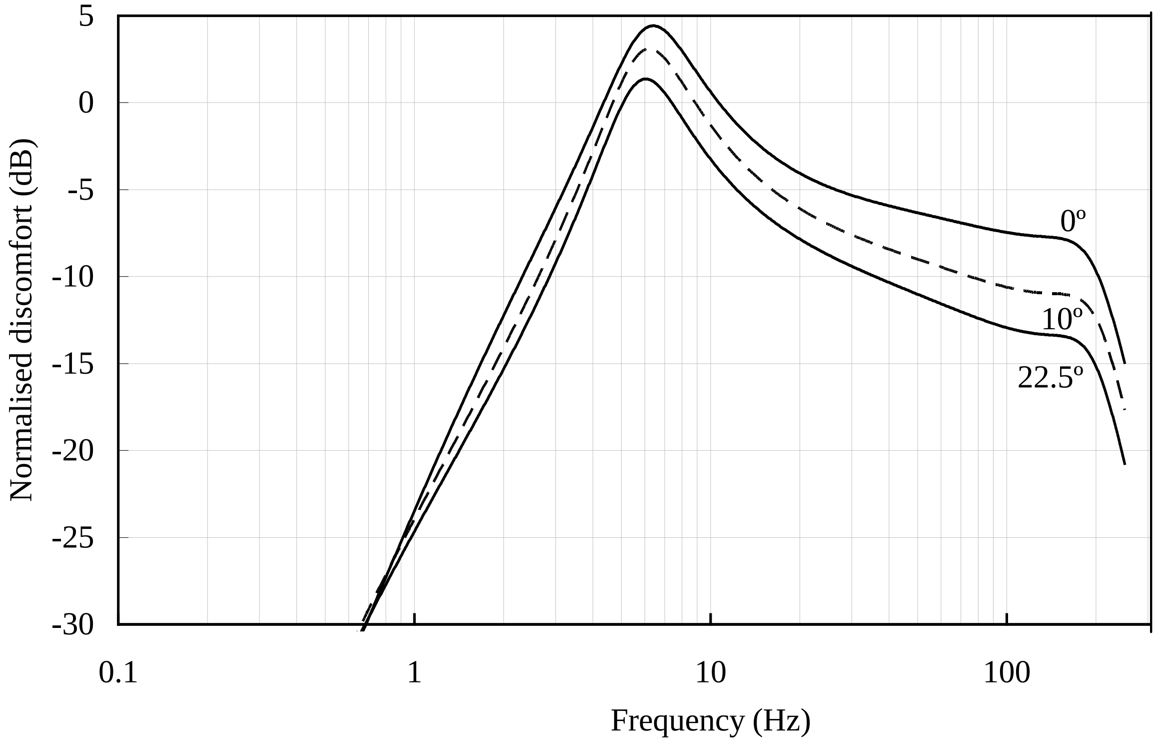


Figure 9. New weighting curves for different backrest angles and the existing ISO 2631-1 Wk curve.



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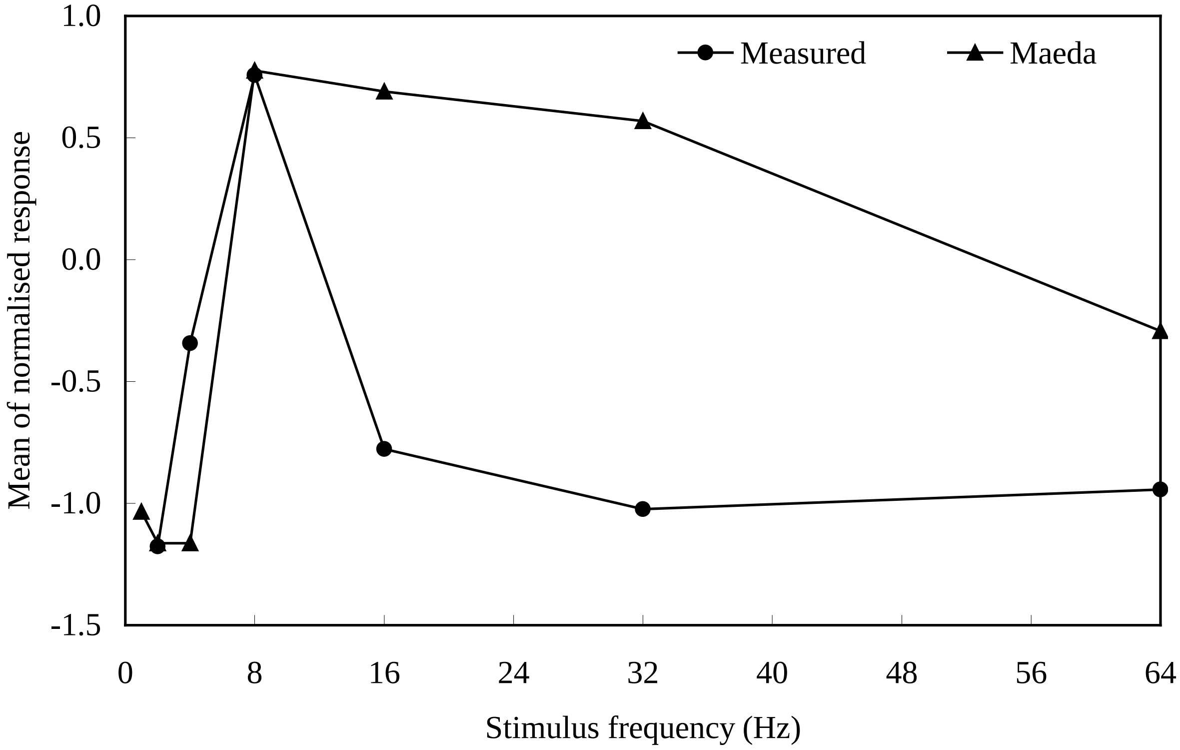

Figure 11. Comparison of subject responses from this study with published data for the 0° posture (recumbent). Data from Maeda *et al.*'s study have been scaled for clarity.

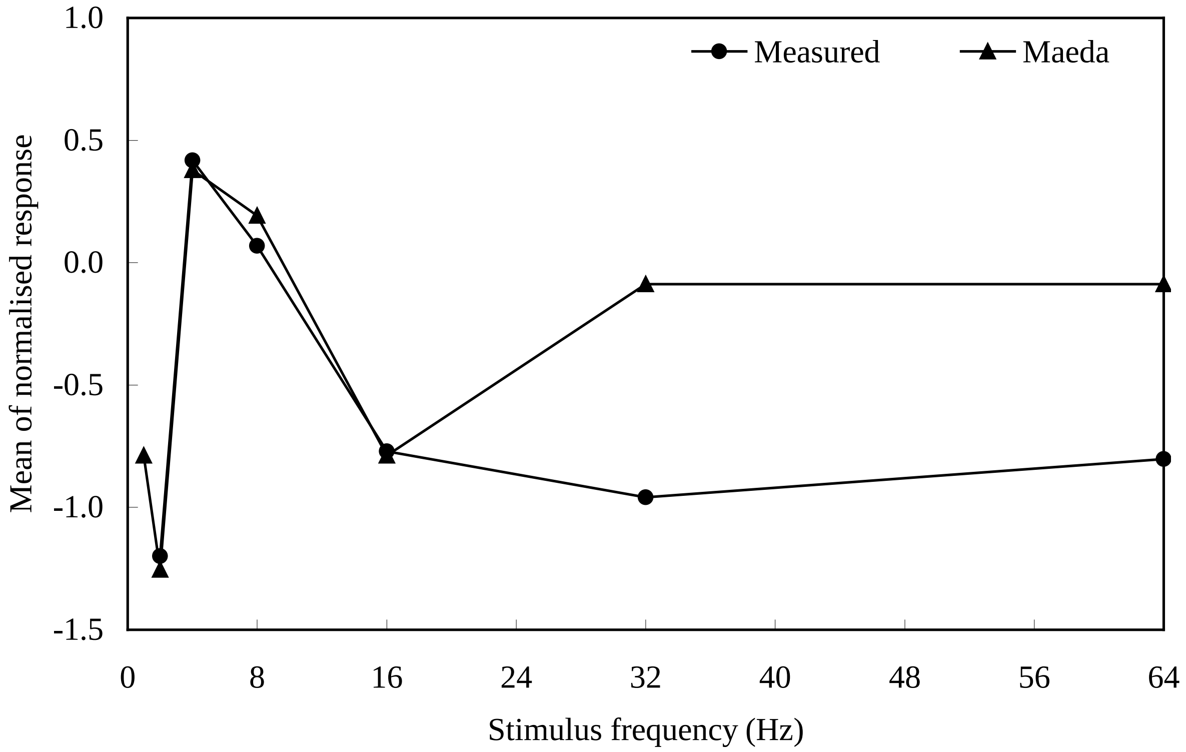

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Table 1. Results from a paired-Samples t-test for Phase II to examine the significance of an effect of backrest angle at a frequency of 8 Hz. Values below 0.05 are considered to be significant.

		Angle				
		0°	22.5°	45°	67.5°	90°
Angle	0°	-	0.000	0.000	0.000	0.000
	22.5°	-	-	0.001	0.000	0.127
	45°	-	-	-	0.003	0.502
	67.5°	-	-	-	-	0.004
	90°	-	-	-	-	-

Table 2. Coefficients for the new frequency weighting curves and for ISO 2631-1 Wk.

	Backrest angle					ISO 2631-1 Wk
	0°	22.5°	45°	67.5°	90°	
f1 (Hz)	6.2	5.81	5.81	5.81	4.73	0.4
Q1	1.53	1.65	1.7	1.75	0.91	$1/\sqrt{2}$
f2 (Hz)	200	200	200	200	100	100
Q2	1.53	1.65	1.7	1.75	0.91	$1/\sqrt{2}$
f3 (Hz)	14.47	12	12	12	14.47	12.5
f4 (Hz)	8.02	8	6.98	5.96	8.16	12.5
Q4	0.1	0.1	0.1	0.1	0.1	0.63
f5 (Hz)	3.13	9	9.01	9.01	3.13	2.375
Q5	0.24	0.24	0.24	0.24	0.24	0.91
f6 (Hz)	5.37	10.9	9.5	8.85	6.71	3.35
Q6	0.34	0.34	0.34	0.34	0.34	0.91
G	7.34	4.23	3.55	3.55	9.13	1

Table 3. Equivalence between the BS and ISO s-domain weighting curve definitions.

BS parameter (Eq. 7 to Eq. 9)	equivalent to	ISO parameter (Eq. 2 to Eq. 6)
w1	↔	w1
w2	↔	w2
w3	↔	w3
w4	↔	w4
w5	↔	w5
w6	↔	w6
Q1	↔	Q1
Q2	↔	Q4
Q3	↔	Q5
Q4	↔	Q6
K	↔	$G\frac{\omega_5^2}{\omega_6^2}$

Table 4. Interpolation coefficients.

	f1	f2	f3	f4	f5
a0	6.20E+00	2.00E+02	1.45E+01	9.67E+00	3.13E+00
a1	-2.41E-02	1.11E+00	-2.56E-01	-1.41E-01	6.08E-01
a2	1.46E-04	-9.05E-02	9.35E-03	4.79E-03	-2.22E-02
a3	9.44E-06	2.19E-03	-1.45E-04	-9.44E-05	3.43E-04
a4	-1.12E-07	-1.63E-05	8.03E-07	6.29E-07	-1.91E-06
	f6	G	Q1	Q2	Q4, Q5, Q6
a0	5.37E+00	7.34E+00	1.53E+00	1.53E+00	No interpolation required
a1	6.24E-01	-2.92E-01	1.86E-02	1.86E-02	
a2	-2.34E-02	1.02E-02	-1.01E-03	-1.01E-03	
a3	3.30E-04	-1.72E-04	2.21E-05	2.21E-05	
a4	-1.61E-06	1.08E-06	-1.56E-07	-1.56E-07	