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Discomfort caused by low frequency lateral oscillation, roll oscillation, and roll-compensated lateral oscillation

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Abstract

Roll compensation during cornering (aligning the feet-to-head axis of the body with the resultant force) reduces lateral acceleration, but how any improvement in comfort depends on the frequency of the acceleration has not previously been investigated. Seated subjects judged the discomfort caused by lateral oscillation, roll oscillation, and fully roll-compensated lateral oscillation at each of seven frequencies (0.25 to 1.0 Hz). Irrespective of whether it was caused by pure lateral acceleration or gravitational acceleration due to pure roll, acceleration in the plane of the seat caused similar discomfort at frequencies less than 0.4 Hz. From 0.4 to 1.0 Hz, with the same lateral acceleration in the plane of the seat, there was greater discomfort from roll oscillation than from lateral acceleration. With fully roll-compensated lateral oscillation, discomfort was less than with either the lateral component or the roll component of the motion from 0.2 to 0.5 Hz, but discomfort increased with increasing frequency and caused similar discomfort to pure roll oscillation at 1.0 Hz.

Keywords: *passenger comfort, tilting trains, low frequency motion, tilt-compensation*

Practitioner summary

Tilting can reduce passenger exposure to vehicle lateral acceleration when cornering, but how comfort depends on the frequency of motion was unknown. This study shows 'tilt-compensation' only improves comfort at frequencies less than 0.5 Hz. The findings affect tilting vehicles and the prediction of discomfort caused by low frequency motions.

1. Introduction

In land transport, people are exposed to low frequency motions that can cause discomfort (Griffin 1990, 2007). When a vehicle traverses a curve, the occupants are exposed to lateral centripetal accelerations determined by the vehicle speed and the curve radius. The lateral acceleration felt within the vehicle can be reduced, or eliminated, if the vehicle rolls so that it remains aligned with the gravito-inertial force.

In tilting trains, 'roll-compensation' is employed to allow high-speeds through curves without unacceptable horizontal forces. The combination of low frequency rotational and translational motion can increase motion sickness, as seen in tilting trains (e.g., Ueno *et al*. 1986, Bromberger 1996, Förstberg *et al.* 1998, Donohew and Griffin 2007, Persson 2010) and in laboratory simulations (e.g., Donohew and Griffin 2007, 2009, Joseph and Griffin 2007, 2008, Beard and Griffin 2012a). Increases in peak roll acceleration have been correlated with increases in the discomfort of high-speed rail passengers (e.g. Suzuki *et al.* 1999, 2001), but there has been little systematic study of the effect of the roll-compensation of lateral oscillation on physical discomfort.

The discomfort caused by translational or rotational oscillation is dependent on the frequency, the direction, and the magnitude of the motion, and the seating. When sitting on a rigid flat wooden seat with backrest, subjects are most sensitive to lateral sinusoidal acceleration at frequencies between 1.25 and 2.0 Hz (Corbridge and Griffin 1986). When sitting on a rigid seat with no backrest and a stationary footrest, subjects show decreasing sensitivity to roll acceleration as the frequency increases above 1 Hz (Parsons and Griffin 1982). The relative discomfort caused by lateral oscillation and roll oscillation at frequencies between 0.2 and 1.6 Hz has been investigated with a rigid seat, both with and without a rigid upright backrest and full-height harness (Wyllie and Griffin 2007). For frequencies less than 0.4 Hz, lateral acceleration in the plane of the seat appeared to offer a good prediction of discomfort, regardless of whether the acceleration was caused by lateral oscillation or roll (i.e., due to gravity). At higher frequencies, acceleration in the plane of the seat caused greater discomfort when it was produced by roll oscillation than when it was produced by lateral oscillation. The discomfort caused by lateral oscillatory acceleration increases as the frequency increases from 0.2 to 1.0 Hz, irrespective of whether the seat is rigid or has a backrest (Beard and Griffin 2012b). At all frequencies, there was least discomfort when sitting with a backrest and greatest discomfort when sitting without a backrest. However, with both lateral oscillation and roll oscillation in the range 0.4 to 1.6 Hz less discomfort has been found when sitting with no backrest than when sitting on a rigid seat with a backrest and a four-point harness (Wyllie and Griffin 2007). This suggests the four-point harness increased the discomfort caused by the motion.

Previous studies of lateral and roll oscillation have not investigated the physical discomfort caused by combined lateral and roll oscillation. The study reported here was designed to investigate the physical discomfort caused by lateral oscillation, roll oscillation, and fully roll-compensated lateral oscillation. From previous studies it was anticipated that with frequencies of oscillation less than about 0.4 Hz, pure lateral acceleration would cause similar discomfort to pure roll oscillation when there was the same acceleration in the plane of the seat. At these frequencies, discomfort was expected to be reduced when lateral acceleration was combined with the equivalent roll oscillation (i.e., it was 'roll-compensated'). With frequencies of oscillation greater than about 0.4 Hz, it was expected that with the same acceleration in the plane of the seat, lateral oscillation would cause less discomfort than roll oscillation, and roll-compensation would be less effective.

2. Method

2.1. Apparatus

Motions were produced by a six-axis motion simulator in the Human Factors Research Unit of the Institute of Sound and Vibration Research at the University of Southampton. The simulator was capable of ±0.5 m vertical motion, ±0.25 m horizontal motion, and about ±20° of rotational motion. Subjects sat on a rigid seat positioned so that the centre of the seat surface was at the centre of the motion platform (approximately 2.5 m by 3.0 m).

The seat consisted of rigid flat horizontal seat pan (51 by 46 cm) located 40 cm above the platform surface, and a rigid flat vertical backrest (62 by 40 cm). The surface of the seat pan was covered in hard rubber less than 5 mm in thickness to increase surface friction. A square block of 5-cm thick foam (40 by 40 cm, 35 kg/m^3, 150 N) was placed on the backrest to increase surface friction and provide lateral support for the upper-body.

Subjects were asked to maintain comfortable upright postures ensuring full contact with the backrest, with their hands on their laps and their feet flat on the platform of the simulator. Subjects wore a loose lap belt for safety.

During motion exposure, subjects wore headphones producing white noise at 65 dB(A) in order to mask the sounds of the simulator. The experimenter communicated with subjects through a microphone connected to the headphones by interrupting the white noise.

2.2. *Design*

The study used a repeated measures (within-subjects) design. The experiment consisted of two parts. In part 1 (equivalent comfort contours) subjects used the method of magnitude estimation to rate the discomfort produced by lateral, roll, and fully roll-compensated lateral oscillations (i.e., the test stimuli) relative to the discomfort produced by a lateral oscillation (i.e., the reference stimulus). Subjects were instructed to "rate the physical discomfort caused by each stimulus, ignoring any symptoms of motion sickness, such as dizziness or nausea". In part 2 (body map), for every stimulus, the subjects used a labelled diagram of the body to indicate where they felt discomfort choosing as many locations as they felt appropriate. The order of presentation of motion stimuli within each experimental part was fully randomised for each subject.

2.3. *Motion stimuli*

The motion stimuli consisted of seven frequencies at the preferred one-third octave centre frequencies from 0.25 to 1.0 Hz. Each frequency was presented at, nominally, eight magnitudes in logarithmic series from 0.08 to 0.40 ms^{-2} r.m.s. Due to simulator limitations a reduced range of magnitudes was used at some frequencies (see Table 1).

TABLE 1 ABOUT HERE

For roll oscillation, the magnitude was defined by the acceleration in the plane of the seat (i.e., due to gravity). For roll-compensated lateral oscillation, the lateral oscillation and the roll oscillation were combined in phase such that the resultant acceleration in the plane of the seat was zero. This procedure is illustrated in Figure 1 which shows the acceleration waveform in the plane of the seat for lateral, roll, and roll-compensated oscillation at 0.5 Hz. All motion stimuli were transient waveforms with a 3.5 cycle duration (as shown in Figure 1) generated from the product of a sine wave of the desired frequency and a half-sine of the same duration. The motions were generated within MATLAB (version R2010a research) using the *HVLab* toolbox (version 1.0).

FIGURE 1 ABOUT HERE

2.4. *Subjects*

Fifteen male and fifteen female volunteers aged between 19 and 30 years (median = 27.0, inter-quartile range, IQR = 4.8) participated in the experiment. The median and inter-quartile ranges of body weight, stature, sitting height, buttock-popliteal length, sitting knee height, shoulder breadth and hip breadth are displayed in Table 2.

TABLE 2 ABOUT HERE

2.5. *Data analysis*

The physical magnitudes of the motion stimuli, Φ, were related to the subjective magnitude estimates, Ψ, using Stevens' power law (Stevens 1975):

$$\psi = k\,\varphi^{\,n} \qquad (1)$$

The exponent, n, (i.e., the rate of growth of discomfort) and the constant, k, were determined by performing linear regression on the logarithmic transformation of Equation 1:

$$\log_{10} \psi = \log_{10} k + n \log_{10} \varphi \qquad (2)$$

Values for n and k were determined for each individual subject for each frequency and direction of oscillation. Equivalent comfort contours for subjective magnitudes, Ψ, of 50, 63, 80, 100, 125, 160, and 200 were calculated for each subject and direction using Equation 1.

The non-parametric Friedman test was used to investigate the overall effects of frequency and direction on the rates of growth of discomfort, n, and the equivalent comfort contours. The Wilcoxon matched-pairs signed ranks test was used to examine specific differences in rates of growth in discomfort and equivalent comfort contours between frequencies and directions. The Bonferroni correction was used where there were multiple comparisons. The median rates of growth of discomfort and median equivalent comfort contours were used to identify overall trends in the data.

3. Results

3.1. *Rates of growth of discomfort*

The rate of growth of discomfort, n, varied with the frequency of oscillation for all three types of oscillation (Figure 2; $p < 0.001$; Friedman), with a decreasing rate of growth of discomfort with increasing frequency of oscillation ($p < 0.001$; Spearman).

The rate of growth of discomfort depended on the type of oscillation at all frequencies except 0.315 and 0.5 Hz ($p < 0.04$; Friedman). The rate of growth of discomfort was greater for lateral oscillation than roll oscillation at 0.63, 0.8, and 1.0 Hz ($p < 0.01$; Wilcoxon), greater for lateral oscillation than roll-compensated lateral oscillation at 1.0 Hz ($p < 0.01$; Wilcoxon), and greater for roll oscillation than roll-compensated lateral oscillation at 0.25 Hz ($p < 0.01$; Wilcoxon). There was no effect of gender on the rate of growth of discomfort for any motion at any frequency ($p > 0.12$; Mann-Whitney U).

FIGURE 2 ABOUT HERE

3.2. Effect of frequency of oscillation on discomfort

For all three types of oscillation, the acceleration required to produce a subjective magnitude of 100 (i.e., the discomfort caused by 0.5-Hz lateral oscillation at 0.20 ms^{-2} r.m.s.) varied with the frequency of oscillation (Figure 3; $p < 0.001$; Friedman). For lateral oscillation and roll oscillation the acceleration required for a subjective magnitude of 100 was approximately constant between 0.25 and 0.4 Hz, but declined from 0.4 to 1.0 Hz at approximately 5 dB per octave for lateral oscillation and at approximately 12 dB per octave for roll oscillation. For fully roll-compensated lateral oscillation, the acceleration required for equivalent comfort reduced at approximately 3 dB per octave from 0.25 to 0.5 Hz, and at approximately 12 dB per octave from 0.5 to 1.0 Hz.

FIGURE 3 ABOUT HERE

3.3. Effect of direction of oscillation on discomfort

At all seven frequencies, the acceleration required to produce a subjective magnitude of 100 differed between the three types of oscillation ($p < 0.001$; Friedman). Equivalent comfort contours for lateral oscillation and roll oscillation did not differ at frequencies less than 0.4 Hz ($p > 0.07$; Wilcoxon) but were greater for lateral oscillation than roll oscillation between 0.4 and 1.0 Hz ($p < 0.02$; Wilcoxon). Equivalent comfort contours were greater for roll-compensated lateral oscillation than pure lateral oscillation at frequencies less than 0.5 Hz ($p < 0.02$; Wilcoxon) but were greater for lateral oscillation than roll-compensated lateral oscillation at frequencies greater than 0.5 Hz ($p < 0.02$; Wilcoxon). Equivalent comfort contours were greater for roll-compensated lateral oscillation than pure roll oscillation at all frequencies except 1.0 Hz ($p < 0.02$; Wilcoxon).

3.4. Effect of magnitude on the frequency-dependence of equivalent comfort contours

Equivalent comfort contours were calculated for subjective magnitudes between 50 and 200 (Figure 4). The magnitude of acceleration had a large effect on the shape of the equivalent comfort contours, as a result of the change in the rate of growth of discomfort with frequency as shown in Figure 2. However, as the frequency-dependence of the rate of growth of discomfort is similar for all three motions, the relative positions of the contours are similar at all magnitudes.

FIGURE 4 ABOUT HERE

3.5. Effect of gender on equivalent comfort contours

Median equivalent comfort contours representing a subjective magnitude of 100 for each type of oscillation were similar in males and females (Figure 5). After Bonferroni correction, the only statistically significant difference suggested that, relative to the reference motion, the females were more sensitive to lateral oscillation at 1 Hz than males ($p = 0.01$; Mann-Whitney U).

FIGURE 5 ABOUT HERE

3.6. Location of discomfort

After pooling judgements from the low magnitude and the high magnitude exposures, more subjects reported discomfort at the head, neck, shoulders, and upper-back with roll oscillation than with roll-compensated lateral oscillation at 0.315 and 0.4 Hz ($p < 0.01$; McNemar). There was a trend for greater incidence of discomfort at the ischial tuberosities with lateral oscillation and roll oscillation than with roll-compensated lateral oscillation, which reached significance at 0.315 and 0.8 Hz ($p < 0.02$; McNemar). At 0.315 and 0.4 Hz, more subjects reported ‘no discomfort’ with fully roll-compensated lateral oscillation than with roll oscillation ($p < 0.01$; McNemar). No other significant trends in the location of discomfort were identified.

FIGURE 6 ABOUT HERE

4. Discussion

4.1. Rate of growth of discomfort

The median rates of growth of discomfort for lateral oscillation, roll oscillation, and fully roll-compensated lateral oscillation decreased as the frequency increased from 0.25 to 1.0 Hz, indicating greater sensitivity to changes in acceleration magnitude at lower frequencies. The equivalent comfort contours therefore show greater dispersion at higher frequencies (Figure 4). Similar findings have been reported with lateral and roll oscillation between 0.2 and 1.6 Hz on a rigid seat with and without a backrest and four-point harness (Wyllie and Griffin 2007). The rate of growth of discomfort was greater for lateral oscillation than for roll oscillation at frequencies between 0.63 and 1.0 Hz, suggesting greater sensitivity to changes in the magnitude of roll oscillation than changes in the magnitude of lateral oscillation. The different rates of growth for lateral oscillation and roll oscillation mean that the relative importance of these axes, as shown in Figure 3, will vary with the magnitude of the motion. However, at frequencies greater than 0.63 Hz, sensitivity to roll oscillation is so much greater than sensitivity to lateral oscillation that roll will often be the dominant cause of discomfort if the two motions have similar magnitudes.

4.2. Effect of frequency of oscillation on discomfort

The equivalent comfort contours for lateral oscillation and roll oscillation are compared with those reported previously in Figures 7 and 8. The figures show increasing sensitivity to lateral acceleration from 0.2 to 2.0 Hz, but decreasing sensitivity at higher frequencies. In the present study, as the frequency of oscillation increased from 0.5 to 1.0 Hz, the acceleration required for equivalent discomfort decreased by approximately 5 dB per octave for lateral acceleration, by 12 dB per octave for the lateral acceleration caused by roll, and by 12 dB per octave for the lateral acceleration associated with fully roll-compensated lateral oscillation. For lateral oscillation and roll oscillation of a rigid seat with backrest and harness, equivalent comfort contours from 0.2 to 1.6 Hz declined at approximately 6 dB and 12 dB per octave, respectively (Wyllie and Griffin 2007), broadly consistent with the current findings. The somewhat steeper contours reported previously are consistent with a four-point harness reducing sensitivity at low frequencies, but increasing sensitivity at high frequencies.

Frequency weighting W_d, suggested for evaluating lateral seat acceleration in BS 6841 (1987) and ISO 2631-1 (1997), appears to offer a close approximation to the experimental contours for lateral acceleration in the plane of the seat (Figure 7). For lateral acceleration at a backrest, the standards suggest the same frequency weighting but with a multiplying factor of 0.5, indicating less sensitivity to acceleration at the back than at the seat. The combination of the two weightings assumes discomfort is slightly greater when seated with a backrest than when seated without a backrest. Studies of the discomfort caused by lateral acceleration when seated with a rigid flat backrest (with and without a four-point harness) and a cushioned backrest (with contours) have produced mixed conclusions (e.g., Wyllie and Griffin 2007, Beard and Griffin 2012b). Further investigation of how the motion of the body and discomfort is influenced by the characteristics of a backrest may assist the optimisation of seats.

FIGURES 7 AND 8 ABOUT HERE

As roll oscillation increases in frequency from 0.2 to 1.6 Hz, increased sensitivity to lateral acceleration in the plane of the seat caused by the roll (i.e., the acceleration due to gravity) has been reported when sitting on a rigid seat with backrest and a four-point harness (Wyllie and Griffin 2007). The equivalent comfort contours in the present study show a similar trend (Figure 4). When expressed in terms of rotational acceleration (rad.s^{-2} r.m.s.), equivalent comfort contours for a rigid seat with backrest show sensitivity increasing at approximately 9 dB per octave as the frequency increases from 0.25 to 0.5 Hz and then remaining approximately constant from 0.5 to 1.0 Hz (Figure 8). However, sensitivity to rotational acceleration of a rigid seat without a backrest increased at approximately 6 dB per octave from 0.2 to 1.6 Hz (Wyllie and Griffin 2007) and from 2 to 16 Hz (Parsons and Griffin 1978, Figure 8).

Frequency weighting W_e, is suggested for evaluating roll acceleration in BS 6841 (1987) and ISO 2631-1 (1997), but appears to give an inaccurate representation of the frequency-dependence of the discomfort caused by roll oscillation of rigid seats (both with and without backrests) over the frequency range 0.2 to 1.6 Hz (Figure 8). With fully roll-compensated lateral acceleration, the lateral acceleration at the seat is zero and predictions of discomfort are solely dependent on the rotational acceleration (assuming the centre-of-rotation is at the seat surface and the translational motions at the backrest and footrest arising from roll are negligible).The accuracy of frequency weighting W_e at low frequencies is therefore crucial for predicting the discomfort associated with fully roll-compensated lateral oscillations.

Using the root-sums-of-squares summation method and the frequency weightings as defined in current standards (BS 6841 1987, ISO 2631-1 1997), Wyllie and Griffin (2007) showed how seven component ride values arising from roll oscillation of a seat may contribute to vibration discomfort: lateral acceleration at the seat surface, the backrest, and the foot support (due to these not being at the centre of roll), translational acceleration at the seat, the back, and the feet (arising from the gravitational component due to roll, g.sinθ), and rotational acceleration at the seat surface. For roll oscillations of a rigid seat with backrest that caused similar discomfort at all frequencies, the root-sums-of-squares summation of these seven components declined with increasing frequency, indicating discomfort was underestimated at high frequencies or, conversely, overestimated at low frequencies (Wyllie and Griffin 2007). The current results are consistent with this conclusion (Figure 9).

With fully roll-compensated lateral oscillation, if the component ride values for the horizontal accelerations and the translational accelerations due to roll were measured separately they would have opposite polarities. The root-sums-of-squares of all such values will ignore polarity and cannot be expected to provide an appropriate prediction of ride comfort. However, if at each location the discomfort is caused by the vector sum of the horizontal acceleration and the acceleration due to gravity, it would be appropriate to measure the resultant acceleration (e.g., using a single translational accelerometer) at each location. The present findings suggest this would provide an appropriate indication of discomfort for frequencies of oscillation less than about 0.4 Hz, but that it would underestimate discomfort at frequencies greater than about 0.4 Hz.

FIGURE 9 ABOUT HERE

4.3. Effect of direction of oscillation on discomfort

The level of the equivalent comfort contours representing a subjective magnitude of 100 was similar for lateral and roll oscillation at 0.4 Hz and lower frequencies (Figure 3), suggesting lateral acceleration in the plane of the seat can predict discomfort in this frequency range irrespective of whether the acceleration is caused by lateral oscillation or roll oscillation. At frequencies greater than 0.4 Hz, lateral acceleration in the plane of the seat caused more discomfort when it was produced by roll oscillation than when it was produced by lateral oscillation. Differences in the discomfort caused by lateral and roll oscillation increased as the frequency increased from 0.4 to 1.0 Hz, consistent with (Wyllie and Griffin 2007).

At frequencies less than about 0.5 Hz, the acceleration of the equivalent comfort contour was greater for roll-compensated lateral oscillation than for uncompensated lateral oscillation, consistent with the 'compensation' reducing discomfort. In this frequency range, the discomfort associated with roll-compensated lateral acceleration was similar to that caused by uncompensated lateral acceleration with half the magnitude of lateral acceleration. However, at 0.63 Hz and higher frequencies, roll-compensated lateral oscillation caused more discomfort than uncompensated lateral oscillation.

Subjects exposed to roll-compensated lateral oscillation experienced zero lateral acceleration at the seat surface (i.e., at the centre-of-rotation) but there was lateral acceleration above and below this position (due to translation arising from the roll). The magnitude of the lateral acceleration increased with increasing distance from the centre-of-rotation and with increasing frequency of oscillation, so the extremities of the body experienced the greatest lateral acceleration during these motions. The feet experienced lateral acceleration of the vibrator table and the head experienced lateral acceleration as a result of the roll motion of the body centred on the seat surface. This translational acceleration at the feet, the head, and other parts of the body can be expected to have contributed to the increased discomfort with roll oscillation at the higher frequencies.

It is also necessary to consider the effect of rotational acceleration (rads^{-2}) on discomfort. To achieve full roll-compensation of lateral acceleration, α, the angle of roll, θ, must satisfy:

$$\alpha = g \times \sin \theta \text{ (where g = gravitational component)} \quad (3)$$

The relationship between α and θ remains constant regardless of frequency, but as the frequency doubles the magnitude of rotational acceleration required to achieve an angular displacement, θ, increases by a factor of 4. Whilst a roll oscillation of 0.5 Hz may yield the same rotational displacement (and therefore the same lateral acceleration in the plane of the seat) as a 1.0-Hz roll oscillation, the magnitude of rotational acceleration at 1.0 Hz will be four times as great. This rapid growth in rotational acceleration with increasing frequency may explain the increased discomfort caused by roll oscillation and fully-roll compensated lateral oscillation at frequencies greater than 0.5 Hz

4.4. Location of discomfort

Fully roll-compensated lateral oscillation caused less discomfort at the ischial tuberosities than both uncompensated lateral oscillation and pure roll oscillation, confirming the expectation of ‘balanced’ lateral forces at the seat surface (i.e., at the centre-of-rotation). Reports of ‘no discomfort’ were most frequent with fully roll-compensated oscillation at frequencies less than 0.5 Hz, consistent with little discomfort in this frequency range (see Figure 3). Roll oscillation at 1 Hz caused greatest discomfort at the head, neck, shoulders, and upper-back, consistent with previous work (Wyllie and Griffin 2007). Compared to sitting on a rigid seat with no backrest, discomfort caused by roll oscillation is greater when seated with a backrest and four-point harness (Wyllie and Griffin 2007). This may be explained by the increased transmission of lateral and roll vibration to the head and upper-body when sitting with a backrest (Paddan and Griffin 1988, 1994) or an inability to make compensatory movements when sitting against a backrest. No difference in discomfort between a ‘head still’ posture (where the upper-body maintained an Earth-vertical orientation) and a ‘move-with’ posture (where the upper-body moved in-line with the seat) when exposed to roll and pitch oscillation (Wyllie 2007), suggests voluntary postural control does not offer a complete explanation.

4.5. Implications for transport

The findings have implications for the measurement of low frequency vibration in transport. Passengers of land vehicles are exposed to horizontal and rotational forces when traversing curves and passing over undulations. The discomfort caused by low frequency lateral and roll oscillations is usually estimated from the resultant translational acceleration in “the lateral axis of the vehicle disregarding whether the measured acceleration arises from lateral acceleration or the component of gravity, i.e., g.sinθ caused by roll” (Wyllie and Griffin 2007, p. 2650). At frequencies greater than 0.5 Hz, fully roll-compensated lateral oscillation causes greater discomfort than pure lateral oscillation, so the resultant translational acceleration alone is clearly insufficient for predicting discomfort in vehicles. An understanding of the discomfort caused by roll oscillation is necessary to predict the discomfort caused by oscillation at these frequencies.

The findings also have implications for the design of vehicles where the suspension influences roll at frequencies in the range 0.5 to 1.0 Hz (e.g., in tilting trains; Ueno *et al.* 1986, Förstberg 2000). The discomfort associated with lateral centripetal acceleration while traversing curves at high speed can be reduced by roll-compensation, but only with motions at frequencies less than about 0.5 Hz. Roll-compensation of lateral acceleration at frequencies greater than 0.5 Hz is likely to worsen passenger comfort and so other techniques for minimising adverse effects of these motions will be required.

5. Conclusions

The discomfort caused by lateral oscillations with frequencies less than about 0.5 Hz can be reduced by appropriate roll oscillations. However, with frequencies greater than about 0.5 Hz, roll-compensation increases the discomfort caused by lateral oscillation.

At frequencies less than about 0.5 Hz, frequency weighting the lateral acceleration in the plane of the seat (using standardised weighting W_d) provides a useful prediction of the discomfort caused by lateral oscillation, roll oscillation, and combined lateral and roll oscillation. At frequencies between about 0.5 and 1.0 Hz, the additional contribution of any rotational acceleration is required to predict discomfort, but the root sums-of-squares method using frequency weighting W_e is not sufficient in its current form in this frequency range. Improved understanding of the factors influencing the discomfort caused by low frequency roll oscillation is required, particularly for predicting discomfort caused by fully roll-compensated lateral oscillation where lateral acceleration in the plane of the seat is zero.

The design of vehicles with tilt compensation requires caution if compensation of lateral acceleration occurs at frequencies greater than 0.5 Hz, as this is likely to worsen passenger comfort.

6. References

Beard, G.F., and Griffin, M.J., 2012a. Motion sickness caused by roll-compensated lateral acceleration: effects of centre-of-rotation and subject demographics. *In preparation.*

Beard, G. F., and Griffin, M.J., 2012b. The discomfort of seated persons exposed to lateral acceleration. *In preparation.*

British Standards Institution,1987. BS 6841: 1987. *Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock*.

Bromberger, L., 1996. Pourquoi vous avez mal au coeur. *La Vie du Rail*, 2556.

Corbridge, C., and Griffin, M.J., 1986. Vibration and comfort: vertical and lateral motion in the range 0.5 to 5.0 Hz. *Ergonomics*, 29 (2), 249-272.

Donohew, B., and Griffin, M.J., 2007. Low frequency motions and motion sickness on a tilting train. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 221, 125-133.

Donohew, B.E., and Griffin, M.J., 2009. Motion sickness with fully roll-compensated lateral oscillation: Effect of oscillation frequency. *Aviation, Space and Environmental Medicine*, 80, 94-101.

Förstberg, J., Andersson, E., and Ledin, T., 1998. Influence of different conditions for tilt compensation on symptoms of motion sickness in tilting trains. *Brain Research Bulletin*, 47 (5), 525-535.

Förstberg, J., 2000. *Ride comfort and motion sickness in tilting trains: Human responses to motion environments in train experiment and simulator experiments*. TRITA-FKT Report 2000:28. Stockholm: KTH Railway Technology.

Griffin, M.J., 1990. *Handbook of human vibration.* London: Academic Press.

Griffin, M.J., 2007. Discomfort from feeling vehicle vibration. *Vehicle System Dynamics*, 45 (7), 679-698.

International Organization for Standardization, 1997. ISO 2631-1: 1997. *Mechanical vibration and shock - evaluation of human exposure to whole-body vibration - Part 1: General requirements*.

Joseph, J.A., and Griffin, M.J., 2007. Motion sickness from combined lateral and roll oscillation: Effect of varying phase relationships. *Aviation, Space and Environmental Medicine*, 78, 944-950.

Joseph, J.A., and Griffin, M.J., 2008. Motion sickness: Effect of changes in magnitude of combined lateral and roll oscillation. *Aviation, Space and Environmental Medicine*, 79, 1010-1027.

Morioka, M., and Griffin, M.J., 2006. Magnitude-dependence of equivalent comfort contours for fore-and-aft, lateral and vertical whole-body vibration. *Journal of Sound and Vibration*, 298, 755-772.

Paddan, G.S., and Griffin, M.J., 1988. The transmission of translational seat vibration to the head – II. Horizontal seat vibration. *Journal of Biomechanics*, 21 (3), 199-206.

Paddan, G.S., and Griffin, M.J., 1994. Transmission of roll and pitch seat vibration to the head. *Ergonomics*, 37, 1513-1531.

Parsons, K.C., and Griffin, M.J., 1978. The effect of the position of the axis of rotation on the discomfort caused by whole-body roll and pitch vibrations of seated persons. *Journal of Sound and Vibration*, 58 (1), 127-141.

Parsons, K.C., and Griffin, M.J., 1982. Vibration and comfort. II. Rotational seat vibration. *Ergonomics*, 25 (7), 631-644.

Persson, R., 2010. Tilting trains: Benefits and motion sickness. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 224, 513-522.

Stevens, S. S., 1975. *Psychophysics: introduction to its perceptual, neural, and social prospects*. Oxford: Transaction Publishers.

Suzuki, H., 2001. Effect of compensated lateral acceleration on the riding comfort in tilt train. *In*: *Proceedings of the Japan Group Meeting on Human Response to Vibration*, 25-27 July 2001,Mito, Japan..

Suzuki, H., *et al*., 1999. Effects of Vibrational Factors on the Riding Comfort Evaluation of Tilting Train Passing Curve Transitions. *In*: *Proceedings of the World Congress of Railway Research*, 1999, Tokyo, Japan, p.42.

Ueno, M., *et al*., 1986. Studies on motion sickness caused by high curve speed railway vehicles. *Japanese Journal of Industrial Health*, 28 (4), 266-274.

Wyllie, I.H., 2007. Effect of posture on discomfort caused by low frequency roll and pitch oscillation. *In*: *Proceedings of the 42nd UK Conference on Human Responses to Vibration*, 10-12 September 2007, University of Southampton, Southampton, England..

Wyllie, I.H., and Griffin, M.J., 2007. Discomfort from sinusoidal oscillation in the roll and lateral axes at frequencies between 0.2 and 1.6 Hz. *Journal of the Acoustical Society of America*, 121 (5), 2644-2654.

Table 1. Ranges of acceleration magnitude in the plane of the seat (ms^{-2} r.m.s.) used at each frequency of lateral oscillation and roll oscillation. Conditions with fully roll-compensated lateral oscillation employed the same range of magnitudes as employed with roll oscillation.

Frequency	Direction	
	Lateral	Roll
0.250	0.08 - 0.20	0.08 - 0.20
0.315	0.08 - 0.315	0.08 - 0.315
0.400	0.08 - 0.40	0.08 - 0.40
0.500	0.08 - 0.40	0.08 - 0.40
0.630	0.08 - 0.40	0.08 - 0.40
0.800	0.08 - 0.40	0.08 - 0.40
1.000	0.08 - 0.40	0.08 - 0.315

Table 2. Subject demographics.

	Age (years)	Body weight (kg)	Stature (m)	Sitting height (m)	Buttock-popliteal (m)	Sitting knee height (m)	Shoulder breadth (m)	Hip breadth (m)
Minimum	19.00	47.50	1.50	0.73	0.32	0.45	0.34	0.23
25^{th} percentile	24.00	57.30	1.65	0.81	0.42	0.50	0.36	0.27
Median	27.00	61.60	1.69	0.84	0.45	0.53	0.39	0.29
75^{th} percentile	28.80	73.90	1.73	0.87	0.46	0.55	0.42	0.31
Maximum	30.00	105.00	1.93	0.92	0.53	0.63	0.49	0.38

Figure captions

Figure 1. Example waveforms for 0.5 Hz showing the acceleration in the plane of the seat for lateral, roll, and fully roll-compensated lateral oscillation.

Figure 2. Median rates of growth of discomfort for lateral, roll, and fully roll-compensated lateral oscillation. Upper and lower error bars show 75th and 25th percentiles, respectively.

Figure 3. Median equivalent comfort contours for lateral, roll, and roll-compensated lateral (combined) oscillation, each producing discomfort equal to that arising from lateral oscillation at 0.5 Hz 0.20 ms^{-2} r.m.s.

Figure 4. The effect of acceleration magnitude on median equivalent comfort contours caused by lateral, roll, and roll-compensated lateral (combined) oscillation. Contours represent discomfort equal to subjective magnitudes of 50, 63, 80, 100, 125, 160, and 200.

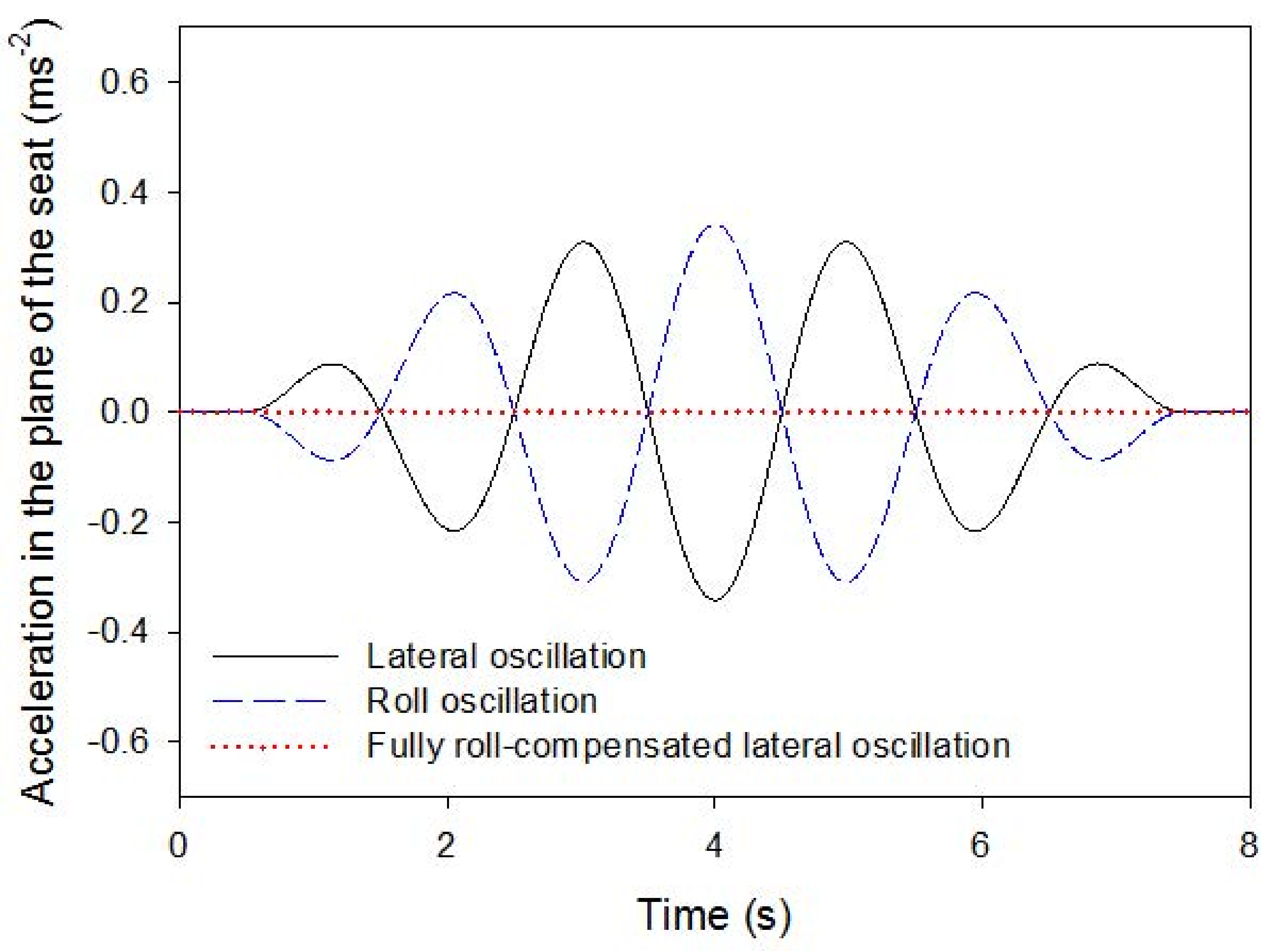
Figure 5. Median equivalent comfort contours for lateral, roll, and roll-compensated lateral (combined) oscillation for males (♂) and females (♀), each producing discomfort equal to that arising from lateral oscillation at 0.50 Hz, 0.20 ms^{-2} r.m.s.

Figure 6. Location on the body where subjects felt discomfort caused by lateral, roll, and fully roll-compensated lateral oscillation at frequencies from 0.25 to 1.0 Hz.

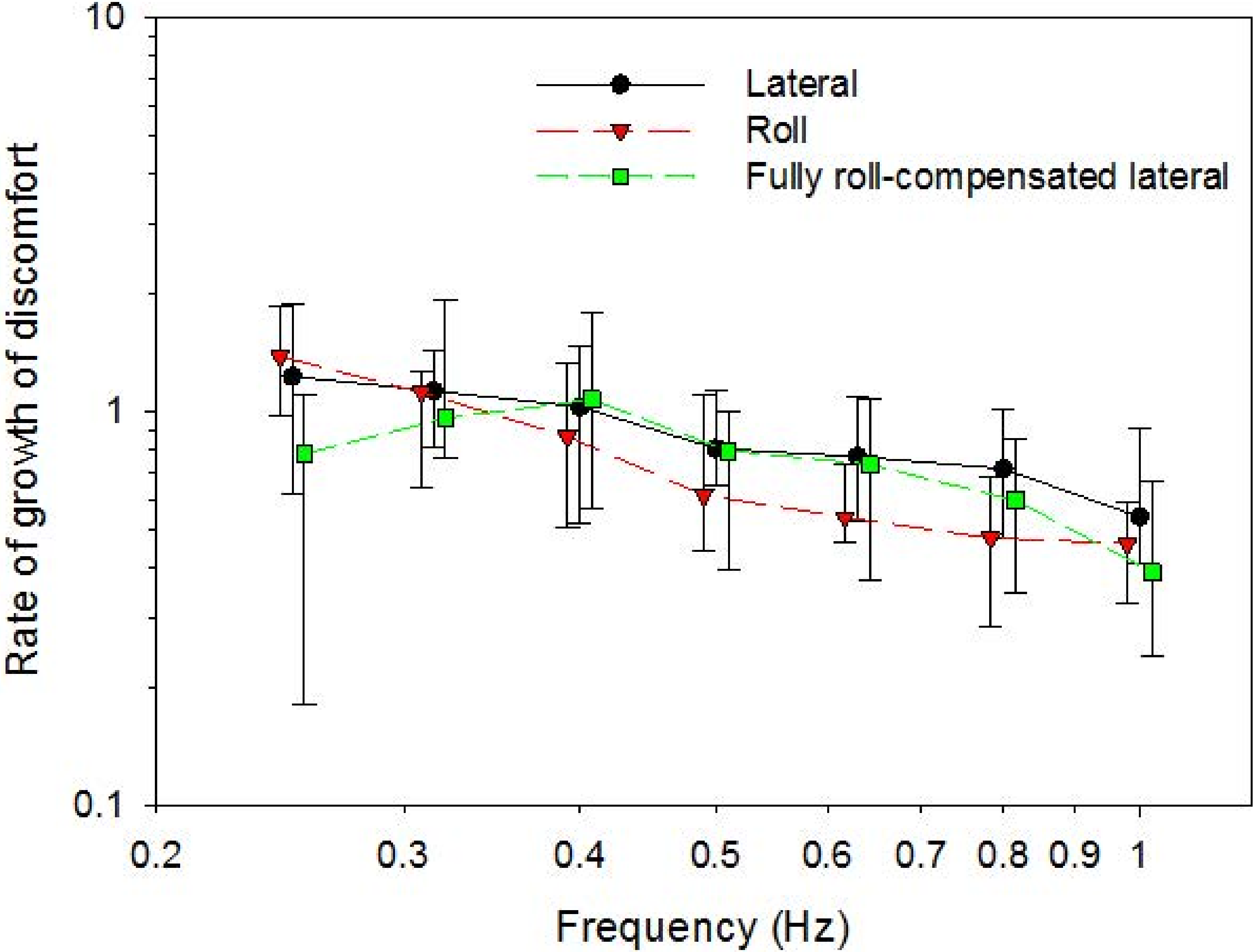
Figure 7. Effect of frequency of oscillation on equivalent comfort contours for lateral oscillation. Contours normalised to represent discomfort equal to that caused by lateral acceleration at 0.5 Hz 0.20 ms^{-2} r.m.s. on a rigid seat with backrest.

Figure 8. Effect of frequency of oscillation on equivalent comfort contours for roll oscillation expressed in terms of rotational acceleration (± $rads^{-2}$ r.m.s.). Contours have been normalised to represent discomfort equal to that caused by lateral acceleration at 0.5 Hz 0.20 ms^{-2} r.m.s. on a rigid seat with backrest.

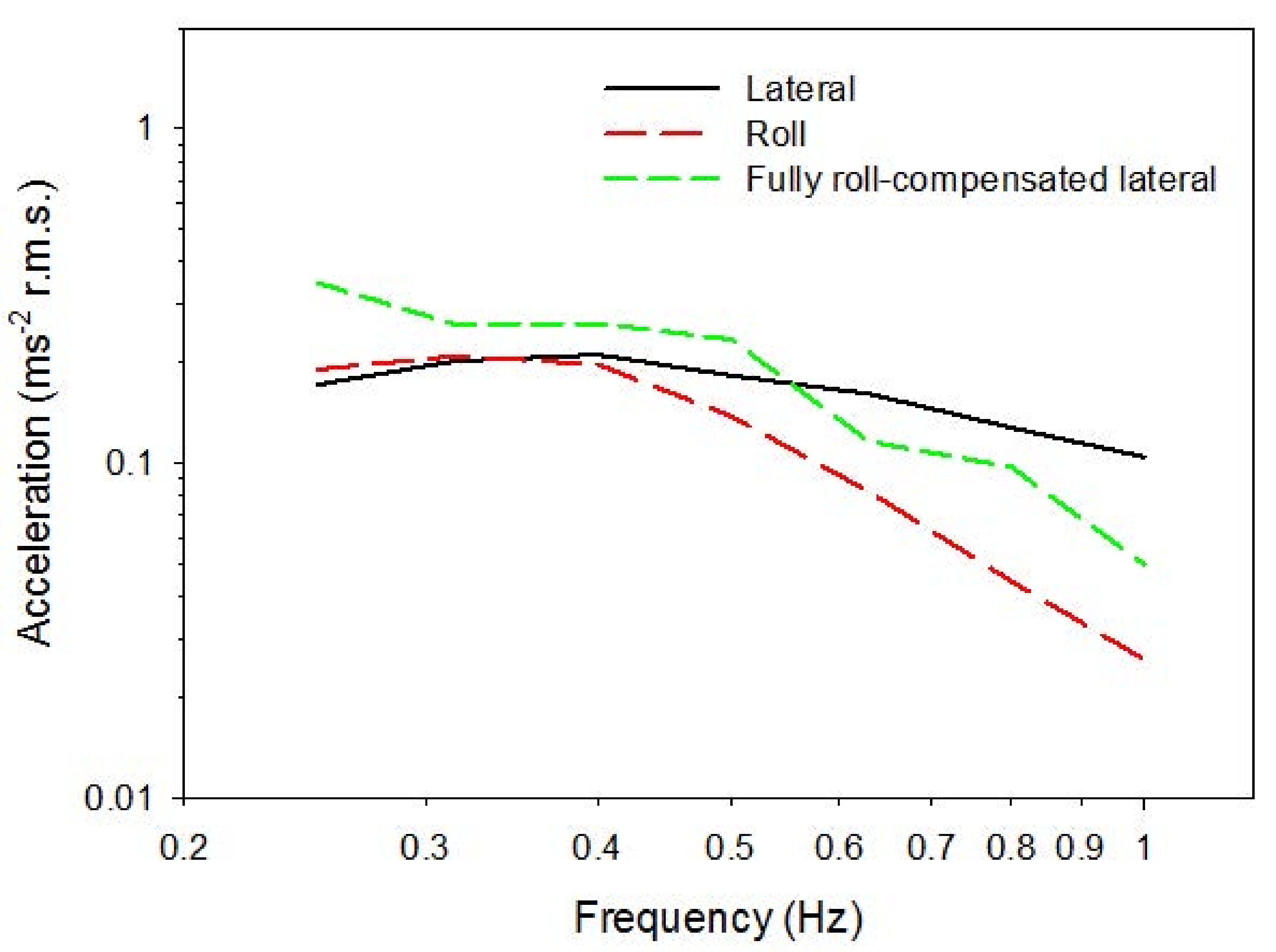
Figure 9. Frequency-weighted accelerations corresponding to median equivalent comfort contours for roll oscillation. Values calculated using asymptotic acceleration weightings given in BS 6841 (1987) that have been extrapolated horizontally at frequencies less than 0.5 Hz.



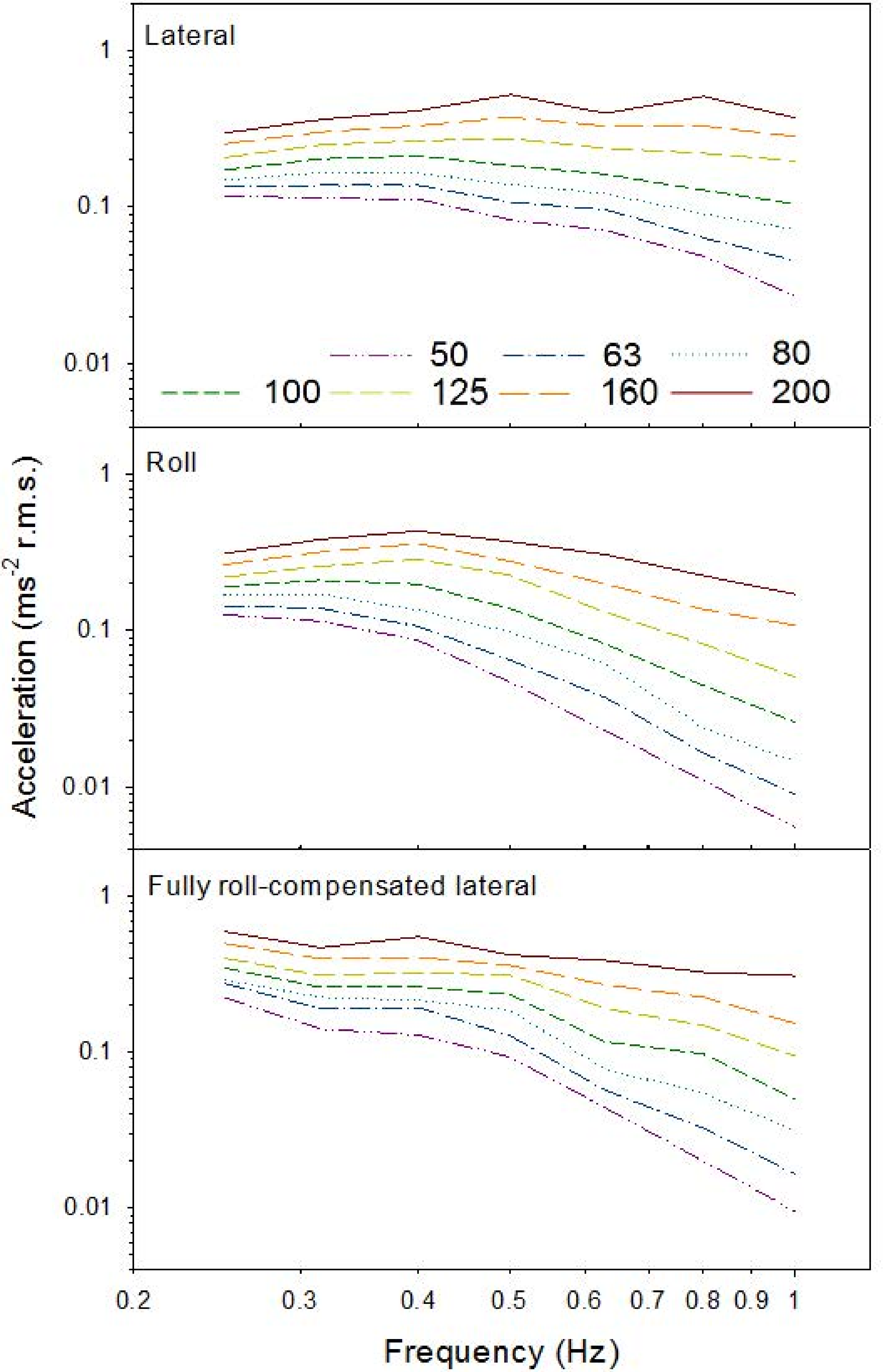
Acceleration in the plane of the seat (ms^{-2})
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
2
4
6
8
Time (s)
Lateral oscillation
Roll oscillation
Fully roll-compensated lateral oscillation

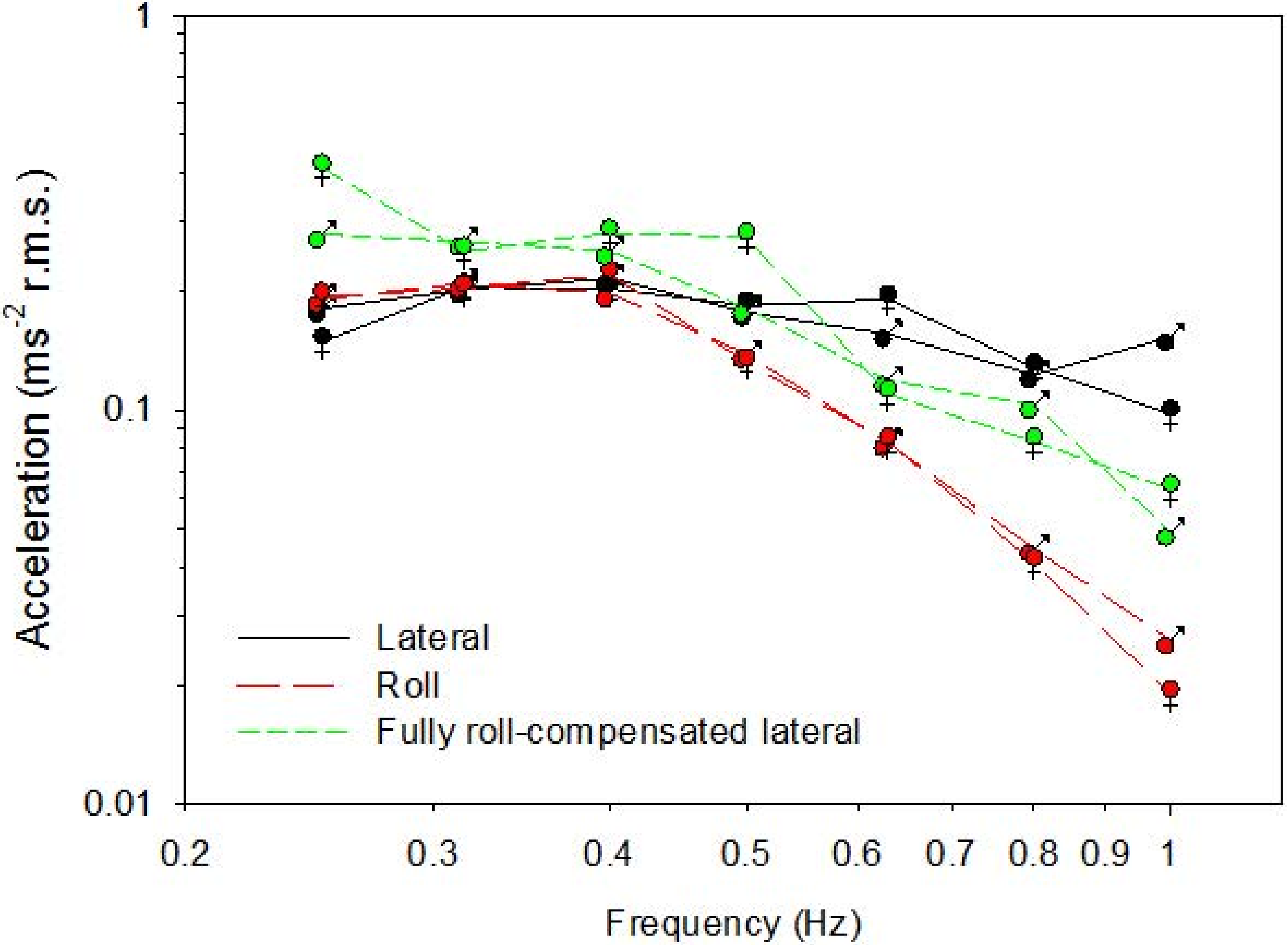


Lateral
Roll
Fully roll-compensated lateral
10
1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Rate of growth of discomfort
Frequency (Hz)

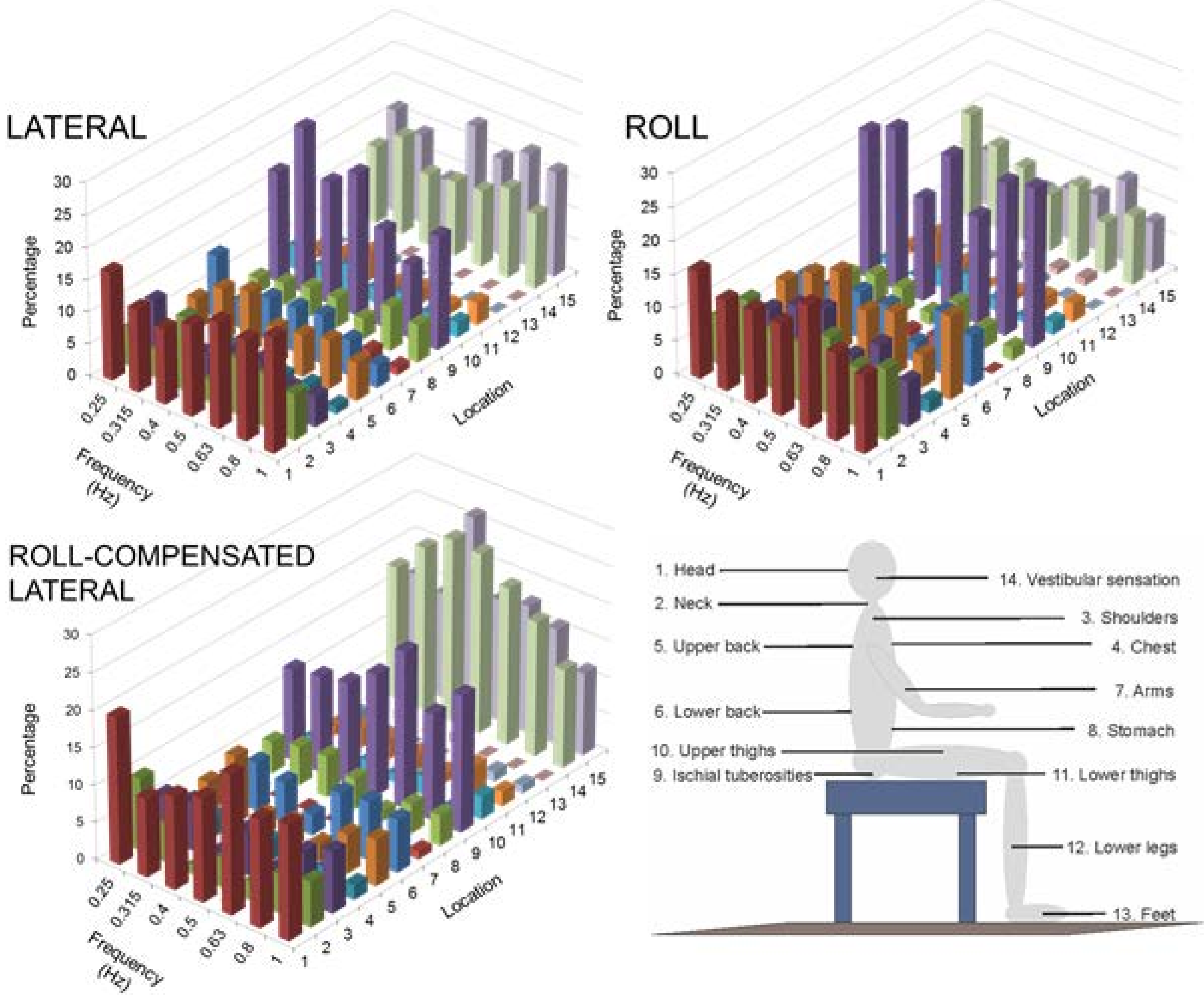


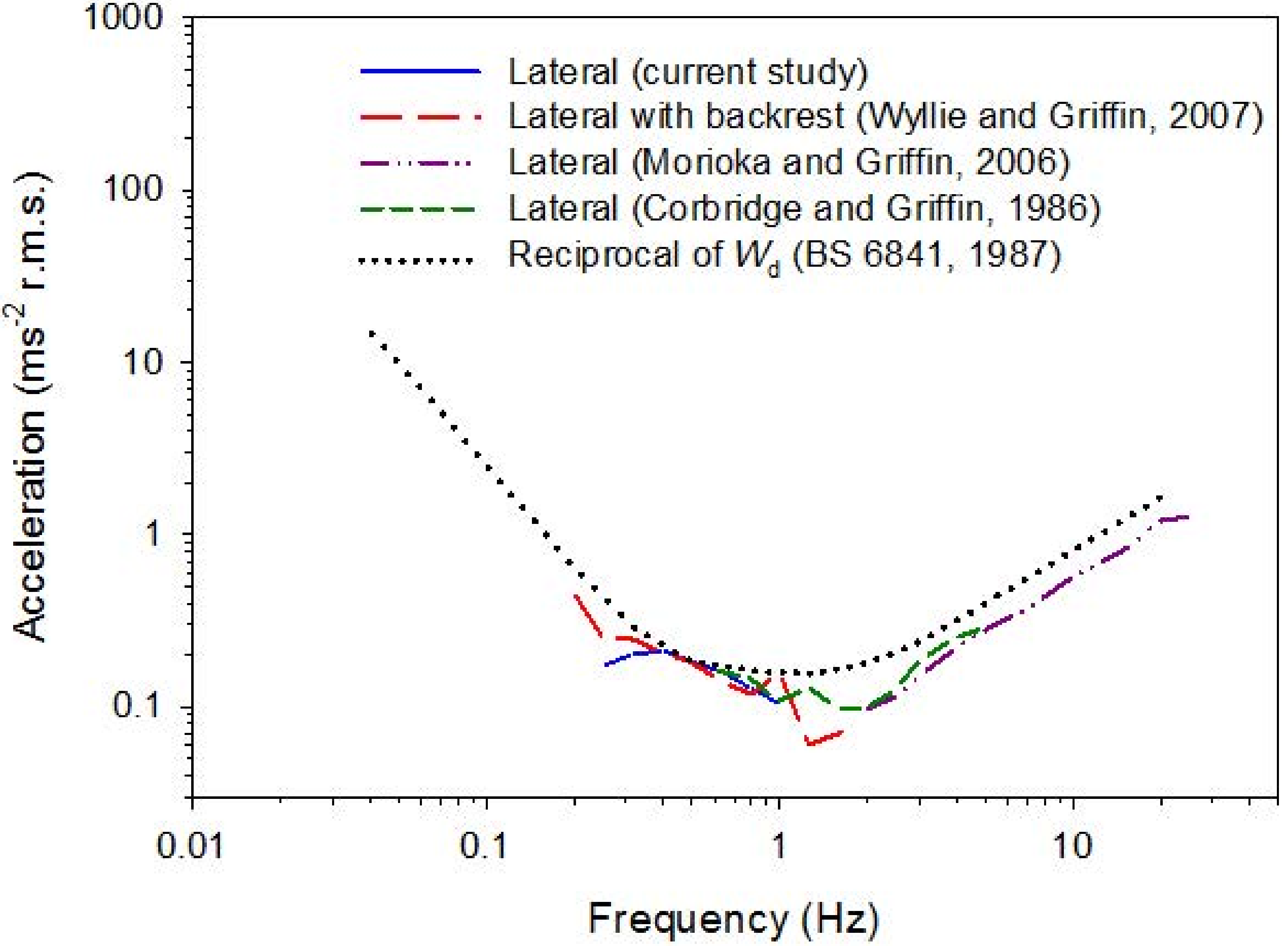
Lateral
Roll
Fully roll-compensated lateral
1
0.1
0.01
Acceleration (ms^{-2} r.m.s.)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Frequency (Hz)


Lateral
Roll
Fully roll-compensated lateral
50
63
80
100
125
160
200
1
0.1
0.01
Acceleration (ms^{-2} r.m.s.)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Frequency (Hz)

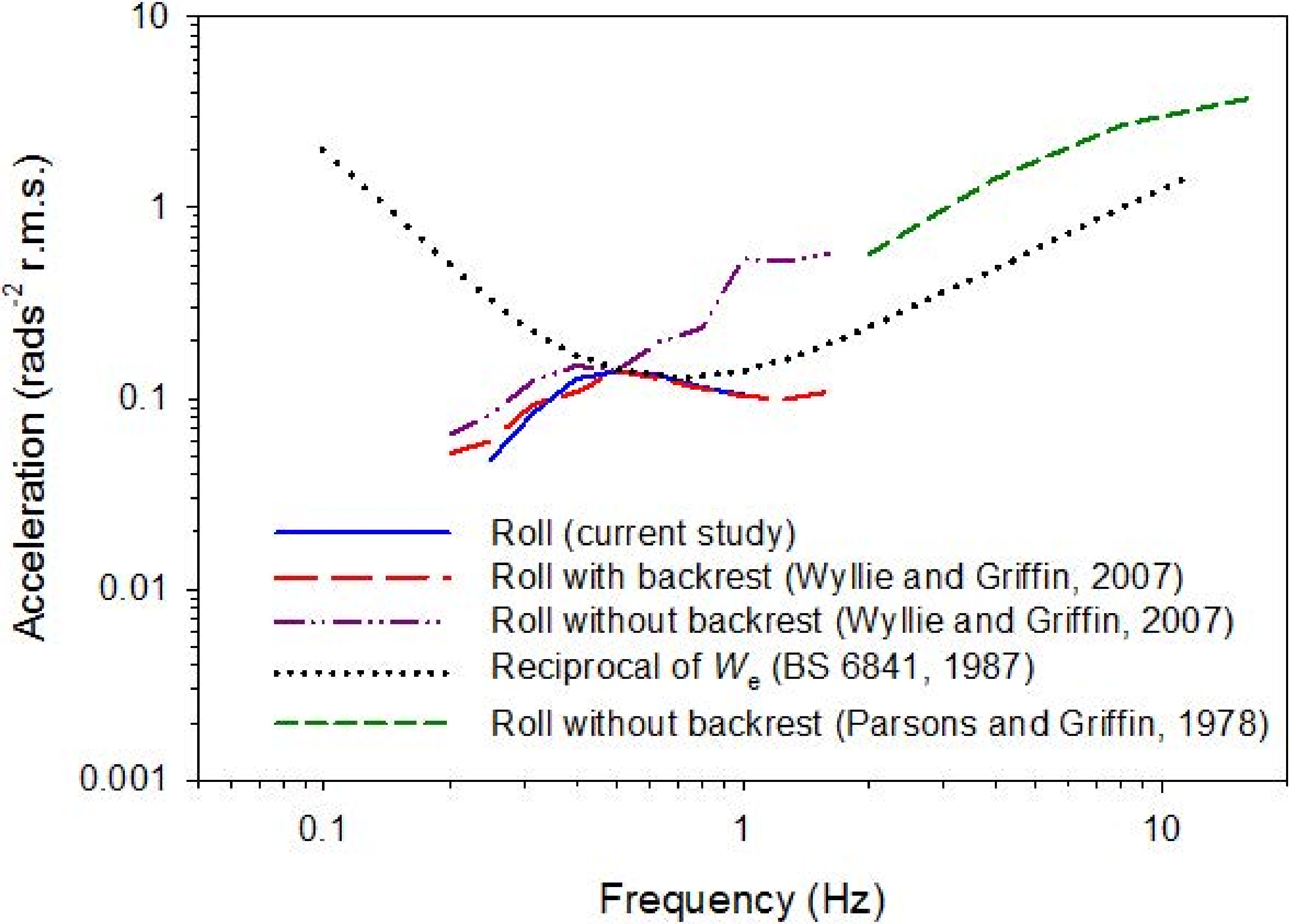


1
0.1
0.01
Acceleration (ms-2 r.m.s.)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Frequency (Hz)
Lateral
Roll
Fully roll-compensated lateral

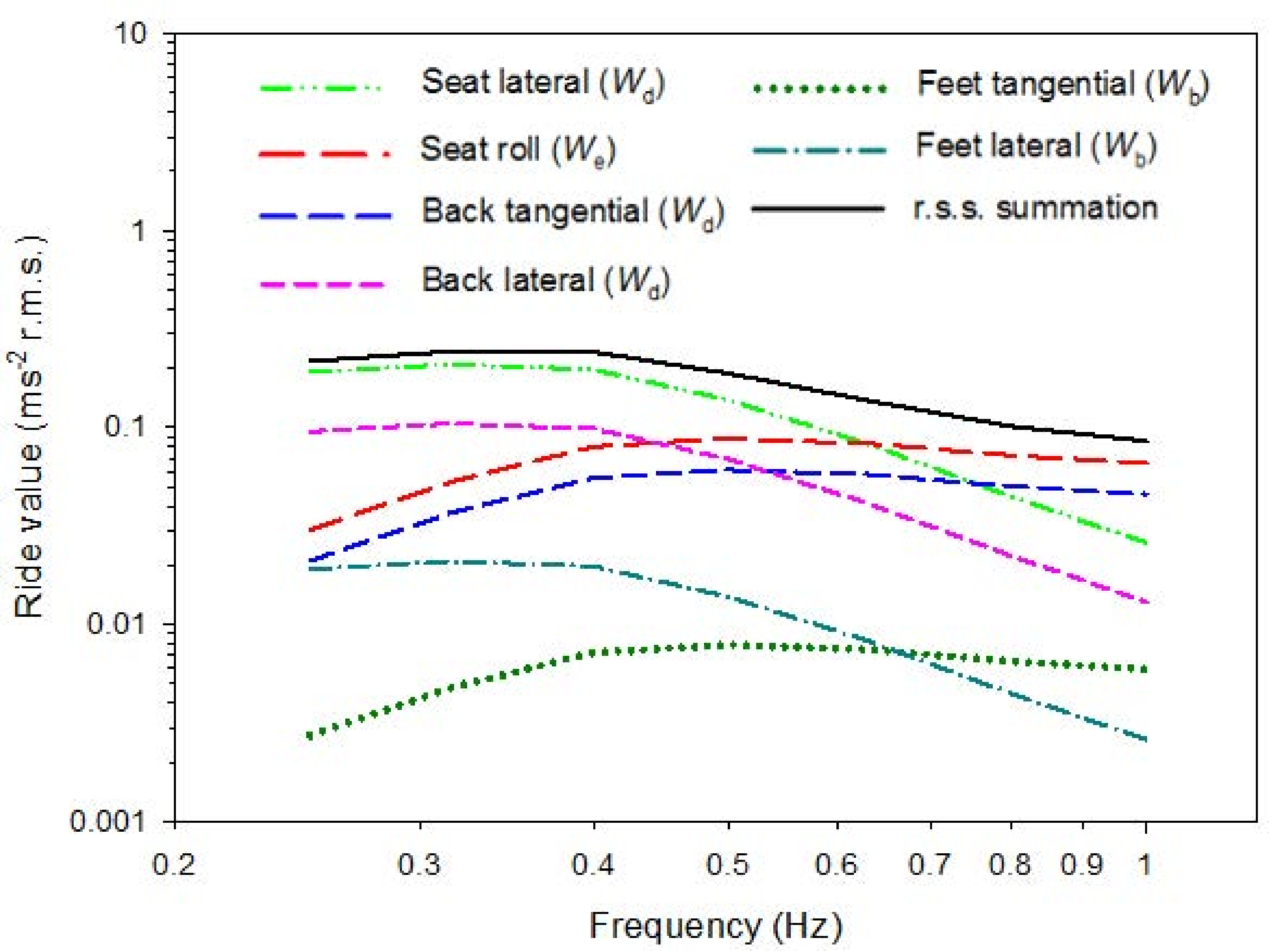

LATERAL
Percentage
0
5
10
15
20
25
30
Frequency (Hz)
0.25
0.315
0.4
0.5
0.63
0.8
1
Location
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
ROLL
Percentage
Frequency (Hz)
Location
ROLL-COMPENSATED LATERAL
Percentage
Frequency (Hz)
Location
1. Head
2. Neck
3. Shoulders
4. Chest
5. Upper back
6. Lower back
7. Arms
8. Stomach
9. Ischial tuberosities
10. Upper thighs
11. Lower thighs
12. Lower legs
13. Feet
14. Vestibular sensation



Lateral (current study)
Lateral with backrest (Wyllie and Griffin, 2007)
Lateral (Morioka and Griffin, 2006)
Lateral (Corbridge and Griffin, 1986)
Reciprocal of Wd (BS 6841, 1987)
Acceleration (ms-2 r.m.s.)
Frequency (Hz)
1000
100
10
1
0.1
0.01
0.1
1
10



10
1
0.1
0.01
0.001
Acceleration (rads^{-2} r.m.s.)
0.1
1
10
Frequency (Hz)
Roll (current study)
Roll with backrest (Wyllie and Griffin, 2007)
Roll without backrest (Wyllie and Griffin, 2007)
Reciprocal of W_e (BS 6841, 1987)
Roll without backrest (Parsons and Griffin, 1978)



Seat lateral (W_d)
Seat roll (W_e)
Back tangential (W_d)
Back lateral (W_d)
Feet tangential (W_b)
Feet lateral (W_b)
r.s.s. summation
Ride value (ms^{-2} r.m.s.)
10
1
0.1
0.01
0.001
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Frequency (Hz)