Whole-Body Vibration Perception Thresholds of Recumbent Subjects

—Part 2: Effect of Vibration Direction—

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Abstract: This paper presents the results of laboratory experiment concerned with perception thresholds for whole-body vibration on recumbent subjects. Thresholds of subjects exposed to x-, y- and z-axis sinusoidal vibration were determined for supine, prone, lying on the left side and lying on the right side subjects (from 1 to 80 Hz). It was clear that the threshold curves, as a function of frequency, had different characteristics for vertical vibrations than for horizontal vibrations in the recumbent postures. Significant differences were found between perception thresholds for vertical vibrations and horizontal vibrations on recumbent subjects.

Key words: Recumbent, Vibration perception, Whole-body vibration, Supine, Prone, Lying on the left side, Lying on the right side, Posture

Introduction

The whole-body vibration perception of recumbent subjects as a function of frequency and posture become important and are considered to be significant in designing sleeping cars of trains, ships, buildings of road traffic-induced vibration, stretcher of the ambulance cars, and stretcher in the hospital to made more comfortable. Although the whole-body perception of sitting and standing subjects has been obtained by many researchers¹⁾, the investigations for the whole-body vibration perception of recumbent subjects are few^{2–4)}. Their results were only obtained from supine posture. But in the real situations, people are lying individual posture, such as supine, prone, lying on the left side, and lying on the right side. It was difficult to design the buildings, stretcher, or the sleeping cars of trains under consideration of the magnitude relative to the whole-body vibration perception

threshold of recumbent subjects from these papers.

A special measurement equipment was necessary to obtain the whole-body vibration perception of recumbent subjects, as a measurement method to get the perception of recumbent subjects.

In a previous paper⁵⁾, the special measurement equipment and the measurement method were investigated for determining the whole-body vibration perception thresholds of supine subjects. The perception of supine subjects exposed to vertical (x-axis) and horizontal (z- and y-axis) sinusoidal vibration, were clear by the previous paper by using this equipment. The results of the previous paper were compared with Miwa's results²⁾. It was clear that the present experimental apparatus were useful to use the measurement of the whole-body vibration perception of recumbent subjects.

In general, people have three different axes vibration in different postures in the real situations. From the results of previous paper and other researches, the whole-body vibration perception thresholds of recumbent subjects in different

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Fig. 1. Example of supine posture.

Fig. 3. Example of lying on the left side posture.

Fig. 2. Example of prone posture.

Fig. 4. Example of lying on the right side posture.

postures of the different vibration directions are not well understood yet in the world.

The laboratory experiment described in this paper was conducted to determine the perception thresholds for the whole-body vibration of supine, prone, lying on the left side and lying on the right side subjects exposed to three different vibration directions (x-, y- and z-axis) according to the ISO 2631-1 standard⁶⁾.

Apparatus

The apparatus was similar to that described for the previous paper⁵⁾.

Table 1. Characteristics of subjects

	subject 1	subject 2	subject 3	subject 4
Height (m)	1.52	1.68	1.58	1.7
Weight (kg)	52	83	51.5	68
Age	58	46	47	32

Method

Each of four male subjects lay, in four different postures (such as supine, prone, lying on the left side and lying on the right side) with their feet, legs, back and head supported by the vibration table as shown in Figs. 1–4. Table 1 shows the subjects characteristics for this experiment, and the method of adjustment by subjects was used in this experiment.

Fig. 5. Mean vibration perception thresholds for vertical (x-axis) sinusoidal vibration of all postures.

Table 2. Analysis of variance summary table for vertical (x-axis) recumbent thresholds

Main effects	Sums of squares	Degree of freedom	Mean square	F ratio
Postures	0.0004043	3	0.0001348	2.77
Frequency	0.0040537	7	0.0005791	11.91**
Errors	0.0010212	21	0.00004863	
Total	0.0054792	31		

** $p < 0.01$. Sums of squares: the sum of the squared deviations of scores from their means. Degree of freedom: the number of squared deviations minus one. Mean square: the sum of squares divided by the corresponding degrees of freedom. F ratio: the ratio of the mean square associated with the method divided by the mean square associated with the error. p : the probability of an F ratio at least as large occurring by chance alone, if the methods are equally effective.

They adjusted the magnitude of the stimulus vibration, using 10-turn potentiometer which had no cue marks, until they could "just feel" the vibration. They repeatedly increased or decreased the vibration magnitude by using potentiometer until they could just feel the vibration, and the experimenter could read the vibration magnitude. This procedure was repeated the three times. The mean of the three readings was taken as the perception threshold. Eight frequencies of three axes sinusoidal vibration (x-, y- and z-axis) of four different posture (supine, prone, lying on the left side and lying on the right side) were investigated (1, 2, 4, 8, 16, 31.5, 63 and 80 Hz). The order of presentation of stimuli was random order. Subjects attended one experimental session of about 30 minutes duration. After each stimulus had been presented, subjects indicated on which part of their body they first detected vibration. Subjects wore their normal clothing with socks but no shoes.

Results

Vibration perception thresholds of different posture subjects exposed to x-axis (vertical recumbent) vibration

Figure 5 shows the results of the measured perception thresholds of sinusoidal vibrations of x-axis (vertical recumbent) in four postures as functions of frequency from 1 to 80 Hz. From Fig. 5, the sensitivity of 8 Hz is high. The vibration acceleration magnitude of 8 Hz is $0.01 \text{ ms}^{-2} \text{ r.m.s.}$ The thresholds from 1 to 4 Hz vibration have the same thresholds and the subjects' sensitivity to vibration acceleration decreased with increasing vibration frequency from 8 to 80 Hz. Although it can be seen that the whole-body perception thresholds are different depending on the postures, but the perception thresholds of different postures were not statistically significant from the results of analysis of variance as shown in Table 2. In general, the analysis of

variance, or ANOVA, as it is frequently called, is a statistical technique employed to analyze multigroup experimental data. By using F test, it allows us to make one overall comparison that tells whether there is a significant difference between the means of the groups.

Vibration perception thresholds of different posture subjects exposed to z-axis (horizontal recumbent) vibration

Figure 6 shows the results of the measured perception thresholds of sinusoidal vibrations of z-axis (horizontal recumbent) in four postures as functions of frequency from 1 to 80 Hz. From Fig. 6, the sensitivity from 1 to 8 Hz is high. The smallest vibration acceleration magnitude from 1 to 8 Hz is about $0.01 \text{ ms}^{-2} \text{ r.m.s.}$ The thresholds from 1 to 8 Hz vibration have the same thresholds and the subjects' sensitivity to vibration acceleration decreased with increasing vibration frequency from 8 to 80 Hz. Although it can be seen that the whole-body perception thresholds differ from

the different posture, the perception thresholds of different postures were not statistically significant from the results of analysis of variance as shown in Table 3.

Vibration perception thresholds of different posture subjects exposed to y-axis (horizontal recumbent) vibration

Figure 7 shows the results of the measured perception thresholds of sinusoidal vibrations of y-axis (horizontal recumbent) in four postures as functions of frequency from 1 to 80 Hz. From Fig. 7, the sensitivity from 1 to 4 Hz is high. The vibration acceleration magnitude is about $0.01 \text{ ms}^{-2} \text{ r.m.s.}$ The thresholds from 1 to 4 Hz vibration have the same thresholds and the subjects' sensitivity to vibration acceleration decreased with increasing vibration frequency from 4 to 80 Hz. The perception thresholds of different postures were also not statistically significant from the results of analysis of variance as shown in Table 4.

Fig. 6. Mean vibration perception thresholds for horizontal (z-axis) sinusoidal vibration of all postures.

Table 3. Analysis of variance summary table for horizontal (z-axis) recumbent thresholds

Main effects	Sums of squares	Degree of freedom	Mean square	F ratio
Postures	0.0006183	3	0.0002061	1.757
Frequency	0.052676	7	0.007525	64.157**
Errors	0.002463	21	0.00011829	
Total	0.0557573	31		

** $p < 0.01$. For abbreviations see Table 2.

First detected areas of the body

Tables 5, 6 and 7 show the areas of the body where vibration was first detected by supine, prone, lying on the left side and lying on the right side exposed to x-, y- and z-axis vibration. From these Tables, in the recumbent postures, vibrations are not felt uniformly on the whole surface of the body but especially sensitive points which vary throughout the body depending on differences in frequency between 1 to 80 Hz. At frequencies below 4 Hz, vibrations were felt throughout the whole body for all directions of vibration and all postures. During horizontal vibration the sensitive points shifted gradually from the upper back to the heel as the frequency increased. Therefore, during vertical vibration all subjects first detected 63 and 80 Hz at the head. From these results, in the supine posture, the first detected areas are different from vertical vibration and horizontal vibration. All subjects first detected on z- and y-axis vibration are almost similar with different postures. The first detected

areas of supine posture are different from other postures, such as prone, lying on the left side and lying on the right side. The same results obtained on the lying on the left side and lying on the right side posture of all vibration directions.

Discussion

Comparison whole-body perception thresholds in recumbent subjects between former results and present results

Figure 8 shows a comparison of the present results of the perception thresholds of the vertical recumbent with the results of previous results. The present results are between Szameitat & Dupuis's results⁴⁾ and Miwa & Yonekawa's results²⁾. The present results as functions of frequency from 1 to 80 Hz, have similar shapes with Miwa & Yonekawa, Parson & Griffin, and Szameitat & Dupuis results. Figure 9 shows a comparison of the present results of the perception

Fig. 7. Mean vibration perception thresholds for horizontal (y-axis) sinusoidal vibration of all postures.

Table 4. Analysis of variance summary table for horizontal (y-axis) recumbent thresholds

Main effects	Sums of squares	Degree of freedom	Mean square	F ratio
Postures	0.00034791	3	0.00011597	1.1819
Frequency	0.033045	7	0.0047207	48.1095**
Errors	0.0020606	21	0.000098124	
Total	0.03545351	31		

** $p < 0.01$. For abbreviations see Table 2.

Table 5. Areas of the body where vibration was first detected by supine, prone, lying on the left side, and lying on the right side exposed to vertical (x-axis) vibration

	Frequency (Hz)	subject 1	subject 2	subject 3	subject 4
x axis supine	1	all	all	all	ch
	2	b, t	t, all	hd	ch
	4	b	t, it	it	b
	8	l, it	t, l	it, b	h, hl
	16	t, b	l	it	h
	31.5	b	t, hd	t	hl, f
	63	hd, hl	hd	hd	hd
	80	hd, hl	hd, ht	hd	hd
x axis prone	1	all	all	all, ch	ch, it
	2	it	ch	ch	it
	4	it	it	ch	it
	8	it	it, ch	it	ch
	16	it, ch	it, ch	hd	f
	31.5	it	l, it	l	f
	63	f	ch, hl	f	ch, it
	80	it, f	f	f	f
x axis lying on the left side	1	all	all	all	all
	2	hd, all	all	all	ch
	4	hd	it	ch	ch
	8	l	l	it	f
	16	l	l	ch	f
	31.5	hl	t	it	f
	63	l, a	hl, sh	ch	ch
	80	sh, a, hl	l	ch, hl	a
x axis lying on the right side	1	all	all	all	all
	2	all	it, all	all	ch
	4	t	it, all	it	ch
	8	l	l	it	ch
	16	l	l	ch	ch
	31.5	t	t	ch	f
	63	f	l	ch	f
	80	ch, f	it	ch	ch

ch, Chest; hd, head; it, ischial tuberosities; f, feet; b, back; a, arms; e, elbows; l, legs; all, all over; t, trunk; sh, shoulder; hl, heels; h, hips.

thresholds of the horizontal recumbent with the results of previous results. Although the present results are also between Szameitat's results and Miwa & Yonekawa's results, Szameitat's results had higher values than the present results. The reason was that they used a different vibration exciter using hydraulic type, and which may generate different background vibration with the generator used in the present study. But, the present results as functions of frequency from 1 to 80 Hz have similar shapes with Miwa & Yonekawa and Szameitat's results. In this experiment, two subjects

Table 6. Areas of the body where vibration was first detected by supine, prone, lying on the left side, and lying on the right side exposed to horizontal (z-axis) vibration

	Frequency (Hz)	subject 1	subject 2	subject 3	subject 4
z axis supine	1	b, t	all	all	all
	2	t, hd	all	all	t, ch
	4	b, t	t, l	all	it
	8	t, hd	t, l	hd, l	it
	16	b, t	t, hd	all	hd
	31.5	t	t, hl	b	it
	63	l, hl	hl	hl	hl
	80	hl	hl, l	hl	hl
z axis prone	1	all	all	hd, all	all
	2	it	hl	hd, all	it
	4	l	l	hd, all	it
	8	it	l, hd	it	l
	16	it, l	ch	ch	l
	31.5	f	it	it	f
	63	l	l, it	it	f
	80	ch, a	a, it	it	f
z axis lying on the left side	1	all	all	all	all
	2	t	all	all	all
	4	t, f	l, hl	all	all
	8	t	h, l	ch	l
	16	ch	a, it	ch	ch
	31.5	it, ch	it	ch	l
	63	f	f, it	f	f
	80	f	ch, it	f	f
z axis lying on the right side	1	all	all	all	all
	2	t	all	all	all
	4	t	sh	all	all
	8	t	it	all	l
	16	it, t	a, it	ch	ch
	31.5	it	l	ch	ch
	63	f	ch, sh	f	f
	80	f	l, f	f	f

ch, Chest; hd, head; it, ischial tuberosities; f, feet; b, back; a, arms; e, elbows; l, legs; all, all over; t, trunk; sh, shoulder; hl, heels; h, hips.

are the same ones of the previous experiment. Although time elapsed was more than 15 years, the frequency characteristics and absolute threshold values of the present results are almost similar to that of the previous values. Wild *et al.*⁹⁾ show that normal values for VPTs (Vibrotactile Perception Thresholds) were obtained as a function of age for four non exposed populations whose VPT were found close to each other despite differences, although these results are not the whole-body vibration perception thresholds. From these results, it is considered that there are no age effect of

Table 7. Areas of the body where vibration was first detected by supine, prone, lying on the left side, and lying on the right side exposed to horizontal (y-axis) vibration

	Frequency (Hz)	subject 1	subject 2	subject 3	subject 4
y axis supine	1	all	all	all	hd
	2	all	b, h	all	sh
	4	t	h	all	hd
	8	t, l	l	all	hd
	16	hd, t	l, f	b	it
	31.5	t	b	b	t
	63	hl, l	sh, hl	hl	b
	80	hl	hl, hd	hl	b
y axis prone	1	all, it	all	all	ch
	2	all, it	it	all	ch
	4	it, ch	it	all	it
	8	l	l	it	it
	16	ch	a, it	it	it
	31.5	it	it	it	f
	63	it	it	it	it
	80	ch, it	l, ch	it	it
y axis lying on the left side	1	all	all	all	all
	2	all	all	all	ch
	4	all	l	t	ch
	8	t	all	ch	ch
	16	t, l	t, l	ch	t
	31.5	f	l	ch	ch
	63	f	it	f	f
	80	f	f	f	ch
y axis lying on the right side	1	all	all	all	hd
	2	all	all	all	sh
	4	t	it	all	ch
	8	t	t	ch	t
	16	l, ch	ch, it	ch	t
	31.5	f	it	it, ch	f
	63	f, ch	f, ch	f	f
	80	f	ch	f	f

ch, Chest; hd, head; it, ischial tuberosities; f, feet; b, back; a, arms; e, elbows; l, legs; all, all over; t, trunk; sh, shoulder; hl, heels; h, hips.

the whole-body perception threshold in recumbent subjects.

For the female subjects, the vibrotactile thresholds depend on the menstrual cycle as reported by Gescheider *et al.*⁽¹⁰⁾. Therefore, the present results may not be used to the female subjects.

From these considerations, it is clear that the results of present experiments as shown Figs. 8 and 9 are obtaining the reasonable results, although the subject numbers of the present experiment are small and the subject's age is over 30 years old.

Szameitat and Dupuis measured the transmissibility of vibrations in x, y and z directions between the vibration table and the various parts of the body surface in the supine posture. These authors reported maximum transmission of vertical vibration to the forehead at 63 Hz, to the chest at 9 Hz, to the abdomen at 5 Hz, to the femur at 5 Hz, and the ankle at 25 Hz. Therefore, it may be considered that the sensitivity of the head at 63 or 80 Hz depends on the transmissibility of the vertical vibration in recumbent subject. Also these authors reported maximum transmission of horizontal vibration to the forehead, foot, and abdomen at 1.7 Hz of y-axis vibration and at 2 to 4 Hz of z-axis vibration. Since the transmissibility of some specific part is not directly related to its sensitivity to vibration from Tables 5–7 and Figs. 5–7, the vibration threshold of the whole-body can not always be estimated from the transmissibility.

Comparison whole-body vibration perception threshold between the present values and sitting and standing values

Although ISO 2631-1 or ISO 2631-2 or BS 6841⁽⁷⁾ is not primarily concerned with the assessment of vibration in buildings it defines a simple means of predicting whether vibration will be perceptible. Using the same frequency weightings defined for assessing vibration discomfort (W_k or W_b for vertical vibration, W_d for horizontal vibration) it states that 50% of alert fit persons can just detect a frequency weighted peak magnitude of 0.015 ms⁻². The interquartile range of responses is quoted as 0.01–0.02 ms⁻², peak. For the assessment of continuous sinusoidal vibration at discrete frequencies these vibration thresholds may be converted to r.m.s. magnitudes as in Figs. 10 and 11. It is clear that the threshold curve for vertical continuous sinusoidal vibration below 4 Hz in the recumbent position is flat with frequency, and the sensitivity in the recumbent position is lower than that in the sitting and standing positions (Fig. 10). By comparing ISO 2631-1 or BS 6841 vertical perception thresholds with the present results, it may be seen that the W_k or W_b weighting appears to be not appropriate for the vertical vibration of recumbent persons. The great discrepancy arises with the use of the W_k or W_b weighting which tends to overestimate the sensitivity to low-frequency vertical vibration, when the present perception results were used instead of the W_k or W_b weighting to evaluate the whole-body vibration as a frequency weighting curve. From Fig. 11, the threshold shapes of perception of horizontal continuous sinusoidal vibration in a recumbent position are similar to those for sitting and standing. But, it is clear that the threshold curve for horizontal continuous sinusoidal

Fig. 8. Comparison vertical (x-axis) perception thresholds between the present results and other results.

Fig. 9. Comparison horizontal (z- and y-axis) perception thresholds between the present results and other results.

vibration below 4 Hz in the recumbent position is almost flat with frequency, and the sensitivity in the recumbent position is lower than that in the sitting and standing positions. The sensitivity above 4 Hz frequency is higher than that in the sitting and standing position as shown in Fig. 11. By comparing ISO 2631-1 or BS 6841 horizontal perception thresholds with the present results it may be seen that the Wd weighting appears to be not appropriate for the horizontal vibration of recumbent persons. The great discrepancy arises with the use of the Wd weighting which

tends to underestimate the sensitivity from 8 to 80 Hz frequency horizontal vibration and to overestimate the sensitivity to low-frequency horizontal vibration. Also, Figure 11 shows the comparison of z-axis horizontal vibration thresholds and y-axis horizontal vibration thresholds. It is clear that although the thresholds above 4 Hz frequency is almost similar, below 4 Hz frequency, the thresholds of y-axis vibration is higher sensitivity than the thresholds of z-axis vibration.

Fig. 10. Comparison vertical (x-axis) perception thresholds for sitting and standing between ISO 2631-1 and BS 6841 vertical perception threshold values and the present results.

Fig. 11. Comparison horizontal (z- and y-axis) perception thresholds for sitting and standing between ISO 2631-1 and BS 6841 horizontal perception threshold values and the present results.

Comparison whole-body perception threshold in recumbent subject between vertical (x-axis) direction and horizontal (z- and y-axis) direction

Figure 12 shows the all recumbent thresholds of the present experiment. The horizontal thresholds are lower than the vertical thresholds from 1 Hz to 4 Hz frequency. Above 8 Hz frequency, the horizontal thresholds are higher than the vertical thresholds. And the x-axis horizontal thresholds are higher than the y-axis horizontal thresholds from 1 Hz to 4 Hz frequency. The international standard ISO 2631-1

and the British standard BS 6841 state that 50% of alert fit persons can just detect a frequency weighted peak magnitude of 0.015 ms^{-2} . For the assessment of continuous sinusoidal vibration at discrete frequencies these vibration thresholds may be converted to r.m.s. magnitudes. The most sensitive magnitude of the discrete frequencies is $0.01 \text{ ms}^{-2} \text{ r.m.s.}$ value. Although the most sensitive threshold value of the recumbent subjects of the both vibration directions and the postures is about $0.01 \text{ ms}^{-2} \text{ r.m.s.}$ value from the present results as shown in Fig. 12, the thresholds values of the recumbent subjects

Fig. 12. Comparison whole-body perception thresholds in recumbent subjects between the present results and other results.

are different from the vibration directions, the frequencies, and the postures. Now the ISO/TC108/SC4/WG2 is considering the threshold values in buildings on the ISO/CD 2631-2 standard⁸). The results of the present experiments may be used to define a standard of determining whether or not vibration will be perceptible to the persons of buildings, sleeping cars of trains, ships, and stretcher of the ambulance cars.

Conclusions

The thresholds of perception of continuous sinusoidal vibration were determined in recumbent subjects as a function of frequency in the vertical and two horizontal directions. The conclusions from this experiment are: (1) the frequency characteristics of vertical vibration as a function of frequency are quite different from those of horizontal vibration. (2) The perception thresholds of different postures in all vibration directions were not statistically significant from the results of analysis of variance. (3) By comparing ISO 2631-1 or BS 6841 vertical perception thresholds with the present results it may be seen that the Wk or Wb weighting appears to be not appropriate for the vertical vibration of recumbent persons. (4) By comparing ISO 2631-1 or BS 6841 horizontal perception thresholds with the present results it may be seen that the Wd weighting appears to be not appropriate for the horizontal vibration of recumbent persons. (5) Although the thresholds above 4 Hz frequency is almost similar, below

4 Hz frequency, the thresholds of y-axis vibration is higher sensitivity than the thresholds of z-axis vibration.

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