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Evaluation of Floor Vibrations Induced by Walking Barefoot in Heavyweight Buildings

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Summary

Floor vibrations induced by humans walking barefoot were investigated in heavyweight buildings. Six floating floors with different floor structures and thick resilient isolators were built in laboratories with the same dimensions and boundary conditions. Subjective tests were performed to assess the vibration serviceability of the floor structures. In the first test, subjects were asked to walk across a floor and then rate the intensity of the vibrations, and the acceptability and serviceability of the floors. In the second test, subjects were seated on a chair in the middle of the floor and asked to rate the floor vibrations when a walker passed by the subjects. Floor vibrations induced by human walking were analysed using peak acceleration, root-mean-square (r.m.s.) acceleration, and the vibration dose value (VDV), with four frequency weighting functions (W_b, W_k, W_g, and W_m). Significant differences in the measured floor vibrations were found across the floor structures with greater floor vibration leading to greater perceived vibration intensity, lower acceptability, and lower serviceability. The VDV was correlated with perceptions of floor vibration when used with all four frequency weighting functions. The impact noise induced by walking did not influence subjective evaluations of floor vibration. A heavy/soft impact source (a standard impact source) provided a useful prediction of differences between the perception of the vibration on different floors.

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1. Introduction

Vibration disturbance in a building often comes mainly from external sources, such as industrial machinery or transportation, but internal sources (e.g., domestic equipment, doors banging, and footfalls) can also produce disturbance [1, 2]. Floor vibration induced by human walking is of special interest because it is the most common vibration source that occurs inside a building, and walking may occur at the natural frequency of the floor resulting in amplitude amplification [3, 4]. Although floor vibration induced by human walking can be small in amplitude it can result in considerable annoyance and discomfort for the occupants of a building.

Studies have investigated floor vibration due to human walking in relation to problems with floor serviceability. Lightweight floors have low mass and low structural damping compared to heavyweight floors, and these characteristics result in the dynamic response being greater, which is perceived as problematic to floor vibration [5]. Thin post-tensioned concrete slabs can result in floor serviceability problems due to the reduction of stiffness [4]. Long span floors with low natural frequency may also have floor vibration problems because humans are more sensitive to acceleration at lower frequencies than at higher frequencies [4]. Most previous studies of floor vibration have therefore focused on lightweight floors and long span floors [6, 7].

A widely used method of reducing floor impact sound in building construction is floating floors. A floating floor is effective in reducing lightweight impact noise caused by human footsteps when a person is wearing shoes, whereas they are limited in reducing heavy-weight impact noise produced by children jumping or adults barefoot walking [8, 9]. Recently, thick resilient isolators have been introduced for the control of heavy-weight impact noise, with increased sound insulation performance [10]. However, a thicker resilient isolator may lead to reduced dynamic stiffness; as the dynamic stiffness decreases, occupants are more likely to complain about floor vibration. Floating floors also show different characteristics from heavy floors in terms of resonance frequency and local deflection of floor surfaces [7]. A recent study investigated the walking discomfort of floating floors on a concrete slab with vari-

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Table I. Floor structures used in the study. d: Total thickness [mm], s': Dynamic stiffness [MN/m^3].

Floor	d	Cross-sectional detail	s'
1	320	Concrete slab (210 mm) + Resilient isolator (25 mm) + Floating floor unit (35 mm) + Mortar (50 mm)	19.7
2	320	Concrete slab (210 mm) + Resilient isolator (60 mm) + Mortar (50 mm)	22.8
3	290	Concrete slab (180 mm) + Isolating pad (10 mm) + Floating floor unit (50 mm) + Mortar (50 mm)	28.0
4	290	Concrete slab (180 mm) + Resilient isolator (20 mm) + Lightweight concrete (45 mm) + Mortar (45 mm)	14.8
5	330	Concrete slab (210 mm) + Floating floor unit (90 mm) + Precast concrete panel (30 mm)	13.3
6	320	Concrete slab (210 mm) + Isolating pad (10 mm) + Resilient isolator (50 mm) + Mortar (50 mm)	14.6

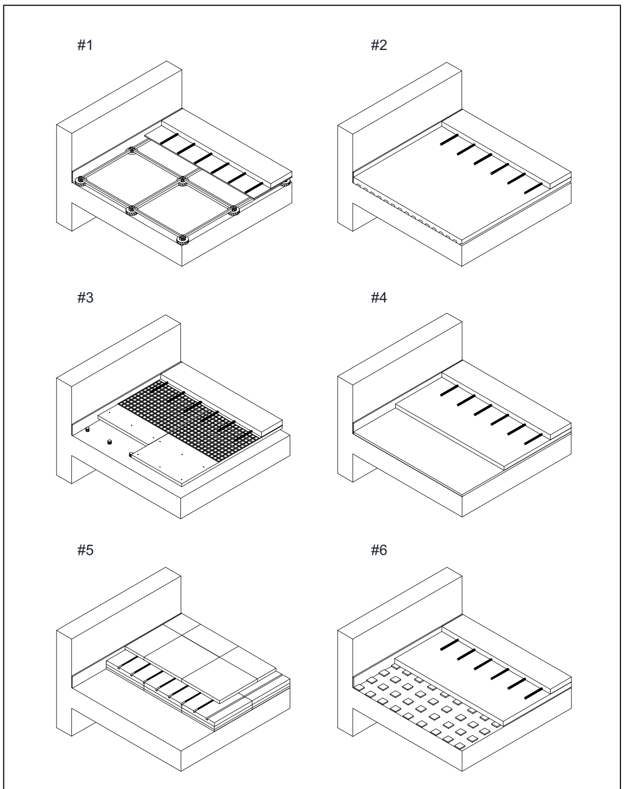

Figure 1. Section of the floor structures used in the study.

ations of panel size and joist spacing [11]. However, resilient isolators were not included in their floor structures. There is little understanding of the vibration performance and serviceability of floating floors with thick isolators.

Floor vibration has been assessed using walking tests in both existing buildings and in laboratories. With a walking man exciting the floor of an office, a measure of floor serviceability was proposed in terms of the root-mean-square (r.m.s.) of the floor vibration [12]. Walking tests have also been conducted on the floor of a large cantilevered office with, among various alternative objective parameters, the vibration dose value (VDV) found to be a reliable measure for evaluating floor vibration [13]. Although four different frequency weighting functions (W_b, W_k, W_g, and W_m) were applied, the relative performance of the alternative frequency weightings was not examined. In laboratory tests, subjects have walked across floor structures (wooden and hollow core concrete floors) and been asked to rate the vibration intensity and acceptability of the floors [14, 15]. The subjects also rated the floor serviceability when seated on a chair with the floors excited by a walker. Floor vibration was measured in terms of the W_m-weighted r.m.s. acceleration, but the relationship between the objective measure and the subjective rating was not investigated. Similarly, subjects have evaluated walking discomfort and floor acceptability after walking freely on mock-up floors with variations of panel size and joist spacing [11, 16]. The W_k-weighted VDV for each walk event (VDV$_\mathrm{i}$) was used to evaluate the floor vibration, and the subjective responses were highly correlated with the VDV$_\mathrm{i}$. Such tests are limited by the boundary conditions of real buildings and so consideration of appropriate objective methods for assessing floor vibrations (frequency weightings, and either the peak, the r.m.s., or the VDV) have also been limited.

The present study was designed to assess alternative methods of predicting human acceptability of floor vibrations induced by people walking in heavyweight buildings. Six floating floors with different thickness and different insulating layers were installed in a test building to reflect the boundary conditions of a living room. Two types of walking test were performed: (i) subjects walking across the floor by themselves, and (ii) subjects seated while another person walked back and forth across the floor. The subjects were asked to evaluate vibration intensity, floor acceptability, and floor serviceability.

2. Methods

2.1. Test building

Floor vibration was measured in a test building used for practical testing and certification. The building had a box frame-type structural system, with each room rectangular (4.5 m × 3.5 m). The ratio of the width to the length was determined to simulate the living rooms of residential buildings in Korea. A sliding door was in the frontal wall to reflect the boundary conditions of the living room. The volume of each room was 37.8 m^3, and all the rooms were unfurnished. The reverberation time at 500 Hz was 1.1 s and the A-weighted equivalent sound pressure level (L_Aeq) of the background noise was less than 23 dB.

2.2. Experimental floor structures

A total of six types of floor structure with different floor insulating layers were investigated. The thickness and the components of the floors are listed in Table I and the floor sections are shown in Figure 1. Total floor thickness varied from 290 mm to 330 mm according to the composition of the floor structure. Basically, the floors consisted of reinforced concrete slabs, an insulating layer, lightweight concrete, finishing mortar, or a precast concrete panel, and all floors had heating pipes for floor heating. Four floors (#1, #2, #5, and #6) had a 210-mm thick reinforced concrete slab, while two floors (#3 and #4) had a 180-mm thick concrete slab. Floors #5 and #6 were installed in the basement so concrete slabs for them were constructed on the ground. For floor #1, each floating floor unit (width: 0.6 m and length: 0.6 m) was supported by four plastic piles with a vibration isolating pad underneath. The 25 mm-thick Expanded Polystyrene (EPS) resilient isolators were placed between the floating floor unit and concrete slab. Floor #2 had an Ethylene Vinyl Acetate (EVA) resilient isolator. The bottom of the resilient isolator was uneven so that there were air cavities between the resilient isolator and concrete slab. For floor #3, the floating floor units (width: 0.6 m and length: 0.6 m) including a 30 mm-thick EPS resilient isolator were placed on the concrete slab. There were six isolating pads on the bottom of each panel. Floor #4 had 20 mm-thick flat resilient isolators (EVA) on the concrete slab. For floor #5, the floating floor unit consisted of 20 mm-thick Expanded Polyethylene (PE) foam, 30 mm-thick EPS resilient isolator, and 40 mm-thick plastic board. A precast concrete panel was then placed on the floating floor units. Floor #6 had a 50 mm-thick EPS resilient isolator. The 10 mm-thick PE isolating pads were evenly distributed under the EPS resilient isolator. The dynamic stiffness of the resilient isolators or the floating floor units measured by ISO 9052-1 [17] are listed in Table I. The dynamic stiffness showed a large variation from 13.3 to 28.0 MN/m^3. Therefore, it was expected that the different compositions of the floor structures would lead to differences in the dynamic properties of the floors.

2.3. Procedure

Prior to subjective evaluations, driving-point mobility was measured to investigate the dynamic characteristics of the experimental floors. The centre of each floor was excited by an impulse hammer, and the resulting vibrations of the floors were measured using an accelerometer located 20 cm from the excitation position. To improve the statistical reliability, the response data were averaged for more than five excitations. The driving-point mobility for each of the six experimental floors was derived from these measurements.

Walking tests were then performed in order to assess the vibration serviceability of the experimental floor structures. The experiments consisted of two walking tests: Test I with the subject walking, and Test II with the subject seated while another person walked, in a similar manner to previous studies [14, 15]. The subjects walked barefoot because it was assumed they were in a living room.

In Test I, as shown in Figure 2a, the test subjects walked across the floor structure themselves, a travel length of about 5.7 m. When they reached the corner of the room, they turned and walked back to the starting position, and then repeated each walk once. The speed of walking (step frequency) is a dominant factor affecting the vibration of floors [18]. The subjects were asked to complete each walk in around 4.5 s, corresponding to a step frequency of 1.7–2.0 Hz for normal walking [4]. Before the measurements, the subjects were trained to walk with a constant step frequency along the path using a metronome. The subjects repeated each test wearing ear plugs to examine the influence of sound on vibration perception.

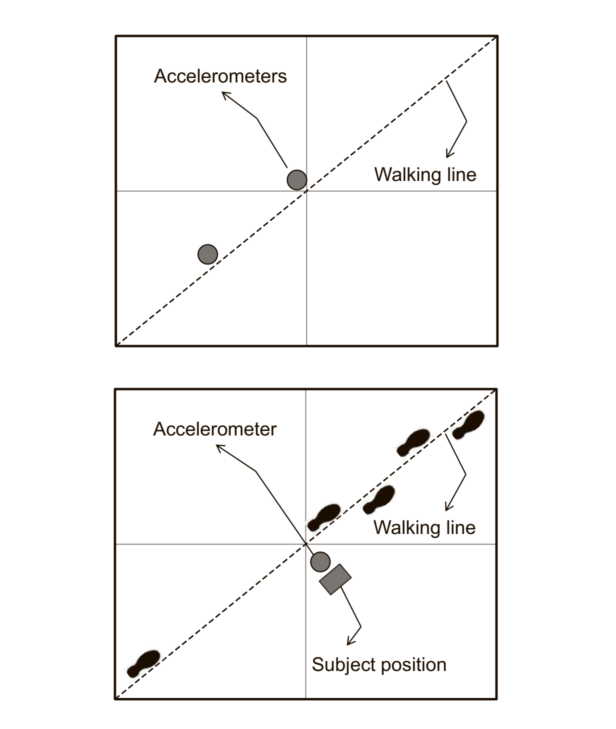

Figure 2. Walking line, observation position, and locations of accelerometers. (a): Test I, (b): Test II.

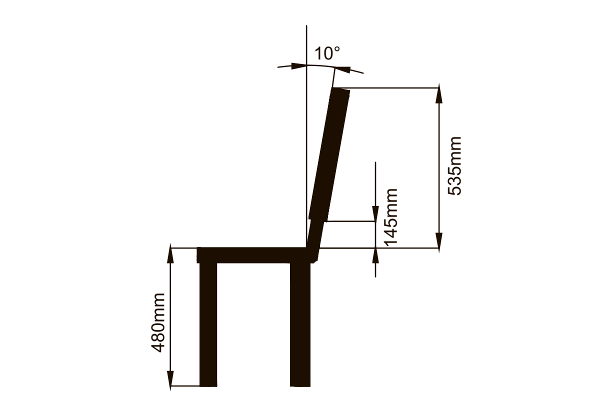

Figure 3. Diagrammatic representation of the rigid seat.

In Test II, the subjects were seated on a rigid chair placed at an observation position about 30 cm from the centre of the room (Figure 2b). As shown in Figure 3, the rigid flat surface of the chair was 480 mm above the floor, while the lower and upper edges of the rigid backrest were 145 mm and 535 mm above the seat surface. The backrest was inclined at an angle of 10° to the vertical.

Table II. Questionnaires used in the subjective tests.

Evaluation	Vibration intensity	Floor acceptability	Floor serviceability
Questionnaire	Please, rate the intensity of the vibrations.	Is the floor acceptable in a newly built apartment?	Please, rate the vibration serviceability (performance) of the floor on a scale from 0 to 10.
Rating scale	1: Imperceptible 2: Barely perceptible 3: Distinctly perceptible 4: Strongly perceptible 5: Extremely perceptible	1: Absolutely unacceptable 2: Unacceptable 3: Marginal 4: Acceptable 5: Absolutely acceptable	0: Very poor 10: Very good

The national statistics of the Korean Government [19] reported that the average weight and height of men aged between 20–70 years were 71.1 kg and 170.6 cm, respectively. Therefore, a male subject with a weight of 68.4 kg and a height of 170.1 cm was chosen as the walker in this study. He walked back and forth on the floor structure with a step frequency of about 2.0 Hz, with a consistent walking pattern for all subjects. The subjects rated their perception of the floor vibrations after the walker had passed the observation point two times.

It is reasonable to assume that optimum comfort within a building requires the absence of perceptible vibration, and that the perception of any building vibrations is unacceptable. However, floor vibration sometimes occurs at vibration levels above the threshold, so some researchers [11, 20, 21] have considered degrees of ‘acceptability’ of floor vibration when it is perceptible in buildings. An alternative criterion is floor ‘serviceability’ [22]. Some studies of floor vibration have therefore obtained subjective evaluations of both floor acceptability and floor serviceability [11, 14, 15, 21]. So, after each test, the subjects rated ‘floor acceptability’ and ‘floor serviceability’ as well as the ‘vibration intensity’. As described in Table II, the ‘vibration intensity’ was assessed using a 5-point scale. They were asked to rate the ‘acceptability’ of the floor structure as if it was installed in a newly built residential building. Finally, they were asked to rate the vibration performance of the floor structure (floor serviceability) on a scale from 0 to 10 (with 0 as ‘very poor’ and 10 as ‘very good’).

2.4. Subjects

A total of 20 subjects (twelve males and eight females) participated in the experiment. Their ages ranged from 24 to 36 years (mean: 29.8 and standard deviation: 3.4). The weights of the subjects varied from 43 to 96 kg (mean: 71.6 and standard deviation: 13.9), and their statures ranged from 159 to 188 cm (mean: 175.3 and standard deviation: 8.6). The number of subjects and the demographics were similar to those used in previous studies [1, 23, 24] of the perception of vibration in a laboratory setting. In addition, all of them had experienced living in apartment buildings with floating floors. The experiment lasted about 60 minutes with all subjects giving their voluntary consent prior to the start of the experiment.

2.5. Apparatus

An impact hammer (Dytran 5803A) and one accelerometer (KB12VD, MMF) were used in the driving-point mobility tests. Floor vibrations induced by walking were measured by accelerometers (KB12VD, MMF). In Test I, two accelerometers were connected to a spectrum analyser (B&K 2032) and a laptop computer to record and analyse the floor vibrations. As shown in Figure 2a, one accelerometer was placed near the corner of the room and another near the centre of the room. In Test II, only one accelerometer was located on the floor near the observation position.

2.6. Vibration analysis

Floor vibrations induced by human walking were analysed in terms of the peak acceleration, root-mean-square (r.m.s.) of the measured accelerations, and the vibration dose value (VDV) using HVLab software. The r.m.s. value of the frequency-weighted acceleration time history, $a_\omega(t)$, over a finite period of time T is one of the basic methods for evaluating the vibration [24],

$$\text{r.m.s.} = \left[\frac{1}{T}\int_0^T a_\omega(t)^2\,\mathrm{d}t\right]^{1/2}. \qquad (1)$$

The r.m.s. does not allow for the effect of vibration duration on human response and, as an average measure, it does not increase with increasing duration. Therefore, the VDV was introduced and included in the standards for the evaluation of the building vibration [25, 26, 27]. As defined in Equation (2), the VDV accumulates the vibration rather than averaging and so increases with increasing duration of vibration. The unit of VDV is $\text{ms}^{-1.75}$.

$$\text{VDV} = \left[\frac{1}{T}\int_0^T a_\omega^4(t)\,\mathrm{d}t\right]^{1/4}. \qquad (2)$$

In the present study, the duration of the measured vibration stimuli was fixed at 4.5 s. Four frequency weightings were used: 1) W_b for vertical vibration based on BS 6472-1:2008 [27]; 2) W_k for vertical vibration based on ISO 2631-1:1997 [25]; 3) W_g for vertical vibration based on ISO 10137:2007 [28]; 4) W_m for vertical or horizontal vibrations based on ISO 2631-2:2003 [29].

Table III. Fundamental frequencies and damping ratios of the experimental floor structures. f_0: Fundamental frequency [Hz], ζ: Damping ratio [%].

Floor	1	2	3	4	5	6
f_0	20	36	21	31	89	54
ζ	17.5	5.6	19.0	6.5	20.8	18.5

2.7. Statistical analysis

Statistical analyses were performed using SPSS for Windows (version 20.0, SPSS Inc., Chicago, IL). Differences in the mean values were tested with the Wilcoxon test to estimate the significance of the differences in the subjective responses between Test I and Test II, and to investigate the effects of sound on subjective responses. The relationships between the objective measures and subjective responses to the floor vibrations were investigated using Pearson's correlation test. In this study, p values less than 5% ($p < 0.05$) were considered statistically significant.

3. Results

3.1. Objective characteristics of the floors

Figure 4 shows the magnitude of driving-point mobility for the six experimental floors on a decibel scale. The frequency characteristics differed across the floors depending on the composition of the floor structures. The measured modal parameters are listed in Table III. The fundamental frequencies (the frequency of the 1st mode) of floors #1 and #3 were found to be less than 30 Hz, whereas floor #5 had a fundamental frequency at 89 Hz. The measured damping ratios, which were evaluated using the half-power bandwidth method, varied from 5.6% on floor #2 to 20.8% on floor #5. Large variations in fundamental frequency and damping ratios were consistent with floor vibrations depending on the dynamic characteristics of the impact isolators in multi-layered floor structures [29].

3.2. Measured floor vibrations induced by walking

Examples of the acceleration power spectral densities of the floor vibrations induced by a male subject (height: 173 cm and weight: 71 kg) are shown in Figure 5. Only the measured data from the accelerometer at the centre were used. The frequency characteristics differed across the floors depending on the composition of the floor structures. Floors #1 and #3 show spectral peaks around 20 and 40 Hz, and floor #6 shows peaks around 20, 40, and 60 Hz. Floor #2 shows a peak around 40 Hz and floor #4 has a peak at 25 Hz. Floor #5 has energy in the range 20 to 50 Hz, but with a magnitude much lower than on the other floors. The unweighted VDV varied greatly between 0.029 and 0.402 ms$^{-1.75}$. The acceleration time histories of the single impacts from the floor vibrations produced by the same person are presented in Figure 6 using the data from the accelerometer at the centre of the floor. There are differences in the peak accelerations and the durations of the impacts between the floor structures.

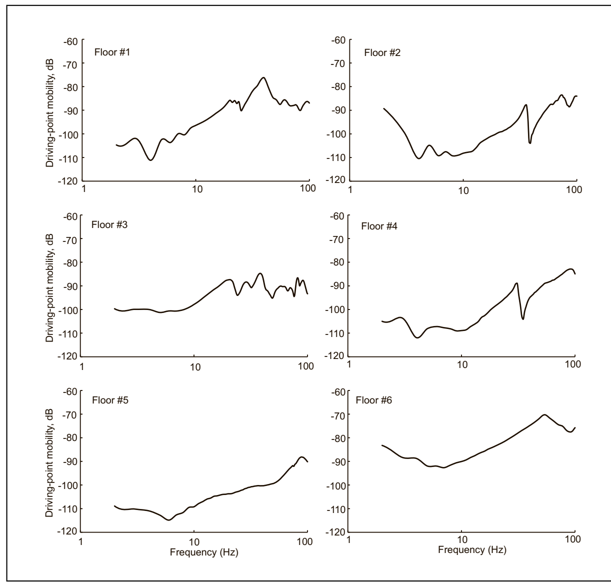

Figure 4. Magnitudes of driving-point mobility for the experimental floors.

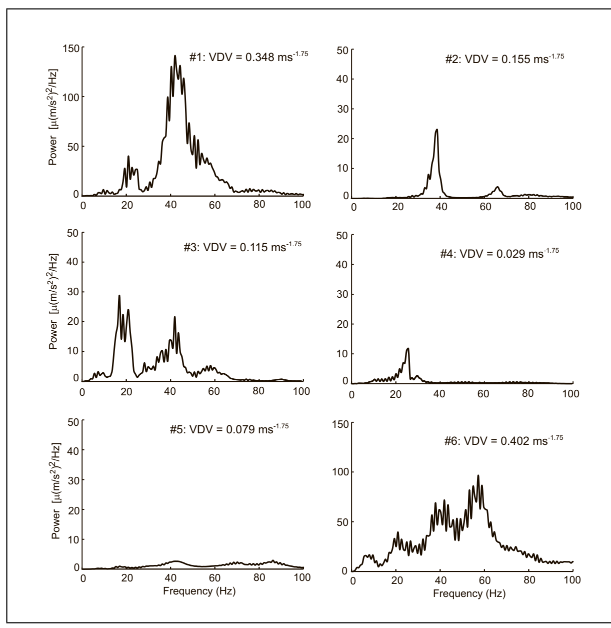

Figure 5. Acceleration power spectral densities of the floor vibrations.

Figure 7 shows the frequency-weighted (W_b) vibrations for Test I in terms of peak acceleration, r.m.s. acceleration, and VDV. The mean values and the standard errors are listed in Table IV. All the data listed in Figure 7 and Table IV are the averaged values from the two accelerometers. It was observed that the vibration level of floor #6 was significantly greater than the other floors. For peak accelerations, floor #1 caused the second greatest vibration level followed by floors #3, #5, #4, and #2. Floors # 1 and #6 with a concrete slab thickness of 210 mm showed greater vibration levels than floors #3 and #4 with 180-mm thick concrete slab. This implies that floor vibrations induced by human walking are affected by the composition of the

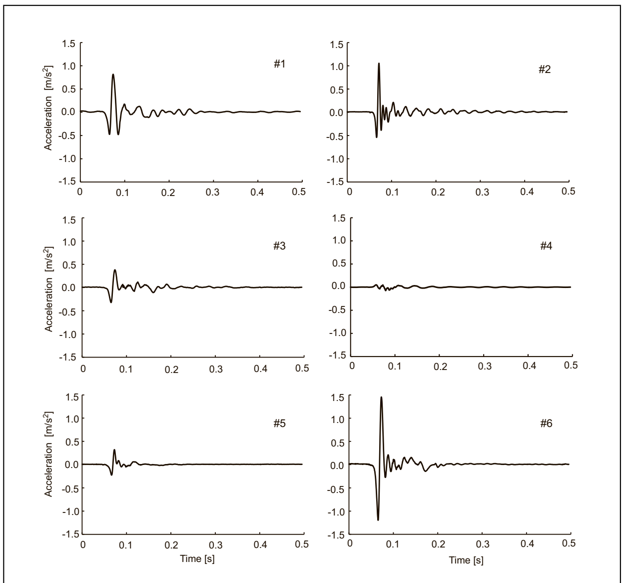

Figure 6. Acceleration time histories of single impacts of the floor vibration.

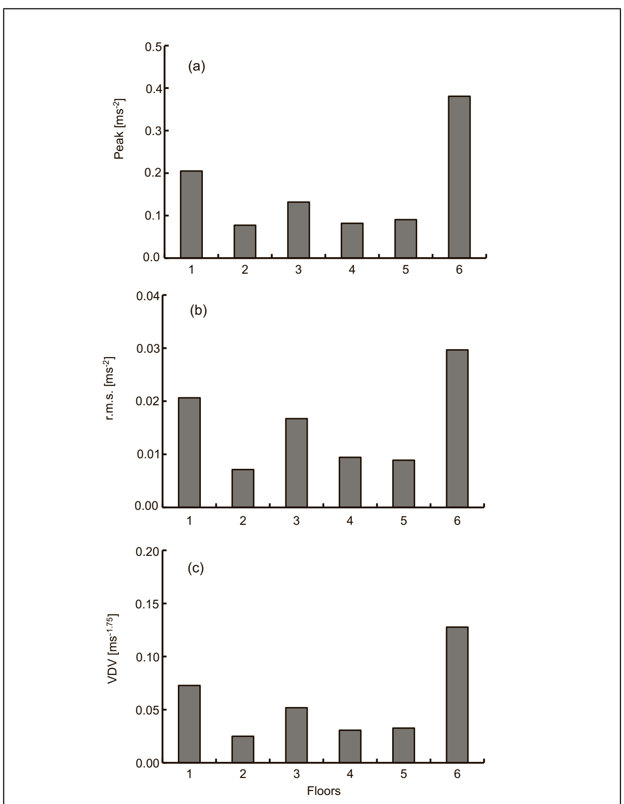

Figure 7. W_b weighted floor vibrations: (a) peak acceleration, (b) r.m.s. acceleration, and (c) VDV.

floor structures including the different types of sound insulating layers. Similar tendencies were found with r.m.s. acceleration and VDV, showing that the vibration levels of floors #6 and #1 were much greater than the other floors. British Standard [27] describes the threshold of vibration perception as 0.015 m/s^2 in terms of peak acceleration. As shown in Figure 7a, the floor vibration levels of every floor structure were more than the threshold. Therefore, it was expected that the subjects would feel the vibration of each floor. The VDV values for the six floor structures were highly correlated with the peak acceleration ($r = 0.99$, $p < 0.01$) and the r.m.s. acceleration ($r = 0.98$, $p < 0.01$).

Table IV. Mean values and standard errors of the frequency weighted (W_b) floor vibrations obtained from Test I (M = mean values, σ_m = standard error of the mean). Peak: Peak acceleration [m/s^2], r.m.s.: r.m.s. acceleration [m/s^2], VDV [m/s$^{-1.75}$].

	Peak		r.m.s.		VDV	
Floor	M	σ_m	M	σ_m	M	σ_m
1	0.205	0.081	0.021	0.008	0.073	0.029
2	0.077	0.038	0.007	0.002	0.025	0.010
3	0.132	0.044	0.016	0.006	0.052	0.017
4	0.082	0.035	0.009	0.003	0.031	0.011
5	0.090	0.087	0.009	0.007	0.033	0.027
6	0.380	0.153	0.029	0.008	0.128	0.045

Table V. Subjective ratings for both Test I and Test II (M = mean ratings, σ_m = standard error of the mean). Vib.: Vibration intensity, Acc.: Floor acceptability, Ser.: Floor serviceability.

	Floors	1	2	3	4	5	6
Test I							
Vib.	M	3.3	1.9	2.4	2.0	2.0	3.4
	σ_m	0.70	0.89	0.51	0.52	0.00	0.72
Acc.	M	1.9	3.3	2.9	3.3	3.3	1.7
	σ_m	0.77	0.87	0.81	0.77	0.86	0.95
Ser.	M	4.2	7.0	6.4	7.0	6.7	2.9
	σ_m	2.14	1.46	1.75	1.03	1.45	1.57
Test II							
Vib.	M	2.6	1.3	2.2	1.7	1.4	2.8
	σ_m	0.73	0.58	1.05	0.70	0.63	0.98
Acc.	M	2.2	3.3	2.9	3.4	3.5	1.8
	σ_m	1.11	1.34	0.77	1.03	0.73	0.91
Ser.	M	3.7	7.4	6.1	6.6	6.1	2.9
	σ_m	1.82	1.21	1.41	2.25	2.11	1.20

Table VI. Regression equations obtained from relationships between the W_b-weighted VDV and subjective ratings; R_I: rating of vibration intensity, R_A: rating of acceptability, R_S: Rating of serviceability (*$p < 0.05$, **$p < 0.01$), R^2: Coefficient of determination.

Regression equation	R^2
Test I	
$R_I = -227.3\text{VDV}^2 + 50.5\text{VDV} + 0.65$	0.96**
$R_A = 175.1\text{VDV}^2 - 44.1\text{VDV} + 4.43$	0.95**
$R_S = 190.5\text{VDV}^2 - 71.6\text{VDV} + 8.90$	0.94**
Test II	
$R_I = -252.6\text{VDV}^2 + 49.8\text{VDV} + 0.43$	0.93**
$R_A = 187.2\text{VDV}^2 - 43.7\text{VDV} + 4.34$	0.96**
$R_S = 445.7\text{VDV}^2 - 10.8\text{VDV} + 9.10$	0.91**

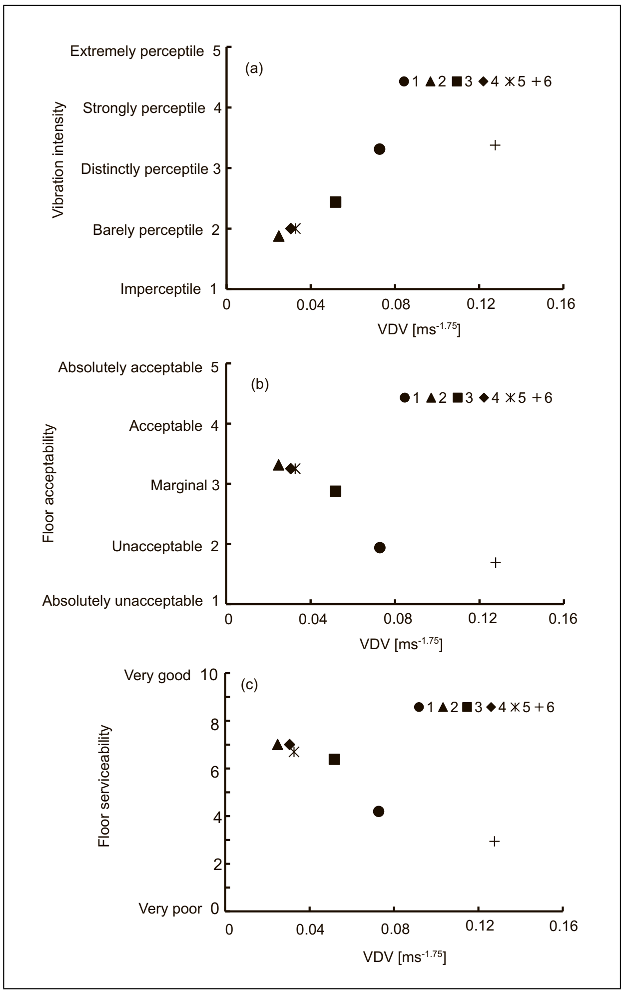

Figure 8. Perceptions of floor vibration for the Test I as a function of W_b-weighted VDV: (a) vibration intensity, (b) floor acceptability, and (c) floor serviceability (Mean values over 20 subjects).

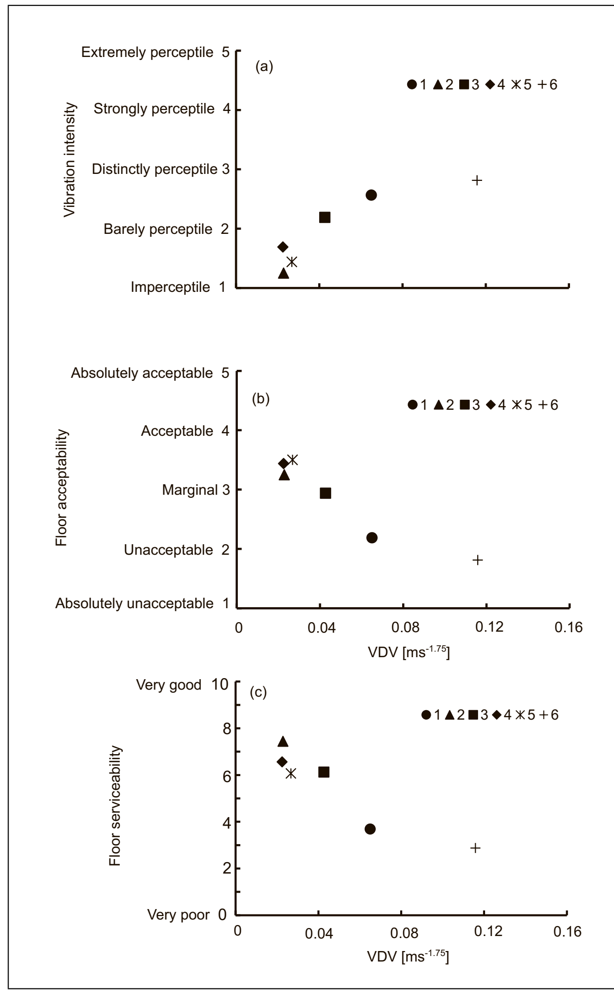

Figure 9. Perceptions of floor vibration for the Test II as a function of W_b-weighted VDV: (a) vibration intensity, (b) floor acceptability, and (c) floor serviceability (Mean values over 20 subjects).

3.3. Perceptions of the floor vibration

Figure 8 presents the perceptions of the floor vibration obtained from Test I with a person's own walking as a function of W_b-weighted VDV. The mean ratings and standard errors are listed in Table V. The vibration intensity ratings increased significantly as the VDV increased. The mean vibration intensities of floors #1 and #6 were more than '3', corresponding to 'distinctly perceptible'. The vibration intensity ratings for the other floors ranged from 2.1 to 2.5. As the VDV increased from about 0.02 $\text{ms}^{-1.75}$ to about 0.08 $\text{ms}^{-1.75}$, the ratings of vibration intensity increased progressively. However, the vibration intensity was not much further increased when the VDV of floor #6 increased to around 0.13 $\text{ms}^{-1.75}$. This suggests that on this scale of vibration intensity the subjects became less sensitive to increases in floor vibration when the VDV was greater than about 0.1 $\text{ms}^{-1.75}$. A number of regression models were tested to select the best model for describing the relationships between the subjective ratings and the objective measures. As listed in Table VI, the best fitting model for the relationship between the VDV and ratings of vibration intensity was a two degree fractional polynomial ($\beta_1 \text{VDV}^2 + \beta_2 \text{VDV}$). Reciprocal tendencies were found in the ratings of floor acceptability and floor serviceability: the ratings of floor acceptability and floor serviceability decreased with increasing VDV. The ratings of acceptability for floors #1, #3, and #6 were less than '3', which means that they were considered unacceptable for floors in newly built residential buildings. Similar to the rating of vibration intensity, the ratings of floor acceptability progressively decreased in the range of 0.02 $\text{ms}^{-1.75}$ to 0.08 $\text{ms}^{-1.75}$, but did not reduce much more when the VDV increased further. As expected, the serviceability ratings of floors #1 and #6 were significantly lower than the others ($p < 0.01$ for all comparisons).

Similar patterns of subjective ratings were observed for Test II when the seated subjects rated the vibration produced by a walking person (Figure 9). The ratings of the vibration intensity increased when the VDV increased, but there was no strong relationship between the VDV and the ratings of vibration intensity when the VDV was less than about 0.04 $\text{ms}^{-1.75}$. This may be because when sitting on the chair the subjects could not feel differences between the floor vibrations when they were not strong. Correspondingly, the ratings of floor acceptability and floor serviceability decreased as the VDV increased. Similar to Test I, the ratings of floor acceptability and floor serviceability for floors #1 and #6 were significantly lower than others. Floors #1, #3, and #6 were rated as 'unacceptable', with acceptability ratings less than '3'.

If VDV values corresponding to a rating of '3' (i.e., 'marginal' on the 5-point scale of floor acceptability) were considered the boundary for acceptance, the allowable limits for Test I and Test II were at 0.037 $\text{ms}^{-1.75}$ and 0.035 $\text{ms}^{-1.75}$, respectively. These values are much smaller than the vibration level corresponding to the acceptance ratio of 50% for floating floors [11]. This is because the previous study [11] measured the floor vibrations in terms of the W_k-weighted VDV_i for a single event once the floors were excited by a heavy/soft impact source [30].

4. Discussion

4.1. Frequency weighting functions for floor vibration induced by human walking

Correlation coefficients between the objective measures and the subjective responses obtained from the two walking tests are listed in Table VII. Four different frequency weighting functions (W_b, W_k, W_g, and W_m) were used to investigate whether the correlations were sensitive to the frequency weighting. For Test I, with subjects judging the vibration caused by their own walking, W_b and W_k gave slightly greater correlation coefficients than W_g and W_m; however, W_g and W_m also gave values that were highly correlated with perceptions. The correlation coefficients obtained between all four frequency weighting functions and ratings of acceptability and serviceability were greater than 0.9. The difficulty in distinguishing between the different frequency weighting functions may be because although there were differences in the vibration spectra, the subjective responses were probably more greatly influenced by the large differences in the magnitudes of the vibration on the six floating floors. As shown in Figure 5, the unweighted VDV of floor #6 (0.402 $\text{ms}^{-1.75}$) was approximately 14 times of that of floor #4 (0.029 $\text{ms}^{-1.75}$).

All three vibration measures (VDV, peak, and r.m.s.) yielded high correlation coefficients between the measured vibration and subjective perceptions of the vibration. The similarity in correlations obtained with these three very different measures is again probably because the vibrations differed greatly in their magnitude (with all three measures) and this had a greater influence on subjective responses than differences in the waveforms (e.g., stimulus durations) that result in differences between the peak, the r.m.s., and the VDV. The VDV is considered an effective tool for quantifying vibration events that vary in magnitude and duration because, unlike the peak value and the r.m.s., it increases with increasing duration of vibration. As the principal advantage of the VDV was lost in this study, further tests are required to investigate perceptions

Table VII. Correlation coefficients between the objective measures and subjective responses for weighting functions ($*p < 0.05$, $**p < 0.01$).

(a) Test I: a person's own walking			
W_b	VDV	Peak	r.ms.
Intensity	0.91**	0.89*	0.95**
Acceptability	-0.94**	-0.93**	-0.96**
Serviceability	-0.96**	-0.96**	-0.97**
W_k	VDV	Peak	r.ms.
Intensity	0.90*	0.89*	0.93**
Acceptability	-0.93**	-0.93**	-0.95**
Serviceability	-0.90**	-0.96**	-0.95**
W_g	VDV	Peak	r.ms.
Intensity	0.88*	0.89*	0.91*
Acceptability	-0.91*	-0.92**	-0.93**
Serviceability	-0.95**	-0.96**	-0.95**
W_m	VDV	Peak	r.ms.
Intensity	0.87*	0.89*	0.90*
Acceptability	-0.90**	-0.92**	-0.93**
Serviceability	-0.95**	-0.96**	-0.95**

(b) Test II: another person walking			
W_b	VDV	Peak	r.ms.
Intensity	0.91**	0.89*	0.95**
Acceptability	-0.94**	-0.93**	-0.96**
Serviceability	-0.97**	-0.97**	-0.96**
W_k	VDV	Peak	r.ms.
Intensity	0.90*	0.89*	0.93**
Acceptability	-0.93**	-0.93**	-0.95**
Serviceability	-0.96**	-0.97**	-0.96**
W_g	VDV	Peak	r.ms.
Intensity	0.88*	0.88*	0.91*
Acceptability	-0.92**	-0.92**	-0.94**
Serviceability	-0.96**	-0.96**	-0.95**
W_m	VDV	Peak	r.ms.
Intensity	0.88*	0.88*	0.91*
Acceptability	-0.92**	-0.92**	-0.94**
Serviceability	-0.96**	-0.96**	-0.95**

when floor vibrations are more variable (e.g., when the stimuli have more similar magnitudes and subjects walk freely without a fixed route or period). The VDV may be expected to be more suitable than the peak value or the r.m.s. value when assessing a wide range of sources of floor vibration (e.g., road or rail traffic, construction work, or machinery) as well as walking-induced vibrations.

In Test II, there was a similar tendency for all four frequency weighting functions to be correlated with human perceptions of floor vibration and all three measures provided high correlation coefficients.

In this study, the four frequency weighting functions (W_b, W_k, W_g, and W_m) had similar performance in predicting subjective responses to floor vibrations, when both walking and when seated. This does not mean that any frequency weighting function can be used when measuring the vibration of floating floors. Previous studies have reported that W_b is more appropriate than the other weighting functions when the levels of vibration are low [30, 31]. Frequency weighting W_b provides a reasonable approximation to the frequency-dependence of equivalent comfort contours and it is closest to the frequency-dependence of the absolute threshold for perceiving vertical vibration. On this basis, W_b seems more suitable for predicting subjective responses to floor vibration in heavyweight buildings. This study also confirms that the VDV is a reasonable measure for understanding subjective responses to floor vibration [11, 13].

4.2. Differences between own walking and sitting and feeling others walk

It might be hypothesized that subjective responses to floor vibration will differ according to the situation. In the present study, two types of test were conducted to obtain judgements of floor vibration both when the subjects walked themselves and when they were seated on a chair and experienced the floor vibration caused by another walker. For judgments of vibration intensity, lower ratings were given when seated than when walking ($p < 0.05$). This is consistent with the measured vibration levels being slightly less in Test II than Test I, although there were no significant differences between the two tests in ratings of floor acceptability or serviceability. Some studies have found the opposite, suggesting vibrations are less acceptable when produced by another person [14, 15]. The disagreement may be due to the different floor structures and different experimental conditions. The two previous studies conducted subjective tests in a laboratory, with simply supported wooden and hollow-core concrete floors. Johansson [15] suggested differences between the two tests occurred because perception of vibration was impeded by the process of one's own walking. In the present study, subjects did not wear shoes, which may have allowed them to experience the vibration of the floor clearly even when walking.

4.3. Probability of adverse comment and allowable limit of floor vibration

British Standard [27] provides VDV ranges expected to result in various probabilities of adverse comment within residential buildings during 16 hours of daytime or 8 hours of night time. For daytime, a low probability of adverse comment is expected with the VDV in the range 0.2 to $0.4\,\mathrm{ms}^{-1.75}$, adverse comment is possible in the range 0.4 to $0.8\,\mathrm{ms}^{-1.75}$, and adverse comment is probable in the range 0.8 to $1.6\,\mathrm{ms}^{-1.75}$. The VDV over a day ($\mathrm{VDV}_{\mathrm{day}}$) can be estimated by using the VDV of single vibration for duration of τ second (VDV_τ) using

$$\mathrm{VDV} = \left(\frac{t_{\mathrm{day}}}{t_\tau}\right)^{0.25} \times \mathrm{VDV}_\tau, \tag{3}$$

where t_{day} is the duration of exposure per day and t_τ is the duration of the single vibration.

Table VIII. Number of walking events required from Test I to reach a low probability of adverse comment ($\mathrm{VDV}_{\mathrm{day}} = 0.2$) according to BS 6472:2008.

Floors	1	2	3	4	5	6
Number of events	58	4146	222	1821	1401	7

In order to determine the possibility of adverse comments, the numbers of events required to reach a $\mathrm{VDV}_{\mathrm{day}}$ of $0.2\,\mathrm{ms}^{-1.75}$ were calculated using the W_b frequency-weighted VDV and a single experience of vibration over 4.5 s. As shown in Table VIII, for Test I there were three floors (floors #1, #3, and #6) that required fewer events to reach a VDV of $0.2\,\mathrm{ms}^{-1.75}$ than the other floors. The VDV of floors #6 and #1 would reach $\mathrm{VDV}_{\mathrm{day}}$ of $0.2\,\mathrm{ms}^{-1.75}$ if there were only seven or 58 4.5-s periods of floor vibration, respectively. On the other hand, floor #2 required more than 4,000 4.5-s periods to reach a $\mathrm{VDV}_{\mathrm{day}}$ of $0.2\,\mathrm{ms}^{-1.75}$.

4.4. Influence of the sound on perception of vibration

Human responses to vibrations generated in buildings depend on various factors including audible noise, visual cues, population type, familiarity with vibration, structural appearance, confidence in a building structure, and knowledge of the source of vibration [28]. The influence of sound on response to floor vibration was investigated in the present study. Subjective ratings with open-ear conditions were compared with those from closed-ear conditions during two walking tests (Figures 10 and 11). Independent t-tests were conducted with subjective ratings as a dependent variable and two different conditions (open-ear and closed-ear) as the independent variables. Significant differences between the open-ear and closed-ear conditions were found only with floor #1 for the ratings of vibration intensity in Test I (where vibration intensity was judged greater when not wearing ear plugs; $p = 0.012$). This may seem inconsistent with previous findings of the influence of noise on the perception of vibration [23, 32, 33, 34]. Howarth and Griffin [35] reported that judgments of vibration in buildings induced by passing trains were affected by the presence of noise, with the effect depending on the relative magnitudes of the vibration and the noise. A series of laboratory experiment by Huang and Griffin [23, 33, 34] found that car interior noise masked the discomfort caused by low magnitudes of vibration, with the masking effect increasing with increasing levels of noise. The different findings may be due to differences in the magnitudes of vibration and the levels of noise used in the studies, and the intermittent nature of the excitation. In the previous studies subjects were exposed to simulations of the sounds and vibrations caused by conventional railway trains and road vehicles: the magnitudes of vibration and the levels of sound were much greater than those in the present study and the stimuli either varied slowly (for railway-induced building vibration) or were steady-state (for car interior noise). The lowest noise level

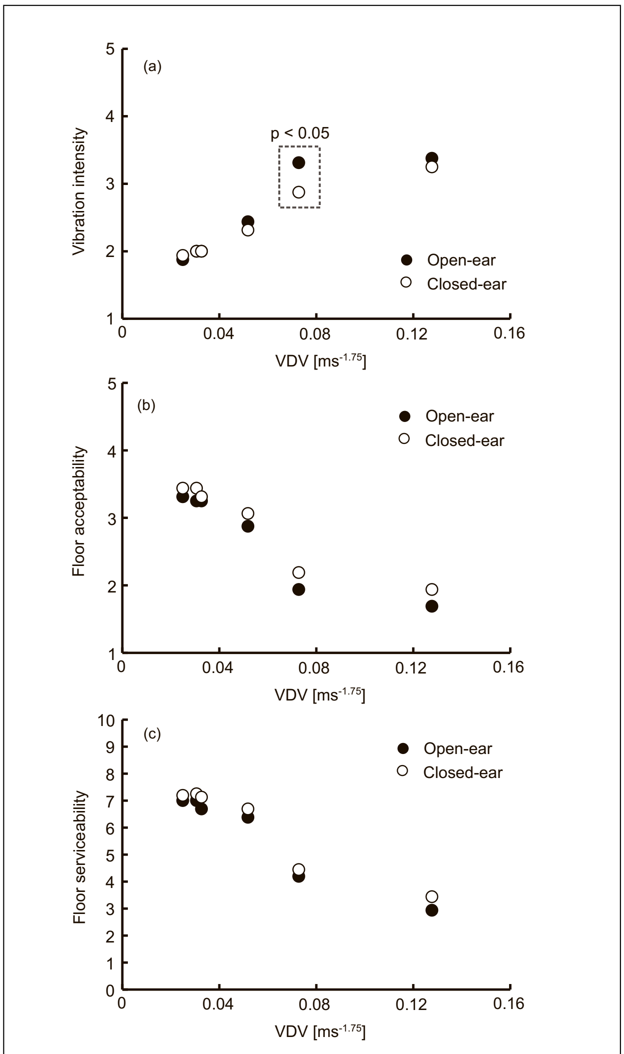

Figure 10. Perceptions of floor vibration for the Test I with and without ear plug as a function of W_b-weighted VDV: (a) vibration intensity, (b) floor acceptability, and (c) floor serviceability (Mean values over 20 subjects).

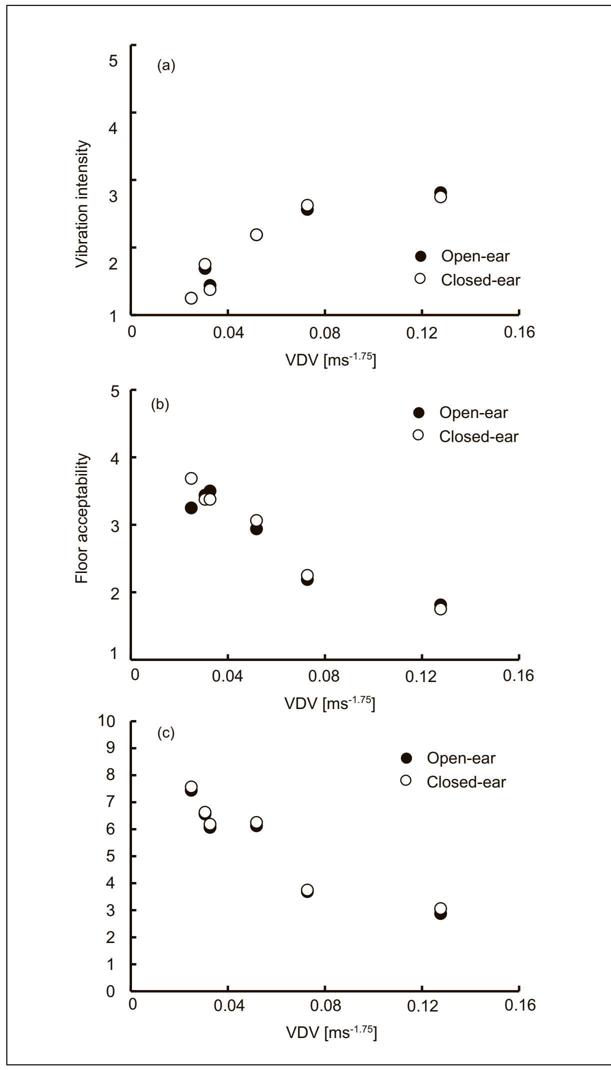

Figure 11. Perceptions of floor vibration for the Test II with and without ear plug as a function of W_b-weighted VDV: (a) vibration intensity, (b) floor acceptability, and (c) floor serviceability (Mean values over 20 subjects).

used in the study of Howarth and Griffin [35] was around 45 dB (in terms of the A-weighted equivalent noise level, L_{Aeq}), and the levels of sound used in the experiments of Huang and Griffin [23, 33, 34] were more than 60 dB. The maximum noise level (L_{Aeq}) produced by walking was less than 40 dB in the present study. It seems reasonable to conclude that perception of vibration induced by human walking was not influenced by the sounds associated with barefoot walking within the range of magnitudes of vibration and levels of sound investigated.

4.5. Prediction of vibration perception using a standard impact source

In the field of building acoustics, human walking has been simulated using an impact source such as a tapping machine or a heavy/soft impact source [30, 36]. It has been suggested that a heavy/soft impact source is a good representative of human walking in terms of mechanical impedance and impact force as well as subjective similarity [37, 38, 39]. A heavy/soft impact source is a hollow rubber ball with a restitution coefficient of 0.8 dropped from a height of 1 m. The standard size of a heavy/soft impact source is 178 mm in diameter and its weight is around 2.5 kg. In the present study, floor vibrations were also measured using a heavy/soft impact source dropped from a height of 1 m, conforming to ISO 10140-5:2010 Annex F. The accelerations were measured while the heavy/soft impact source was dropped at five positions along the walking line (Figure 2).

Figure 12 shows the relationships between the measured VDVs induced by human walking for Test I and the VDVs induced by the heavy/soft impact source. The VDV of floor vibrations induced by the heavy/soft impact source were highly correlated with the VDVs induced by human walking, for all frequency weightings. The correlation coefficients were 0.97 for W_b, W_k, and W_m ($p < 0.01$), and 0.96 for W_g ($p < 0.01$). This implies that the relative importance of vibration with different floors might be

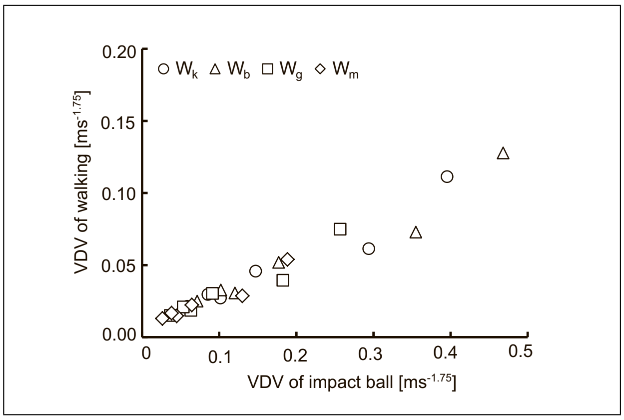

Figure 12. Relationships between accelerations induced by human walking and impact ball in terms of VDV.

obtained using a heavy/soft impact source instead of field measurements with humans walking. However, the VDVs produced by the heavy/soft impact source were about four times greater than those induced by human walking, because the impact force from the heavy/soft impact source dropped from a 1-m height is greater than that from human walking. Previous studies have used different dropping heights of a heavy/soft impact source to simulate adult walking and jumping on lightweight floors [16, 40]. A 10-cm drop has been chosen to produce a similar sound pressure level as adult jumping [40], while Kim and Jeon [16] used 0.2 m when considering the impact forces from adult walking. It would also seem appropriate to reduce the dropping height of the heavy/soft impact source with heavy-weight floors.

The VDVs induced by the heavy/soft impact source showed a strong association with the subjective judgements obtained in Test I. With the frequency weighting W_b, the correlation coefficients were more than 0.9 (0.97 for vibration intensity and −0.99 for floor acceptability and serviceability, $p < 0.01$ for all). This is also consistent with the heavy/soft impact source providing a useful prediction of the perceptions induced by humans walking on heavy-weight floors.

A recent study reported that the tapping machine was found to have an acceptable uncertainty of the injected power even at low frequencies [41]. It has also been shown that a modified tapping machine is much closer to human walking than the tapping machine in terms of mechanical impedance and impact sound pressure level [42], and that the force spectrum of the modified tapping machine can be similar to that of the adult walking [37]. The use of the tapping machine and the modified tapping machines may be appropriate in future studies.

4.6. Relationships between dynamic characteristics of the floors and perceptions

In the present study, structural properties (thickness of floors and resilient isolators) and modal parameters (fundamental frequency and damping ratio) were not significantly associated with subject perceptions in either Test 1 or Test 2. This result is not consistent with a previous study [11] in which the walking discomfort of floating floors was related to structural components such as thickness and joist spacing. However, that study was a parametric study with variations of panel thickness and spacing of the supporting beams, and the floor structures were simpler than those used in the present study. Insignificant relationships between the modal parameters and vibration perceptions are also inconsistent with floor design criteria since these often rely upon the fundamental frequency. These inconsistencies might have arisen because the present study conducted a simple driving-point mobility test with a single accelerometer and did not consider the full dynamic behaviour of the floors such as the mode shapes. It may be valuable to investigate the impact of the dynamic properties on subject perceptions with different resilient isolators (e.g. different thickness and dynamic stiffness) with more precise modal testing.

5. Conclusions

Different levels of floor vibration were produced by humans walking on six different types of floating floors used in the apartments of heavyweight buildings. Subjective ratings of the floor vibration were highly correlated with the magnitude of vibration after weighting using any of four different frequency weighting functions (W_b, W_k, W_g, or W_m). The vibration dose value, VDV, provided reliable correlations with the subjective responses to the vibration of the floating floors. Judgements of floor vibration induced by barefoot walkers were not influenced by the sound of footsteps. Perceptions of floor vibration were highly correlated with vibration produced using the heavy/soft impact source as defined in ISO 10140-5. Dynamic properties of the floors were not associated with the subjective ratings.

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