Review of the Impact Ball in Evaluating Floor Impact Sound

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The purpose of this study was to review the use of a new standard impactor, the impact ball, in evaluating heavy-weight impact sounds in multi-story reinforced concrete residential buildings. Physical properties such as impedance and force of the impact sources, including the impact ball and human activity, were measured. In particular, noise from the impact ball was analyzed and the relationships between sound levels and subjective responses were investigated. The results showed that the noise from the impact ball is similar to the noise of children running and jumping, and that subjective responses to the noise correlate well with Zwicker's Loudness model and the newly defined floor impact sound level ($L_{i,Fmax,AW}$). It was also found that the noise level of the impact ball is slightly higher than that of the bang machine, although the impact ball has a lower impact force. In addition, when the noise from the impact ball was evaluated under both laboratory and in-situ conditions, the allowable sound level was found to be 54 dB ($L_{i,Fmax,AW}$).

1. Introduction

In Korea, concern about the effects of floor impact sound has been increasing, along with the number of civil complaints. For the rational settlement of social disputes concerning floor impact noise, a method for objective evaluation of that noise is required. The most objective measure would be to use real impact sources such as jumping and running children, but such a measure is not reproducible. The next best method is to develop an impact source which accurately simulates real impact sounds and then evaluate subjective responses to the new impact source. This method should be simple and easy for end users to assess the performance of floor impact sound insulation.

The frequency characteristics of current standard impact sources such as the tapping machine and bang machine are different from those of real impact sources [1, 2, 3]. Watters [4] reported that the floor impact spectrum of light-weight impact noise (as the steel hammer of the tapping machine is lighter than any other impact sources) generated by a tapping machine is different from the spectrum of the hard-heeled foot traffic of women. In addition, Bodlund [5] found that on a concrete floor, the noise spectrum of a 75 kg male walking or running is dominated more by low frequency bands than is the noise spectrum produced by a tapping machine. Warnock [6, 7] emphasized the usefulness of the tapping machine, but also pointed out that it does not produce low frequency noise [8]. Furthermore, several publications have reported on the impedance levels of modified versions of the standard impact source for structure-borne noise [9, 10, 11]. These efforts have led to the proposal of a modified standard tapping machine [12]. Although this modified tapping machine reasonably simulates a human walking (300–500 N), it still cannot simulate the problematic impact noise such as children running (600–1,000 N) and jumping (2,000–3,000 N).

The low frequency floor impact sound pressure level generated by the modified tapping machine was lower than real running and jumping noise in reinforced concrete residential buildings. Although ISO 717-2: 1996(E) - Annex A suggests the use of additional weight to simulate the low frequency of light-weight impact sounds, there are difficulties applying the spectrum adaptation term 'C_I'; namely, (a) there is a large difference in heavy-weight impact sound levels with different slabs, and (b) since the floor impact is an impulsive sound, the impact sound should be evaluated by L_{max} not by L_{eq}.

For the past thirty years, floor impact noise in wood-frame and reinforced concrete (RC) houses has been evaluated with the bang machine in Japan and Korea. However, the impact force of the bang machine (4,200 N) is above the range of actual impact forces and may damage the structural components of wood-frame houses. Therefore, a new standard impactor with a lower impact force was needed. The impact ball was specifically developed to reduce the potential damage to structural components in wood-frame houses [13]. As it is standardized for light-weight floor impact and more accurately approximates real impact noise, the impact ball has been adopted as the second standard impact source in Japan [1, 3, 13, 14, 15]. Tachibana *et al.* [3] examined the actual performance of impact balls in different Japanese residential buildings (RC, wood and steel structures). When they measured the noise frequencies of four impact sources (tapping machine, bang machine, impact ball and jumping of a 25 kg child), they found that the characteristics of the impact ball were the most similar to the noise frequency characteristics of real impact noise. At present, the light-weight (tapping machine) and the two heavy-weight impact sources (bang machine and impact ball, so classified because of their peak levels) are used in Japan [1], but in Korea the impact ball has not yet been adopted as a standard impact source.

The structural system of multi-story residential buildings in Korea used in the present study is different from that of Japanese residential buildings. Apartment buildings in Korea typically contain a floor heating system which has a box frame-type RC structure with load-bearing walls and without columns and beams. These structures usually have hard floors and walls throughout the interior areas. Therefore, it is necessary to estimate the possible applications of an impact ball as a standard heavy-weight floor impact source in RC structures by comparing its characteristics with those of the bang machine and tapping machine. This study also compares the noise generated by the impact ball to real impact noises in a typical Korean RC residential structure. In addition, this study proposes categories of floor impact sound generated by the impact ball based on subjective evaluations.

2. Social survey

A survey of the major impact noise sources in 611 apartments in the Seoul area was conducted. The ages of children responsible for heavy-weight floor impact sound were recorded. As shown in Figure 1, the results indicate that children ages 6 to 9 years are the primary sources of floor impact sound. A recent survey in Korea on the national physique shows that the average weight of boys in this age range is 26.5 kg; that of girls is 25.6 kg.

The aggravating aspects of floor impact noise are the inconsistent spatial factors of noise generated by children [16, 17]. As shown in Figure 2, this study revealed that the jumping and running of children are the principal cause for the majority of complaints.

3. Characteristics of the impact ball

An impact ball (JIS A 1418-2) weighing 2.5 ±0.2 kg with a diameter of 185 mm was used. The thickness of the outer wall was 30 mm. The height of the free fall impact was 1 m with an impact time of 20 ms. Table I shows a comparison of the impact ball and the bang machine. In many respects

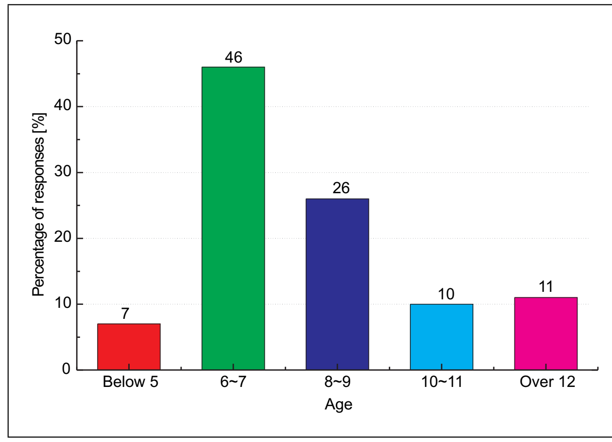

Figure 1. Children's ages related to floor impact sound.

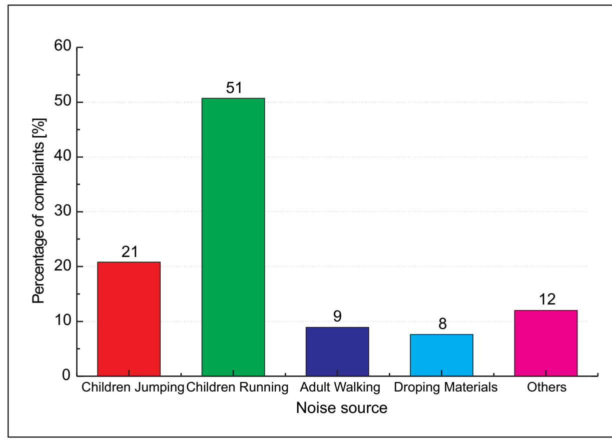

Figure 2. Main sources of floor impact sound.

Table I. Comparison of the impact ball with the bang machine.

	Impact Ball	Bang Machine
Weight	2.5±0.1 kg	7.3±0.2 kg
Handling	1 person	2 persons
Preparation	Quick and easy	Complicated
Electricity	Not required	Required
Maintenance	None	Often
Damage to structures	None	Wood structure

the impact ball is more useful than the bang machine, including in its operation and maintenance.

3.1. Difference between the old and new impact ball

The old impact ball used in this study was developed just before a newly designed impact ball was released in 2001 by the Japanese company RION. Although the old one satisfies JIS A 1418-2, it is made of SBR (Styrene Butadiene Rubber) and its impact force varies with temperature [18, 19, 20]. The newer version is made with silicone rubber, which minimizes the effect of temperature. In addition, the effective mass, size and coefficient of restitution have been modified. The differences in the physical properties between the old and new balls are shown in Table II.

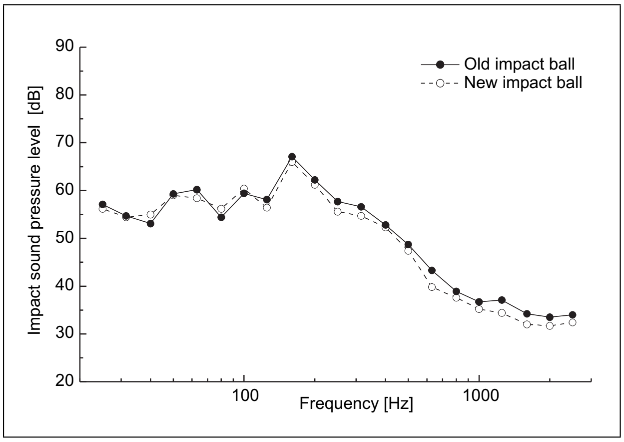

Figure 3. Frequency characteristics of the old (JIS impact ball) and the new impact ball dropped on a concrete floor.

Table II. JIS impact ball (old) vs. new impact ball.

	Old impact ball	New impact ball
Effective mass	2.5±0.2 kg	2.5±0.1 kg
Restitution coefficient	0.7±0.1	0.8±0.1
Diameter	185 mm	178 mm Shell
thickness	30 mm	32 mm
Material	SBR	Silicone rubber

We compared the frequency characteristics of the two impact balls in 1/3 octave bands as indicated in Figure 3. The impact balls were tested in a newly built multi-story apartment building. The floor structure consisted of a 150 mm concrete slab, heating pipes on 60 mm light-weight concrete (insulation) and 45 mm finishing mortar. The total area of an individual unit was 100 m^2 and the test was conducted in the living room and two bedrooms. As indicated in the 1/3 octave band analysis shown in Figure 3, the impact sound level of the new impact ball is, on average, approximately 1 dB lower than the that of the old impact ball at all frequencies except 63 Hz. The correlation coefficient for the spectrum of the two impact balls was 0.995 with a significance level of $p < 0.01$.

3.2. Real versus standard impact sources

3.2.1. Impedance

In order to make a comparison of physical properties between standard impact sources and human impact sources, the mechanical impedance of each impact source was measured. The standard sources tested were the old impact ball, the tire of the bang machine, the original tapping machine and the modified tapping machine which is ISO 140-11 regulated. The human impact sources included an adult walking barefoot and a 7-year-old child.

For the impedance measurement, random excitation signals were sent to the impact sources through a shaker. Contrary to previous studies [9, 10, 11], the shaker was placed horizontally in order to avoid the effect of the impact source's own mass, and the simulation impact source was bonded with epoxy to a 100 cm^2 aluminum plate. As

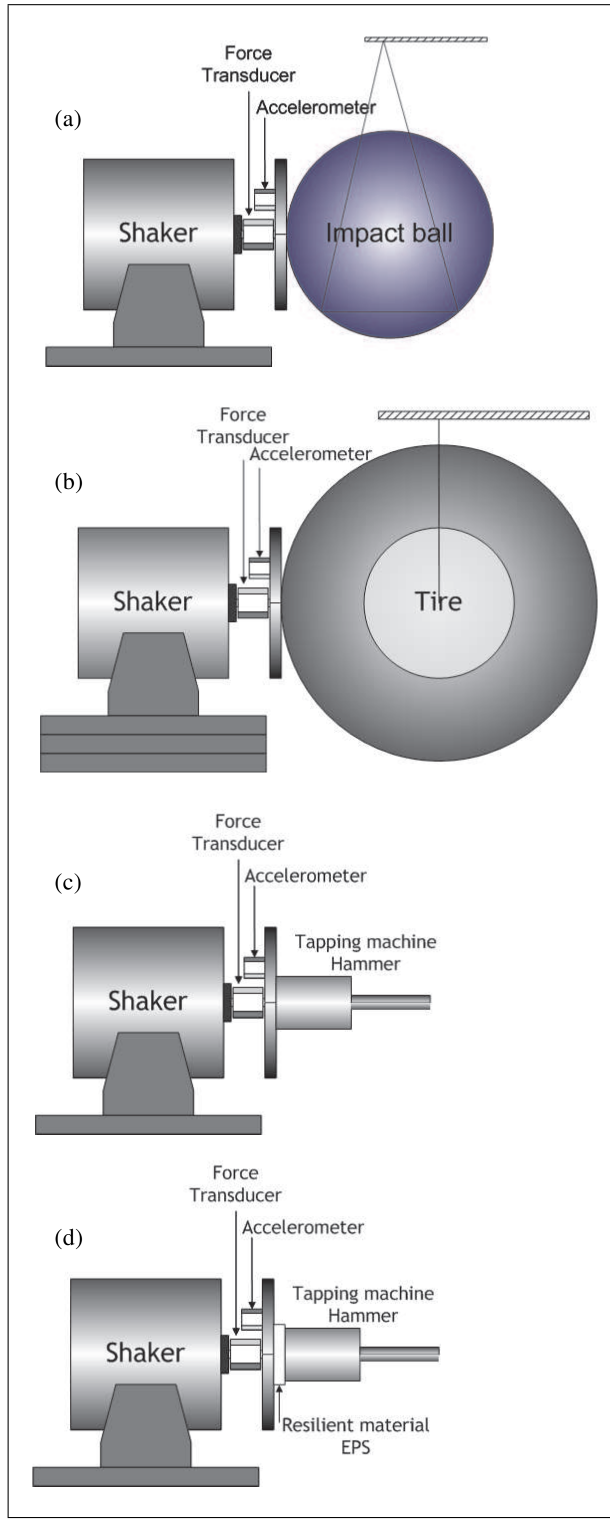

Figure 4. Impedance measurement setup for each impact source. (a) Impact ball (b) Tire of bang machine (c) Steel hammer of tapping machine (d) Modified tapping machine.

shown in Figure 4, the aluminum plate, force transducer and accelerometer were installed, and the excitation force and vibration acceleration were measured simultaneously. The natural frequency of the plate was greater than 4 kHz and its impedance was excluded in the calculations of the impact sources' impedance. Figures 4a-c show the measurement setup for the impact ball, the tire of the bang machine and the steel hammer of the tapping machine. For the modified tapping machine, resilient material with similar properties as an elastic layer (dynamic stiffness = 34 MN/m^3 ± 10%, loss factor = 0.2) was placed under the hammers laid on the test floor. As shown in Figure 4d, the measurement setup for human bare foot was similar, but the whole human body was hung in the air with a hammock to create the same measurement condition. Impedance of the adult (65 kg) and the 7-year-old (20 kg) child, both barefoot and with a straight leg, was measured.

As shown in Figure 5, the impedance of all impact sources increased as the frequency was increased, and decreased after the maximum value. The first resonance frequency of both the impact ball and the tire of the bang machine was about 20 Hz and that of the modified tapping machine was about 40 Hz. These values were much higher than the first resonance frequency of the human bare foot, which was about 4 Hz.

In comparison with previous studies [9, 10, 11], these results were different at the low frequency band but similar at the high frequency band. However, the impedance characteristics of the human bare foot were almost the same as those found in human body vibration studies [21]. Griffin [22] reported that the impedance or apparent mass of the human body had a maximum value at 3–7 Hz and the frequency at the maximum value changed according to the magnitude of applied vibration and the subject's posture.

In the case of the tapping machine's steel hammer, resonance frequency was not observed because the steel hammer had rigid body characteristics. The spring stiffness of the modified tapping machine originated from its resilient material. The modified tapping machine had one degree of freedom in its system characteristics, attributed to the steel hammer mass.

As shown in Figure 5, the second, third and forth modes of impedance of the impact ball and tire were determined. For example, the second mode of the impact ball was 80 Hz but its impedance level was very small. Therefore, we can surmise that the floor impact vibration is mainly generated by the first resonance modes of the impact ball and tire. From these results, the impedance of each standard impact source was found to be somewhat different from human impact, but the resonance frequency and impedance level of the impact ball were most similar to those of a human bare foot.

In the experiment, the excitation force was transmitted through the plate to the fixed impact sources on the plate. These impact sources were fixed by various methods to specific areas rather than to points, and a change would occur in the fixed area or the contact area when impact sources hit the floor. The area of contact of the impact source with the floor was smaller than the projected surface area. In this case, the effect of the change in contact area on the first resonance mode was very small. This is because the stiffness of the first mode is mainly influenced by the stiffness of the impact source at the moment its shape is changed into the first mode. Therefore, impedance of the impact source will not change, even if the contact area continuously changes as the impact source affects the floor.

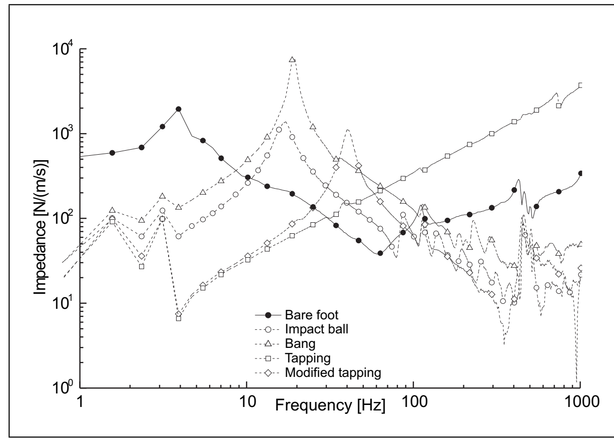

Figure 5. Measurement result of impedance for each impact source.

Figure 6. Installation of impact force sensor (PF-10, RION).

3.2.2. Impact force

As another physical property, the force from standard impact sources and human impact sources was measured. Figure 6 shows the impact force sensor (PF-10 & UA-06A, RION) used in this experiment. The four standard impact sources used in the impedance experiment were also tested.

As human impact sources, adults walking and a child (20 kg weight) jumping from a height of 30 cm and running were tested. The measured impact forces of the child's running and jumping were 600–800 N and 1,000–1,600 N, respectively. Figure 7 shows the results of the impact force measurements. As shown in Figure 7, the bang machine had the highest level of impact force at the 63 Hz band. The impact force spectrum of the impact ball was more similar to the impact of children than adults. The force spectrum of the modified tapping machine was similar to that of the adults; however, its impact force was very small compared to that of children.

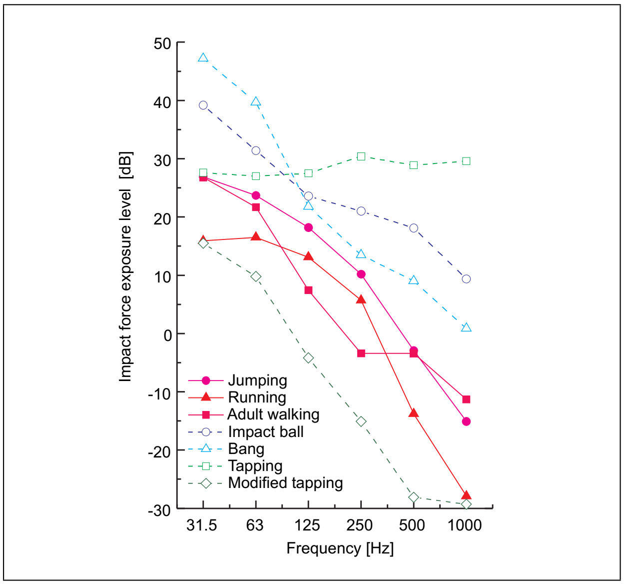

Figure 7. Impact force spectrum for standard impact sources and human impacts.

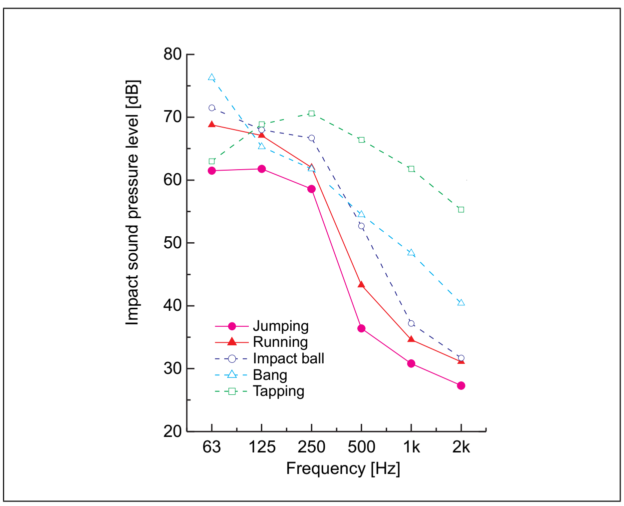

Figure 8. Frequency characteristics of real impact sounds generated by a 26-kg child and by standard impactors.

3.2.3. Impact sound pressure level

The frequency characteristics of the noise generated by a 25 kg child jumping and running, the bang machine, the tapping machine and the old impact ball in an apartment building were compared. The floor impact sounds generated by the standard impactors were measured and recorded according to JIS A 1418 ("Measurement of floor impact sound insulation of buildings"). The floor was impacted at five positions (in the center and at four corners) in the living room on the upper floor. Measurements were recorded on the ceiling of the apartment directly under the impact positions.

Figure 8 compares the standard impactors with real impacts. Of the three standard impactors, the frequency characteristics of the impact ball were the most similar to those of a running child. The correlation coefficient between the sound levels of the impact ball and running child was 0.981 (p <0.01). However, the impact sound pressure levels of the impact ball were about 4 dB higher than those of a jumping child. The impact sound level of the bang machine was about 2–5 dB higher than the impact sound levels of a child jumping and running, respectively, but at low frequencies, the bang machine generated the highest sound pressure levels of any of the five impact sources. The tapping noise had much higher levels than any of the other impact sounds in the 250 Hz to 4 kHz bands. As shown in Figure 8, when evaluating floor impact sound, the impact ball had a higher level than the bang machine. The difference in frequency characteristics of the three impactors is due to the differences in their respective impact forces and impact times.

Table III. Correlation coefficients between real impact sources and standard impactors (p <0.01).

	Impact Ball	Tapping Mach.	Bang Mach.
Jumping	0.97	0.71	0.92
Running	0.98	0.69	0.95

As shown in Table III, when the correlations between the real impact sound and the standard impact sounds were calculated, the real impact sound from the 25 kg child correlated well with that of the impact ball. The correlation between real impact sound and the tapping or bang machine noise was weaker. As shown in Figure 8, the difference in the A- weighted overall sound level between a child running and an impact ball is about 5 dB.

3.3. The impact sound levels at different drop heights

The impact ball was dropped from heights of between 5 cm and 120 cm (at 5 cm intervals from 5–20 cm; 10 cm intervals from 20–120 cm). The sound levels were measured in the master bedroom of the apartment. As shown in Figure 9, from 63 to 500 Hz in the standard octave band, the impact sound levels below the floor increase logarithmically with increases in drop height. The impact sound levels at 500 and 250 Hz were more sensitive to increases in drop height than those at lower frequencies. However, at the standard drop height of 100 cm, a drop height difference of about 10 cm was not significant (less than 1 dB).

3.4. Comparison of impact sound levels with other impactors

To determine the floor impact sound level, $L_{i,Fmax,AW}$, inverse A-weighted impact sound pressure level in JIS [23] of a given specimen, and measured maximum impact sound levels (L_{max}) were plotted against four octave band frequencies from 63 to 500 Hz and compared to the reference inverse A-weighting contour (83, 73, 66, 60, 57 and 56 dB at the frequencies of 63, 125, 250, 500, 1000 and 2000 Hz, respectively).

The impact sound pressure level values from the tapping machine were calculated according to JIS A 1419-2 [23] ($L'_{n,AW}$, the inverse A-weighted normalized impact sound pressure level for light-weight impact noise). JIS A 1419 uses a reference curve for impact sound levels (octave bands) which is different from the reference curve used in ISO 717-2. JIS A 1418 states that light-weight impact noise must have an equivalent sound pressure level (L_{eq}) in the frequency range of 125–2,000 Hz. The maximum deviation at any frequency should not exceed 10 dB; and the single value is read from the standard contour and the 500 Hz ordinate.

Although the direct comparison of two different types of levels such as $L_{i,Fmax,AW}$ of the bang machine and impact ball and $L'_{n,AW}$ of the tapping machine makes interpretation very difficult, it is necessary to compare the impact sound levels with different impactors used in a same floor. Correlations between the sound levels of the impact ball and the bang machine, and the impact ball and the tapping machine, were sought. The measurements were made on 32 concrete slabs of different sizes and thicknesses as shown in Figure 10. The R^2 value was low (0.24) between the impact ball and the tapping machine because the tapping noise is strongly affected by floor surface material. As shown in Figure 10, the R^2 values between the bang machine and the impact ball are relatively high (0.83) because both impacts are classified as heavy-weight impact sources due to their peak levels.

As shown in Figure 10, from the regression line, the level difference of the impact ball on the 32 different slabs was 20 dB ($L_{i,Fmax,AW}$), whereas that of the bang machine was 14 dB ($L_{i,Fmax,AW}$), and 12 dB ($L'_{n,AW}$) for the tapping machine. Among the three standard impact sources, the impact ball had the largest floor impact sound pressure level. From the result it also had the widest range in impact sound levels from the 32 box-frame type structures, thus making it more objective and useful in distinguishing the impact sound for isolated structures and materials than the other impact sources.

4. Subjective evaluation of floor impact sound

4.1. Floor impact sound measurements

Floor impact sound was measured in eight unoccupied units of a 28 storey building complex (RC, reinforced-concrete structure) located in Seoul. The floor consisted of a 150 mm thick concrete slab, an 80 mm thick light-weight concrete insulation layer, heating pipes and a 50 mm layer of finished cement mortar. The total area of each unit was 132 m^2 and the test was conducted at 30 impact positions (6 rooms, 5 points per room) in the living room, kitchen and four bedrooms. The frequency characteristics of an adult jumping and running, an impact ball, a bang machine and a tapping machine were measured in the eight unfurnished apartments. When the upper floor was impacted at the center of the rooms, binaural sound signals were recorded through a dummy head for auditory evaluation. The impact and recording positions were the locations at which previous social survey respondents had experienced the most floor impacts.

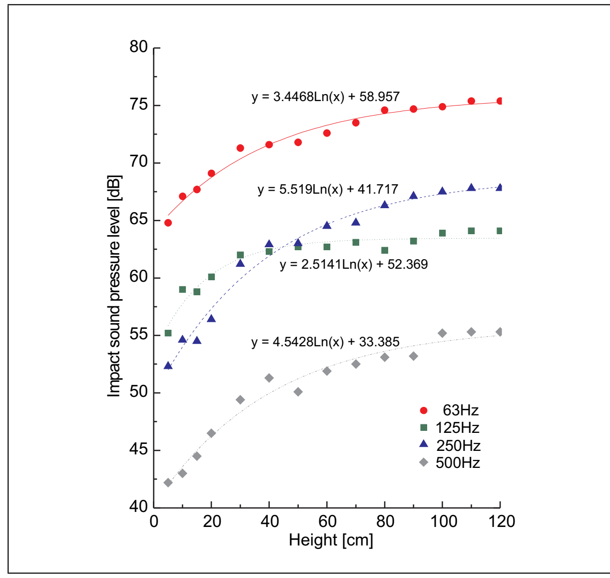

Figure 9. Sound levels of the impact ball dropped from different heights.

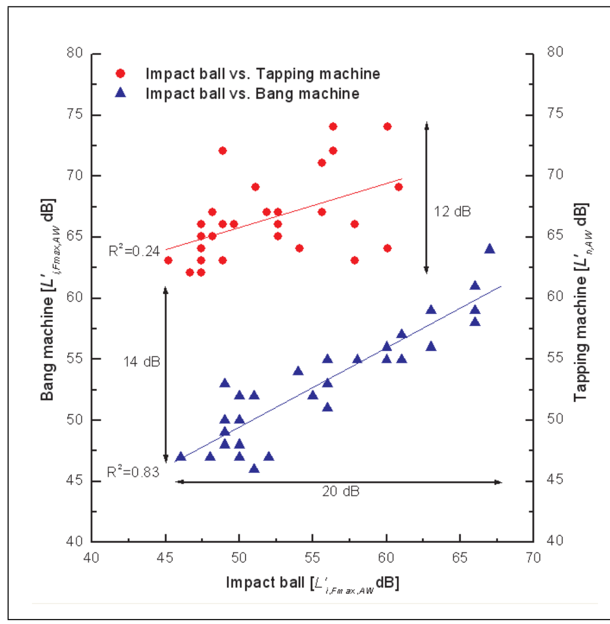

Figure 10. Comparison of sound levels between the impact ball and other impactors.

In this investigation, a 65 kg adult generated the jumping impact sound because arranging for a child to jump at night was difficult. Floor impact sound measurements and recordings were performed according to JIS A 1418. The floor structures consisted of one standard floor (P) and seven sound insulation structures. The sound insulation treatments are identified as follows: 'F' - a floating floor with a 10 mm impact isolator, 'W' - treatment of the walls with a 2 mm rubber sheet and a 9.5 mm gypsum board, and 'C' - treatment of the ceiling with a vibration hanger, a 2 mm rubber sheet and a 9.5 mm gypsum board. Thus 'FWC' means all three sound isolation treatments were applied to the box frame structure.

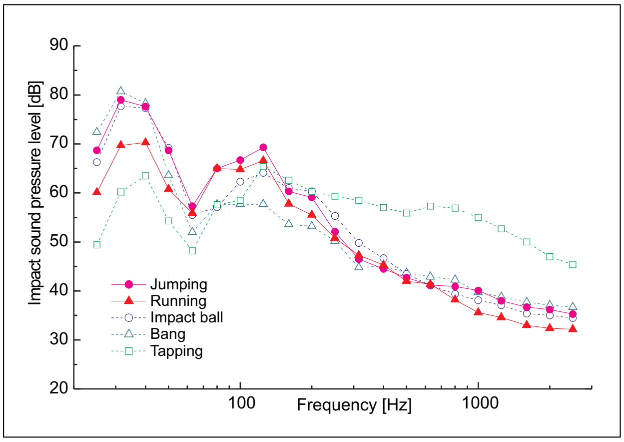

Figure 11. Frequency characteristics of impact sounds generated by a 65-kg adult and by standard impactors.

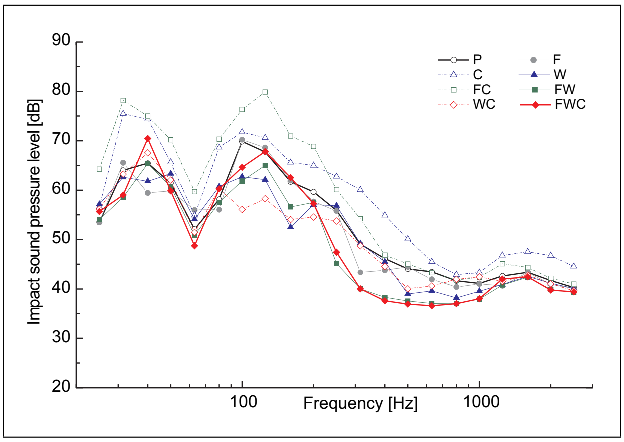

Figure 12. Measured sound level of the impact ball on treated structures.

The frequency characteristics of each of the five different impactors averaged from the eight units are shown in Figure 11. The figure illustrates that the noise of the impact ball is more similar to the adult jumping and running noises than to the child jumping noise (refer to Figure 8). The average $L_{i,Fmax,AW}$ difference of 5 dB between the adult and child jumping noises is due to the weight difference of 40 kg. The impact sound pressure level of the impact ball was higher than that of a child's jumping or running, and lower than that of an adult jumping or running. Therefore, the sound level of the impact ball can be taken as the actual, average impact sound level from tenants in reinforced concrete residential buildings.

Table IV shows the correlation coefficients between the frequency characteristics (L_{max}) of real jumping and running noises and those of the three standard impact sounds for each noise insulation construction. Of the three impact noise sources, the impact ball had the highest average correlation with the real noise. The bang machine had the highest correlation with the real jumping noise in the standard (P) and wall insulation (W) structures. The measured sound levels of the impact ball on treated structures are shown in Figure 12.

Table IV. Correlation coefficients between real impact noise and standard sources ($p < 0.01$). Abbreviations: IB: Impact ball, TM: Tapping machine, BM: Bang machine.

(a) Jumping			
Insulated components	IB	TM	BM
P (Plain)	0.97	0.65	0.97
F (Floor)	0.94	0.49	0.88
C (Ceiling)	0.94	0.36	0.94
W (Wall)	0.97	0.52	0.98
FC	0.97	0.70	0.95
FW	0.98	0.62	0.94
WC	0.98	0.57	0.93
FWC	0.97	0.72	0.93
Overall	0.97	0.58	0.94
(b) Running			
Insulated components	IB	TM	BM
P (Plain)	0.97	0.75	0.93
F (Floor)	0.95	0.61	0.81
C (Ceiling)	0.93	0.51	0.92
W (Wall)	0.96	0.56	0.91
FC	0.97	0.69	0.92
FW	0.95	0.55	0.94
WC	0.96	0.55	0.87
FWC	0.95	0.76	0.90
Overall	0.96	0.62	0.90

4.2. Auditory perception test

To select the best evaluation method for the impact ball, relationships between subjective responses and physical values such as '*Arithmetic Mean*' (the mean value of octave band sound pressure level), L_{Amax}, Inverse-A and Zwicker's loudness of the standard impact sources were analyzed.

Experiments were performed in a testing booth with approximately 25 dBA of background noise. An electrostatic headphone (STAX SRX-3030) was used for the binaural hearing. The noise source through the standard structure (P) was used as the standard stimulus, and 47 comparison stimuli were obtained from the treated (insulated) floor structures. Both standard and comparison stimuli were 1.6 seconds each and presented in random order. Subjective loudness was evaluated by pair on a five scale score. If the first stimulus was louder or much louder than the second stimulus, subjects marked +1 or +2, respectively, and marked 0 if the first and second stimuli were the same. If the second stimulus was louder or much louder than the first stimulus, subjects marked −1 or −2, respectively. Thirty subjects participated in the experiment. The subjects consisted of undergraduate and graduate students.

Table V shows the relationship between subjective responses and physical measurements. The R^2 value of L_{Amax} with the impact ball was 0.70. The R^2 value of the *Arithmetic Mean* was 0.57. L_{Amax} had a stronger correlation with the subjective response than the other indices.

The relationship between subjective response and Inverse-A ($L_{i,Fmax,AW}$) was 0.69.

Table V also shows the calculated relationship between Zwicker's loudness and the subjective responses, with an R^2 value of 0.74. The relationship between Zwicker's percentile loudness N_{10} [24] and subjective responses was 0.77. Therefore, the evaluation method best related to subjective responses is N_{10} for the standard impactors. Tachibana [25] made the same conclusion in his subjective evaluation of major noise sources. Although the values of Zwicker's loudness for the impact ball are highly correlated with the subjective responses, Zwicker's psychoacoustic parameters are difficult to determine because of the equipment needed and the calculation methods used. Therefore, it is better to use measures such as L_{Amax} or $L_{i,Fmax,AW}$.

The relationship between the subjective evaluation and physical measurements of the tapping noise is also shown in Table V indicating that the standard tapping machine produces better correlation due to the steady-state aspect of the tapping machine noise. The R^2 value of $L'_{n,w} + C_{I,63-2000}$ was 0.73 and the R^2 value of the *Arithmetic Mean* was 0.84. The R^2 value for the relationship between subjective response and Inverse-A ($L'_{n,AW}$) was 0.79, for Zwicker's loudness, 0.84, and for N_{10}, 0.88. Rindel and Rasmussen [26] indicated that $L'_{n,w} + C_{I,50-2500}$ calculated by ISO 717-2 (1996) [27] is highly correlated with subjective responses for timber joist floors and for concrete floors with soft and hard floorings. However, unlike European floor structures, the arithmetic mean and the Inverse-A ($L'_{n,AW}$) values are more highly correlated with subjective responses in composite floor structures with floor heating systems.

5. Classes of floor impact sound using the impact ball

5.1. On-site auditory experiment

The purpose of the on-site experiment was to acquire a rating for the impact ball noise level according to the annoyance felt by subjects in a real life situation. Along with the impact ball, the tapping machine, bang machine, and an adult jumping were added as noise sources.

Auditory experiments were conducted with 98 subjects in a living room of a multi-story residential building. Three questionnaire forms were used for the evaluation of the floor impact sound [28]. As shown in Table VI, the floor impact sound was evaluated according to its 'audibility' (Evaluation Scale 1), 'disturbance' (Evaluation Scale 2) and 'amenity' (Evaluation Scale 3). These three aspects of noise perception seem to affect people's annoyance with residential noises.

The values for the subjective evaluation were divided into three groups (1–3, 4–6, 7–9) to help reduce the subjects' difficulty in determining the points on the scale. In addition, after careful consideration of the groups' borders, the annoyance limit at which the noise became bothersome to people was intentionally set as Evaluation Point 4.

Table V. Relationship between subjective responses and physical measurements. Abbreviations: IB: Impact ball, TM: Tapping machine.

	IB (R^2)	TM (R^2)
Arithmetic mean	0.57	0.84
L_{Amax}	0.70	–
Inverse-A	0.69	0.79
$L'_{n,W} + C_{I,63-2000}$	–	0.73
Loudness	0.74	0.84
Percentile loudness N_{10}	0.77	0.88

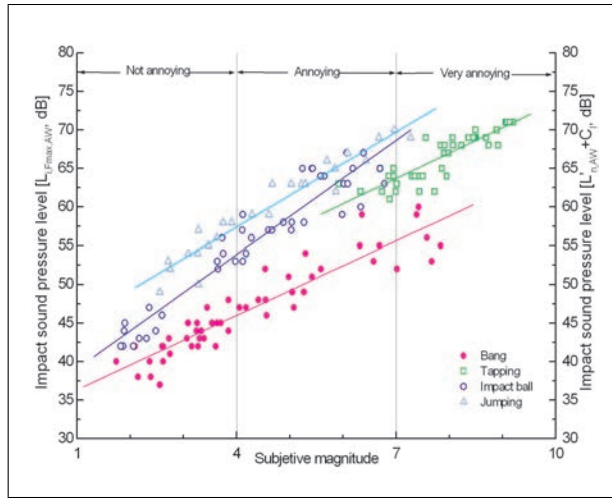

Figure 13. Relationship between floor impact sound and subjective score.

For on-site auditory experiments, the impact ball and tire were dropped from various heights. The tapping noise level was varied by changing floor materials. Subjects recorded their responses to the three questionnaire sheets while on the floor directly below the impact locations. The distribution and regression analyses of the floor impact sound levels ($L_{i,Fmax,AW}$ and $L'_{n,W} + C_i$) corresponding to the average subjective responses were investigated.

The subjective evaluation resulted in a linear relationship between the subjects' responses and the floor impact sound level. The classes of floor impact sound levels according to subjective responses are shown in Table VI; the value of Evaluation Point 4 for the impact ball noise was 54 dB.

The relationship between the floor impact sound levels and the subjective evaluation scores are shown in Figure 13. The perceived floor impact sound level of a jumping adult is about 3 dB lower than the impact ball noise, and more than 10 dB lower than the bang machine noise.

The just noticeable differences (JNDs, minimum perceived noise levels) of the impact ball were investigated to evaluate the appropriate levels for floor impact sound classification. The auditory experiments were conducted using a pair comparison method of 10 postgraduate students in their late twenties. The sound pressure level of the stan-

Table VI. Impact sound pressure levels ($L_{i,Fmax,AW}$) vs. subjective scores.

Annoyance Group	Subjective Score	Scale 1 Noisiness	Scale 2 Disturbance	Scale 3 Amenity	$L_{i,Fmax,AW}$ (dB)
	1	Hardly perceivable	At ease	Excellent	40
Not annoying	2	Far-off noise	Not affected	Very fine	44
	3	Unconcerned	Undisturbed	Good	49
	4	Slightly heard	Detectable	Controllable	54
Annoying	5	Heard	Noticeable	Endurable	59
	6	Clearly heard	Discernable	Yielding	64
	7	Noisy	Obvious	Unbearable	69
Very annoying	8	Very noisy	Undoubted	Intolerable	74
	9	Extremely noisy	Serious	Let's move OUT!	79

Table VII. Classes of floor impact sound.

Impact ball ($L_{i,Fmax,AW}$)	Class 1	44 ≤ Class 2	49 ≤ Class 3
	< 44 dB	< 49 dB	< 54 dB

dard stimulus was increased by 1 dB increments, starting from 2 dB up to 5 dB. The subjects listened through headsets and judged the higher floor impact sound level within a test chamber.

The duration of the sound source was 0.8 s with an inter-stimulus interval of 1 s. The stimuli were presented randomly to the subjects. It was found that the JNDs of the sound generated by the impact ball and tapping machine were about 2 dB. Eighty-six percent of the respondents recognized this 2 dB difference for the impact ball and eighty-nine percent recognized it in the tapping noise.

5.2. Criteria of floor impact sound

Although the limen of the impact ball noise was found to be about 3 dB among the respondents, subjective responses to the three different evaluation scales showed, on an average, a 5 dB level difference between evaluation classes. Rindel [29, 30] also suggested 5 dB as the level difference for rating floor impact noise. In order to aid the tenants' understanding of the impact sound classes, an attempt was made to clarify the meaning of VDI 4100 classifications such as CAC (Classes of Acoustical Comfort) [31].

The meaning of 'annoyance limit' must be recognized as a starting point for annoyance and so used as a guideline for allowable limits. Table VII shows the proposed classes for floor impact sound levels generated with an impact ball. In this table, noise levels lower than 44 dB are classified as 'Class 1'. 'Class 2' noise levels are lower than 49 dB, and 'Class 3' noise levels are lower than 54 dB.

6. Discussion and conclusions

Of the three standard impact sources, the frequency characteristics of the impact ball noise were found to be the most similar to real impact sounds in a multi-story residential building. The impact ball noise was subjectively evaluated as being more similar to jumping noise than to the bang machine noise. Both the impact ball and jumping have higher noise levels in the 125 Hz band than the bang machine. The overall noise level of the adult jumping was slightly higher than that of the bang machine or the impact ball [20], whereas a jumping child produced noise that was 5 dB lower than the standard impactors.

The impact ball has the widest physical and subjective evaluation ranges among the three standard impactors, indicating that it should be the one used for evaluating the performance of reinforced concrete floor structures with different floor treatment. Correlation analyses between the subjective responses and physical measurements showed that the subjective responses to the impact ball correlated well with $L_{i,Fmax,AW}$, whereas the impact ball noise had higher correlation with Zwicker's loudness.

Measurement results of the frequency characteristics for the three standard and the real impact sources in RC residential buildings demonstrated that noise from the impact ball was most similar to the noise of children jumping and running. Floor sounds generated with a bang machine have different characteristics because the impact force of a bang machine is much greater than that of a real source. The method for measuring floor impact sounds where the impact ball was the only source, and an evaluation method using inverse-A weighted floor impact sound pressure level ($L_{i,Fmax,AW}$), were both highly correlated with subjective responses.

The allowable sound pressure level of the impact ball, based on subjective evaluations in both the laboratory and in-situ conditions, was 54 dB ($L_{i,Fmax,AW}$). Three classes of impact ball noise were set up with 5 dB differences between grades. Still, the clarity and understandability of the impact ball noise questionnaire could be improved. This will be a part of a future work.

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