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Correlation Between Single-Number-Quantities of Impact Sound Insulation and Various Noise Ratings of Walking on Concrete Floors

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Summary

The aim of this study was to investigate whether the low frequency range of 50–100 Hz should be taken into account when impact sound insulation of concrete floors is determined. Another aim was to determine the correlation between objective noise ratings of walking noise and single-number-quantities (SNQs) based on sound spectra produced by the tapping machine. Impact sound pressure levels (SPL) generated by the tapping machine on an uncovered concrete slab and on the same slab covered with eight floor coverings were measured. For each of these nine structures, eight various SNQs were calculated. The SPLs generated by three walkers wearing socks, soft-heeled shoes and hard-heeled shoes were also measured as well as noise generated by chair moving and super ball bouncing. These sounds were objectively evaluated by three noise ratings: equivalent A-weighted SPL, $L_{A,eq}$, maximum A-weighted SPL, $L_{A,F,max}$, and loudness level, L_N. At frequency bands below 100 Hz, walking with socks generated higher linear SPLs than those generated by walking with hard-heeled or soft-heeled shoes. Walking on floating floors installed on the concrete slab also generated high SPLs in the low frequency range. The noise ratings of walking with hard-heeled shoes and chair moving correlated strongly with the SNQs based on the tapping machine. However, no statistically significant correlation between the noise ratings of walking with socks and the SNQs was detected. This indicates that there is a need for a new objective SNQ in order to improve the correlation between the different walking sounds and objective rating of the concrete floors.

PACS no. 43.55.-n

1. Introduction

Requirements for a single-number-quantity (SNQ) describing impact sound insulation of floors in residential dwellings were defined in 1949 by Gösele [1]. His definition required that the SNQ should be based on an objective sound source and measurement equipment, but the results determined by the objective method should correspond as well as possible to the occupants' subjective experience of sounds related to walking on a floor. Furthermore, the measurement result of two floors should be similar if these floors were subjectively judged similar.

The first attempts to connect impact sound insulation of floors to subjective experience of transmitted impact sounds were done in the late 1950's [2, 3], but research dealing with this question became more active after the international standardization of the tapping machine in 1960. The tapping machine was criticized soon after its standardization, because its loudness and sound spectra were considered to differ too much from the sound generated by walking [4, 5, 6]. It was also shown that no such a constant or formula can be derived that could in all situations be used to calculate the walking spectrum from the spectrum generated by the tapping machine [7].

After the standardization of the tapping machine, there have been several ways of approaching the relation of the subjective experience of impact sounds and objective SNQs of impact sound insulation. A first approach is replacing the standard tapping machine with a new sound source such as a rubber ball [8, 9]. Even though the international standards [10, 11] now allow the use of the rubber ball in laboratory measurements, it seems obvious that the unmodified standard tapping machine will still remain as the official impact sound source in Europe [12].

A second approach in finding the correlation between the objective SNQs of impact sound insulation and the subjective rating of walking sounds is to carry out listening experiments where recorded walking sounds are evaluated by a group of test persons [13, 14, 15, 16, 17, 18]. A third approach is trying to find a correlation between objective SNQs and subjective evaluation based on questionnaires or

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interviews *in situ* [19, 20, 21]. Finally, a fourth approach is finding the correlation of the objective SNQs with noise ratings like the equivalent A-weighted sound pressure levels (SPL), $L_{A,eq}$, the maximum A-weighted SPL $L_{A,F,max}$, loudness or loudness level [22, 23, 24, 25, 26]. In references [13]–[17], a detailed description of the tested floors was not always included or the derivation of the noise ratings describing the walking sounds has not been thoroughly reported. Due to the lack of information on the sound spectra generated by walking on different floors, the reasons for the subjective ranking of the floors are not necessarily clear.

Impact sounds in residential dwellings cover several sound sources like moving the furniture, playing children, falling objects and walking. The impact sound spectrum excited by walking depends on several factors including the floor structure, the personal walking style and the footwear. In most of the previous studies, the impact sounds have been produced by a test person using shoes. In many cases, the test persons have worn hard heeled shoes as they have been considered to be the worst case [6, 7, 15, 22, 23, 24, 27, 28, 29]. In many countries, for example in Finland and in other Nordic countries, occupants do not usually wear shoes at home. In some recent publications dealing with wooden floor structures, there are also results achieved by using impact sound spectra from walking with socks [13, 14, 18, 21].

An important question related to the sound spectrum of impact sounds and the rating of impact sound insulation is the frequency range to be measured. Enlarging the lower limiting frequency band from 100 Hz to 50 Hz was considered already in the 1960's on the basis of studies dealing with concrete structures [6]. In later studies, the necessity of doing measurements below 100 Hz has concerned especially wooden floors [13, 14, 19, 24, 25]. The recent European research has also focused on the impact sound insulation of wooden floors and on low-frequency sounds generated by walking on them [18, 21, 30]. Wooden floors often include a floating floor which improves impact sound insulation significantly at high frequencies.

There are some results implicating that the consideration of impact SPLs below 100 Hz should be done also in the case of concrete floors. Such reported cases include walking on floating floors [7, 22, 31, 32, 33], constructed on the bearing concrete slab. Currently, a vast majority of European dwellings are constructed of concrete or other massive structures [34]. The volume of concrete structures in housing stock and earlier reported flaws in low-frequency impact sound insulation of concrete floors [7, 22, 31, 32, 33] make them a relevant research topic, especially because of the lack of knowledge related to the sound generated by walking with different footwear on a wide scale of present-day floor coverings and floating floors installed on concrete floors.

The aim of this study was to investigate whether the low frequency range 50–100 Hz should be taken into account when impact sound insulation of concrete floors is determined. Another aim was to define the correlation between objective noise ratings of walking and single-number-quantities (SNQs) of impact sound insulation based on the tapping machine. The study was carried out using a wide range of floor coverings in order to cover the most typical impact sound insulation spectra found in dwellings.

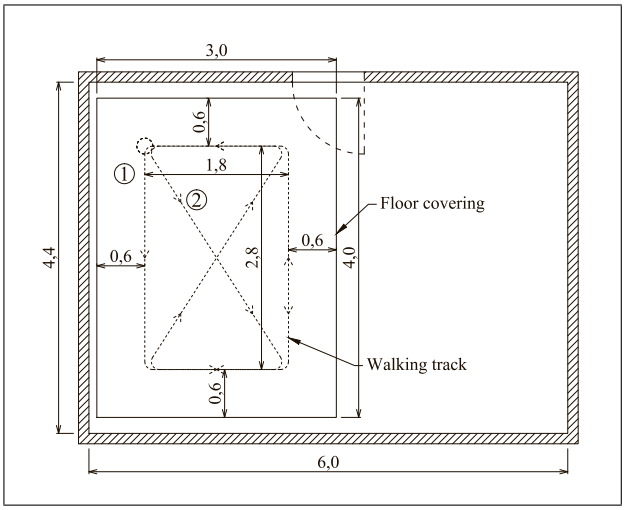


Figure 1. Placement of the floor coverings and walking track in the source room of the laboratory.

2. Materials and methods

2.1. Testing laboratory

The impact sound measurements were carried out at Upofloor laboratory in Nokia, Finland, where the bearing structure of the floor separating the vertically adjacent source and receiving rooms is a 265 mm thick concrete hollow core slab (400 kg/m^2). It was the most usual prefabricated slab type in Finnish apartment buildings during the 1980's and 1990's [35]. The width and length of the source room were 4,4 m and 6,0 m. The floor area of the receiving room beneath the source room was 24 m^2 and its volume was 60 m^3. There were no diffusors in the receiving room. Measured reverberation times of the receiving room (Table I) corresponded well with those of typical furnished rooms in Finnish dwellings [36]. Therefore, the sound spectra measured in the receiving room correspond well with the typical spectra in residential dwellings.

In the laboratory, all the floor coverings were installed in the same place on the slab. The size of the floor covering was 3,0 × 4,0 m^2 (Figure 1). The floor coverings were installed as carefully as possible in order to avoid the effects of workmanship on the deviation of measured SPLs.

2.2. Measured structures

The study was carried out using a wide range of floor coverings in order to cover the typical impact sound insulation spectra found in dwellings. Eight different floor coverings on the bearing slab were used (Table II). One measurement was also carried out without floor covering (F1). In a laboratory test series, when floor coverings have to be

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Table I. Measured reverberation times in the receiving room at octave bands.

Octave band	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Reverberation time	1,3 s	0,4 s	0,4 s	0,4 s	0,4 s	0,5 s	0,4 s

Table II. Structural layers of the floor coverings denoted with letter F and a number 1–9.

	Structural layers of floor covering
F1	No covering
F2	Cushion vinyl, $\Delta L_w = 2$ dB
F3	Cushion vinyl, $\Delta L_w = 21$ dB
F4	Multilayer parquet 14 mm Soft underlay, $\Delta L_w = 20$ dB
F5	Wall-to-wall carpet, $\Delta L_w = 21$ dB
F6	Wall-to-wall carpet, $\Delta L_w = 37$ dB
F7	Multilayer parquet 14 mm Soft underlay 2 x plasterboard 15 mm (30 kg/m^2) Mineral wool 13 mm, $s' = 16{,}1$ MN/m^3
F8	Multilayer parquet 14 mm Soft underlay 2 x plasterboard 15 mm (30 kg/m^2) Mineral wool 50 mm, $s' = 11{,}5$ MN/m^3
F9	Multilayer parquet 14 mm Soft underlay 4 x plasterboard 15 mm (60 kg/m^2) Mineral wool 50 mm $s' = 11{,}5$ MN/m^3

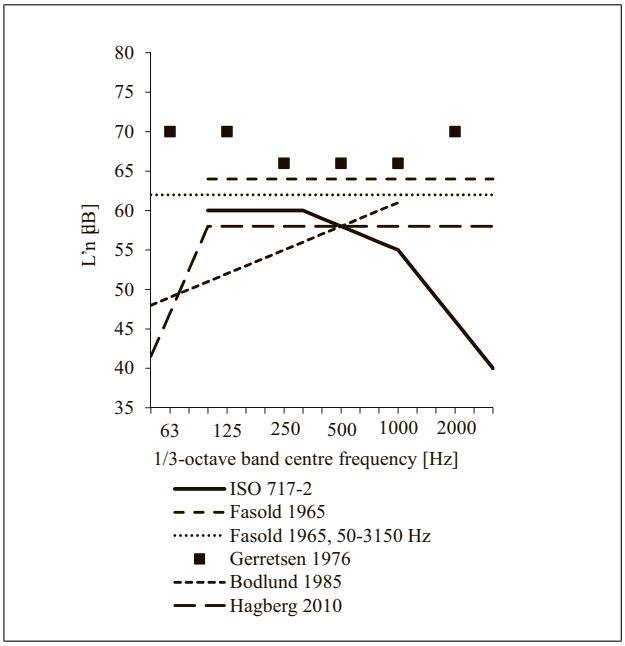


Figure 2. The reference curves used in calculation of the standardized (ISO 717-2) and the suggested SNQs, shown by the other curves.

quickly changeable, it was not possible to use cast concrete or cement screed as floating layers of floating floors. Thus, floating layers were constructed of varying number of plasterboards and mineral wool layers with varying thicknesses in order to compose structures having different resonance frequencies at the frequency range below 100 Hz. Cushion vinyls and multi-layer parquets were used in order to achieve resonance frequency around 400–500 Hz. Also very hard cushion vinyl and very soft floor-to-floor carpet were used.

The weighted reductions in impact sound pressure level ΔL_w shown in Table II were defined according to standard ISO 717-2 [37]. The dynamic stiffnesses s' of the insulation layers of the floating floors were measured according to standard ISO 9052-1 [38].

2.3. Single-number-quantities based on tapping machine

The measurements were done according to the field measurement standard ISO 140-7 [39] as the laboratory constructed in the 1980s did not fulfil the present requirements for the laboratories in all respects. There were four fixed tapping machine positions on the floor of the source room and the sound generated by the tapping machine was measured in four fixed microphone positions. Two corner positions for loudspeakers were used in the reverberation time measurements. The number of the fixed microphone positions was four per each loudspeaker position. In each position, two decays were measured. The normalized impact SPLs L'_n were calculated from the spatial averages of 16 impact SPL measurements and 16 reverberation time measurements.

The standardized SNQs were determined on the basis of the normalized impact sound pressure levels L'_n. The weighted normalized impact sound pressure levels $L'_{n,w}$ as well as the sum of $L'_{n,w}$ and spectrum adaptation terms C_I and $C_{I,50-2500}$ were calculated according to the standard ISO 717-2 [37].

In addition to the standardized SNQs, four suggested SNQs were calculated. Reference curves defined by Fasold [6], Gerretsen [28], Bodlund [19] and Hagberg [20] were used (Figure 2). The SNQs are denoted by $L'_{n,Fas}$, $L'_{n,Ger}$, $L'_{n,Bod}$ and $L'_{n,Hag}$, respectively. As the SNQ presented by Fasold can be calculated from the measured L'n at frequency range 100–3150 Hz or 50–3150 Hz, the lower limit of the frequency range is indicated for $L'_{n,Fas}$. In the calculation of each SNQ, the maximum allowable sum of unfavourable deviations from the reference curve has been 32 dB, as it was shown in 1985 that changing the evaluation rule by varying the sum of unfavourable deviations does not have a significant effect on the rating of the floors [19]. In order to achieve a more precise understanding of the correlation between the SNQs based on the tapping machine and the SNQs based on walking, the principles of reference [40] were followed and all SNQs were defined by moving the reference curve in steps of 0,1 dB.

2.4. Noise rating of impact sounds

Each of three male walkers W1, W2 and W3 (Table III) wore socks, soft-heeled shoes and hard-heeled shoes. The

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Table III. Description of the walkers. The shoe sizes correspond to the European measures.

Walker	Age	Mass	Height	Shoe size
W1	22	86 kg	188 cm	46
W2	40	125 kg	191 cm	44
W3	23	91 kg	183 cm	42

Table IV. Mean value, standard deviation and maximum deviation of $L_{A,eq}$ [dB] of the repeated walkings on floor F1 by all three walkers wearing soft-heeled shoes.

Walker	M	STD	MD
W1	21,4	0,5	1,3
W2	15,0	0,4	1,3
W3	19,4	0,6	1,0

same footwear was used through the test series. Each walker walked along a rectangular and an hourglass-shaped track on each floor covering (Figure 1). The SPLs were recorded in the receiving room at two microphone positions as a function of time with time weighting FAST. The measurement and walking duration was 40 seconds in all cases. The measured frequency range was 20–20000 Hz. All walkings were performed twice.

Before calculating the noise ratings, the measured walking SPLs were background-noise corrected. Equivalent level of A-weighted background noise $L_{A,eq}$ was 17–18 dB. At 50 Hz, the background noise level was 20–25 dB which was well below the measured impact sounds. At highest frequency range, the measured sound consisted in many cases of background noise only. The situation was such especially in the case of walking with socks and walking on floating floors and on softer wall-to-wall carpet.

Background-noise corrected time-varying walking sounds were objectively rated by three noise ratings: equivalent A-weighted SPL $L_{A,eq}$, calculated over the 40 s measurement period, maximum A-weighted SPL $L_{A,F,max}$, and loudness level L_N. Similar noise ratings have been used in evaluation of walking sounds [22, 23, 24, 25, 26], even though the derivation of the rating from walking sounds may differ from the procedure presented here.

It is usually expected that the experienced loudness of a time-varying sound is determined by the loudest momentary spectrum [41, 42, 43]. However, both $L_{A,F,max}$ and L_N vary frequently over relatively long time as each step generates a sound slightly different from other steps (Figure 3). For this reason, the momentary maximum spectra were selected from the time-varying sound pressure by calculating both $L_{A,F}(t)$ and $L_N(t)$ of the walking sound as functions of time. Depending on the walker, typical number of maxima was 50–60 per each recording.

Plotting the spectra of all momentary maxima of two repeated walks recorded in two measurement positions resulted in a sample of spectra based on either maximum A-weighted SPLs (Figure 4) or loudness levels. The sam-

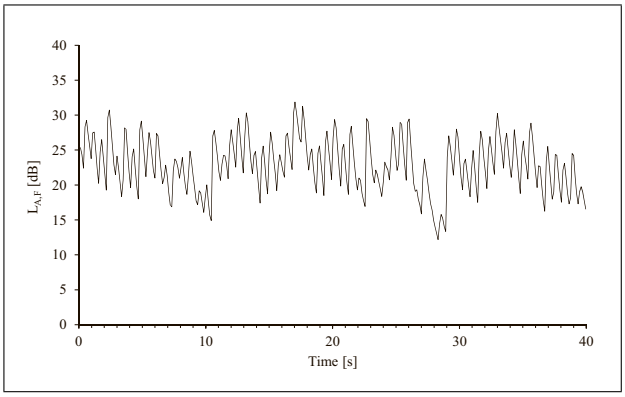


Figure 3. An example of the variation of the LA,F generated by walker W1 wearing socks walking on floor F4. Each peak represents a momentary maximum (an individual step).

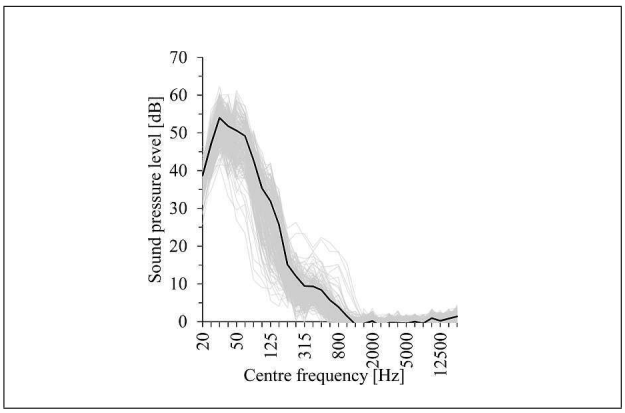


Figure 4. Examples of the spectra of momentary maxima of $L_{A,F}(t)$ described in Figure 3. The energetic average $L_{A,F,max}$ representing a typical step sound is shown with black line.

ple size consisted typically of 200–250 momentary maxima. From these maxima, the typical spectra of each walking were calculated as energetic averages of the sample of the spectra. The results, i.e., $L_{A,F,max}$ and L_N, were then calculated from these energetic averages. The calculation of loudness level $L_N(t)$ was carried out according to standard ANSI S3.4-2007 [44], which includes the loudness model by Moore and Glasberg [45, 46] being the newest standardized model. The loudness levels were calculated on the basis of the SPLs at 1/3-octave bands in frequency range from 50 Hz to 16000 Hz according to the standard.

There are several sources of impact sounds in dwellings like jumping, moving the furniture, falling objects or children playing. In addition to walking, two other impact sounds were studied here. The first represented one possible sound spectra caused by playing children: a so called superball (weight 45 g) was thrown towards the floor at the center point of the floor covering. The bouncing was repeated so that the ball was turned back towards the floor from the same height (1 meter). Also the sound produced by moving a wooden chair was measured. The sound was generated as follows: first, a walker pulled the chair away from a table, then the person moved to the front of the chair and moved it towards the table, sat down on the chair,

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Table V. The standardized and suggested SNQs [dB] of the nine floors F1…F9 based on the tapping machine.

SNQ	F1	F2	F3	F4	F5	F6	F7	F8	F9
$L'_{n,w}$	79,9	77,7	58,7	59,1	58,5	42,7	50,1	43,2	41,3
$L'_{n,w} + C_I$	66,7	65,8	58,0	59,0	58,0	44,7	53,0	45,0	42,1
$L'_{n,w} + C_{I,50-2500}$	66,7	65,8	58,1	59,1	58,1	47,3	55,9	52,4	47,6
$L'_{n,Fas}$	68,4	67,3	59,4	60,4	59,4	44,7	52,1	45,2	43,0
$L'_{n,Fas,50}$	68,4	67,3	59,4	60,4	59,4	49,0	55,6	52,2	47,8
$L'_{n,Ger}$	66,4	65,6	58,4	59,8	58,6	41,9	50,3	43,6	41,5
$L'_{n,Bod}$	66,0	65,9	62,6	63,9	62,8	56,5	62,8	59,8	55,3
$L'_{n,Hag}$	68,7	67,8	60,7	61,8	60,5	54,5	61,2	61,0	56,1

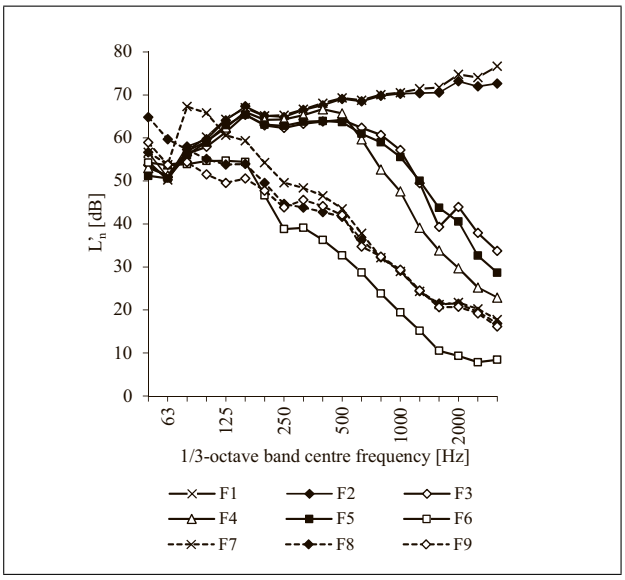


Figure 5. Normalized impact SPLs L'n produced by the tapping machine placed on the nine floors.

stood up, pushed the chair away from the table and finally pushed the chair back under the table. In both cases, the measurement procedure was similar to the measurement of walking sounds. Floor F6 (wall-to-wall carpet for dwellings) was so soft that moving the chair in the way described before was impossible, and thus it was not measured.

With floors F4 and F8 three more impact sound sources were tested: vacuum cleaning, falling of knife from a table and female walker. The results from measurements of these sound sources are not included here for following reasons: vacuum cleaning appeared to be the most quiet of all sounds, and, thus, is obviously not a significant sound source; falling knife generated sound spectra similar to chair moving; the shape of the spectra generated by the female walker was similar to the male walkers, and loudness of the female walker was inside the range of the sounds generated by the male walkers. These test were carried out in order to study whether these three sound sources generate spectra significantly different from the other impact sound sources described earlier, but that was not the case.

2.5. Correlation between single-number quantities

The correlation between the noise ratings and the different SNQs based on the tapping machine (see Table VII) were studied by calculating the squared Pearson product-moment correlation coefficients, i.e., the coefficients of determination r^2 for all combinations of sound sources, footwear and floors.

2.6. Repeatability of walking sounds

In order to ensure that the walking of each walker remained similar during the test period of one month, walking with soft-heeled shoes on the first test floor F1 was repeated by all three walkers on six days. On each day, the walking was repeated twice so that there was an interval of 5–10 minutes between the first and the second walk. The procedure described in chapter 2.3 was followed in the measurements. The mean value (M), standard deviation (STD) and maximum deviation (MD) of $L_{A,eq}$ of the 12 walks are shown in Table IV (cf. page 978).

3. Results

3.1. The tapping machine

The normalized impact SPLs generated by the tapping machine on the nine floors are shown in Figure 5. The SNQs calculated from them are given in Table V. The range of investigated impact sound pressure levels cover well the typical range found in buildings.

3.2. Noise ratings of walking and other impact sound sources

The mean spectra of walking based on the energetic averages of the momentary maxima of the time-varying $L_{A,F,max}$ are shown in Figure 6. Similar curves could be drawn for $L_{A,eq}$ and for the momentary maxima of the time-varying loudness level L_N. These noise ratings based on these curves are given in Table VI.

The noise ratings of the superball bouncing and the chair moving are also given in Table VI. The corresponding energetic averages of momentary maxima of time-varying A-weighted SPL are shown in Figure 7.

3.3. Correlation between noise ratings and SNQs based on the tapping machine

The calculated coefficients of determination r^2 between the noise ratings (Table VI) and the SNQs based on the tapping machine and the reference curves (Table V) are given in Table VII. The sample size was 9 which means

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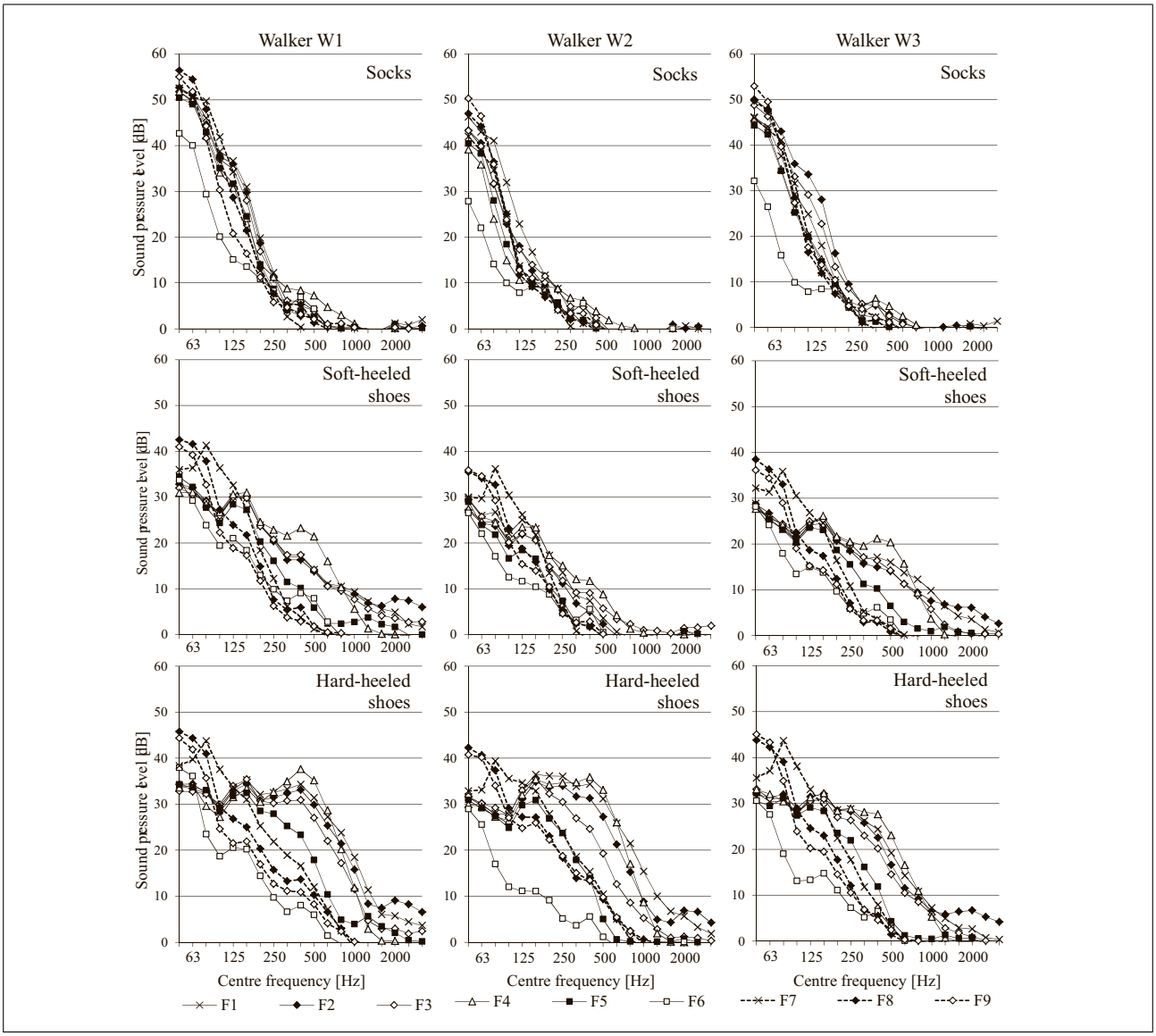


Figure 6. Energetic averages of walking sound spectra based on momentary maxima of $L_{A,F}(t)$ during 40 s.

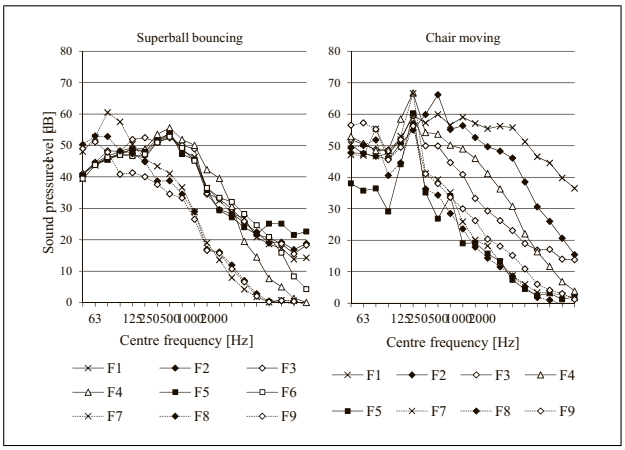


Figure 7. Energetic averages of sound spectra of ball bouncing and chair moving based on momentary maxima of $L_{A,F}(t)$ during 40 s.

that r^2 values exceeding 0,34 have a significance level of $p < 0,05$ and r^2 values exceeding 0,56 have a significance level of $p < 0,01$.

4. Discussion

4.1. Sound spectra of walking on concrete floors

Walking with socks generated the highest SPLs below 200 Hz. Walking with hard-heeled or soft-heeled shoes also generated highest SPLs below 100 Hz, but hard-heeled shoes generated SPLs exceeding typical background noise levels of Finnish dwellings [47] at frequency bands from 200 Hz to 1000 Hz as well (Figure 8). Below 100 Hz, the walking levels correspond to the levels measured by other researchers from walking on wooden floors [22, 24, 43]. This means that low-frequency walking sounds are not prevalent only with wooden floors but they are also present with concrete floors.

In most Finnish dwellings, the background SPLs generated by HVAC systems are below 38 dB at 50 Hz and

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Table VI. Noise ratings determined for the various impact sound sources for the nine floors F1…F9.

Walker	SNQ	F1	F2	F3	F4	F5	F6	F7	F8	F9
	$L_{A,eq}$ [dB]	27,8	27,7	26,6	26,1	25,6	18,9	28,5	30,1	27,7
W1, socks	$L_{A,F,max}$ [dB]	30,6	30,2	29,3	28,5	28,1	21,1	31,4	32,6	30,2
	L_N [phon]	31,3	30,3	28,4	27,3	26,4	15,8	29,4	29,5	25,3
	$L_{A,eq}$ [dB]	18,1	18,1	18,0	16,0	16,4	12,7	17,3	20,8	23,3
W2, socks	$L_{A,F,max}$ [dB]	20,4	20,4	20,4	17,6	18,4	13,4	19,6	23,3	25,8
	L_N [phon]	16,0	16,8	15,5	13,9	13,7	13,1	14,3	17,5	19,4
	$L_{A,eq}$ [dB]	21,3	25,1	23,6	20,4	19,7	13,8	21,5	23,6	25,7
W3, socks	$L_{A,F,max}$ [dB]	23,6	27,8	25,9	22,8	21,9	15,1	24,0	26,0	28,2
	L_N [phon]	21,5	27,2	23,9	17,8	17,1	13,1	19,6	20,6	22,3
	$L_{A,eq}$ [dB]	21,3	21,2	20,9	22,7	19,4	16,4	21,3	20,5	20,2
W1, softheeled shoes	$L_{A,F,max}$ [dB]	23,7	23,8	23,4	25,8	21,1	17,7	24,0	22,3	21,4
	L_N [phon]	32,7	34,4	32,2	35,0	23,8	17,2	23,8	19,5	16,6
	$L_{A,eq}$ [dB]	14,6	13,5	14,4	15,3	12,7	12,1	15,8	14,9	14,7
W2, softheeled shoes	$L_{A,F,max}$ [dB]	16,9	15,3	16,5	17,5	13,7	12,7	18,7	16,4	15,9
	L_N [phon]	17,4	14,9	19,3	20,3	13,3	12,8	17,0	13,8	12,3
	$L_{A,eq}$ [dB]	19,0	18,3	18,5	20,1	15,9	13,1	17,4	16,4	16,2
W3, softheeled shoes	$L_{A,F,max}$ [dB]	21,9	21,2	21,2	23,4	17,8	13,9	19,5	17,9	17,4
	L_N [phon]	30,9	30,4	28,4	31,6	20,1	13,2	18,6	14,6	12,8
	$L_{A,eq}$ [dB]	31,0	29,9	27,9	32,9	23,9	17,9	23,9	23,0	21,8
W1, hardheeled shoes	$L_{A,F,max}$ [dB]	35,2	33,9	32,0	37,2	27,2	19,3	26,8	25,0	23,4
	L_N [phon]	49,7	48,4	44,6	49,0	36,0	17,3	31,7	27,0	23,6
	$L_{A,eq}$ [dB]	30,7	27,9	24,5	31,1	19,1	13,0	21,8	20,2	20,0
W2, hard-heeled shoes	$L_{A,F,max}$ [dB]	35,6	32,8	29,0	36,1	23,0	13,8	25,9	22,7	22,0
	L_N [phon]	49,3	45,5	38,7	47,9	27,3	13,0	31,2	25,9	25,4
	$L_{A,eq}$ [dB]	23,9	23,4	22,2	25,3	19,0	13,9	22,6	20,8	21,5
W3, hard-heeled shoes	$L_{A,F,max}$ [dB]	27,4	27,0	25,2	28,9	21,7	14,9	25,6	22,7	23,1
	L_N [phon]	37,5	38,0	33,5	39,1	25,2	13,5	27,0	21,0	19,6
	$L_{A,eq}$ [dB]	42,5	42,2	43,1	44,8	42,4	42,6	37,9	33,2	29,0
Superball bouncing	$L_{A,F,max}$ [dB]	49,0	49,2	50,0	52,0	48,9	48,8	43,6	39,0	35,1
	L_N [phon]	64,2	65,3	66,5	64,7	66,2	63,7	52,6	49,3	45,3
	$L_{A,eq}$ [dB]	59,8	55,3	44,5	52,4	42,8	-	49,3	40,5	40,3
Chair moving	$L_{A,F,max}$ [dB]	63,1	60,6	49,1	55,7	47,0	-	53,5	44,2	44,6
	L_N [phon]	82,5	76,3	63,6	69,0	51,3	-	58,1	49,6	54,6

below 32 dB at 100 Hz (Figure 8). Below 100 Hz, most of the measured SPLs generated by walking with socks on all floors were greater than the levels of background noise in typical Finnish dwellings. The excess was 10–15 dB regarding walking with socks on floating floors and 5–10 dB regarding walking with hard-heeled shoes on floating floors. This indicates that walking on concrete floors covered with floating floors is a noticeable source of low-frequency sound. The results presented here are in agreement with earlier results [7, 31, 32] even though the floor structures in the earlier studies have not been reported in detail.

It is noteworthy that walking with socks generated more sound below 100 Hz than walking with shoes. The level difference at the lowest frequency bands typically exceeded 10 dB except in the case of floor F6. It can thus be stated that walking with socks on concrete floors usually generates more sound in the low frequency range than walking with shoes. The result also indicates that walking with socks should be included in future walking tests.

4.2. Noise ratings versus single-number-quantities

In recent studies [13, 14, 18, 21], concrete floors have been excluded or they have been used only as reference material to wooden floors. All floors studied in our research can be considered massive as they had a concrete slab as a bearing structure. The standardized and the suggested SNQs rated the measured floors mostly on the basis of the sounds generated at mid-frequencies by the tapping machine. This frequency range is significant regarding walking with hard-heeled shoes. The values of noise ratings based on walking, however, were often determined by the walking sounds in the low frequency range.

The noise ratings $L_{A,eq}$, $L_{A,F,max}$ and L_N based on the same walker (Table VI) wearing socks were pretty similarly independent of floor structure. The within-walker differences were below 7,3 dB, 7,4 dB and 6,8 phon for $L_{A,eq}$, $L_{A,F,max}$ and L_N, respectively, for floors F1–F9 if floor F6 is ignored. For instance, walker W1 generated a maximum sound level $L_{A,F,max}$ of around 28–30 dB in the case of

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Table VII. Coefficients of determination r^2 between the noise ratings and SNQs based on tapping machine. Values exceeding 0,34 are bolded and values exceeding 0,56 are additionally underlined.

		$L'_{n,w}$	$L'_{n,w}+C_I$	$L'_{n,w}+C_{I,50-2500}$	$L'_{n,Fas}$	$L'_{n,Fas,50}$	$L'_{n,Ger}$	$L'_{n,Bod}$	$L'_{n,Hag}$
W1, socks	$L_{A,eq}$	0,05	0,04	0,14	0,04	0,08	0,05	0,14	0,28
	$L_{A,F,max}$	0,05	0,05	0,15	0,05	0,09	0,06	0,15	0,29
	L_N	0,33	**0,34**	**0,51**	0,33	**0,42**	**0,35**	**0,51**	**0,64**
W2, socks	$L_{A,eq}$	0,02	0,06	0,01	0,04	0,02	0,04	0,04	0,01
	$L_{A,F,max}$	0,01	0,03	0,00	0,02	0,01	0,02	0,01	0,02
	L_N	0,00	0,05	0,01	0,04	0,02	0,04	0,06	0,01
W3, socks	$L_{A,eq}$	0,04	0,02	0,07	0,03	0,04	0,03	0,04	0,15
	$L_{A,F,max}$	0,05	0,03	0,09	0,03	0,05	0,04	0,05	0,17
	L_N	0,26	0,18	0,27	0,19	0,23	0,19	0,17	**0,36**
W1, soft-heeled shoes	$L_{A,eq}$	0,22	0,28	**0,37**	0,28	0,31	0,31	**0,42**	**0,41**
	$L_{A,F,max}$	0,27	**0,37**	**0,45**	**0,36**	**0,38**	**0,39**	**0,52**	**0,45**
	L_N	**0,72**	**0,83**	**0,78**	**0,83**	**0,80**	**0,85**	**0,79**	**0,61**
W2, soft-heeled shoes	$L_{A,eq}$	0,00	0,00	0,02	0,00	0,00	0,00	0,04	0,06
	$L_{A,F,max}$	0,02	0,05	0,10	0,04	0,06	0,04	0,16	0,16
	L_N	0,19	0,33	0,29	0,32	0,29	**0,34**	**0,40**	0,19
W3, soft-heeled shoes	$L_{A,eq}$	**0,42**	**0,50**	**0,56**	**0,51**	**0,51**	**0,54**	**0,57**	**0,52**
	$L_{A,F,max}$	**0,49**	**0,59**	**0,63**	**0,59**	**0,59**	**0,63**	**0,65**	**0,56**
	L_N	**0,76**	**0,85**	**0,80**	**0,86**	**0,82**	**0,87**	**0,76**	**0,62**
W1, hard-heeled shoes	$L_{A,eq}$	**0,63**	**0,70**	**0,72**	**0,72**	**0,71**	**0,74**	**0,70**	**0,63**
	$L_{A,F,max}$	**0,66**	**0,75**	**0,76**	**0,76**	**0,75**	**0,79**	**0,74**	**0,64**
	L_N	**0,77**	**0,86**	**0,86**	**0,88**	**0,86**	**0,90**	**0,82**	**0,70**
W2, hard-heeled shoes	$L_{A,eq}$	**0,60**	**0,62**	**0,68**	**0,63**	**0,65**	**0,65**	**0,63**	**0,66**
	$L_{A,F,max}$	**0,63**	**0,68**	**0,73**	**0,68**	**0,70**	**0,71**	**0,70**	**0,69**
	L_N	**0,70**	**0,73**	**0,78**	**0,74**	**0,76**	**0,76**	**0,72**	**0,72**
W3, hard-heeled shoes	$L_{A,eq}$	0,30	**0,34**	**0,43**	**0,34**	**0,37**	**0,37**	**0,43**	**0,48**
	$L_{A,F,max}$	**0,39**	**0,45**	**0,54**	**0,45**	**0,47**	**0,48**	**0,54**	**0,55**
	L_N	**0,71**	**0,80**	**0,81**	**0,81**	**0,80**	**0,83**	**0,79**	**0,69**
Superball bouncing	$L_{A,eq}$	**0,35**	**0,50**	0,33	**0,49**	**0,40**	**0,48**	**0,41**	**0,14**
	$L_{A,F,max}$	**0,38**	**0,53**	**0,35**	**0,52**	**0,42**	**0,51**	**0,42**	0,15
	L_N	**0,42**	**0,52**	**0,35**	**0,53**	**0,43**	**0,53**	**0,36**	0,14
Chair moving	$L_{A,eq}$	**0,76**	**0,71**	**0,77**	**0,68**	**0,75**	**0,65**	**0,69**	**0,78**
	$L_{A,F,max}$	**0,79**	**0,74**	**0,80**	**0,71**	**0,77**	**0,67**	**0,70**	**0,80**
	L_N	**0,79**	**0,68**	**0,72**	**0,69**	**0,73**	**0,66**	**0,54**	**0,71**

floors F1–F5 and around 30–33 dB in the case of floating floors F7–F9. The range of loudness levels L_N were 26–31 phon and 25–30 phon, respectively. In the case of walkers W2 and W3 wearing socks there were results rating floating floors even louder than floors F1–F5.

In other words, the noise ratings based on walking with socks thus rate the floating floors equal to or louder than the bare concrete floor or floors with a light covering installed directly on the bearing concrete slab. The standardized and suggested SNQs based on the tapping machine, however, rate the best floating floor F9 about 10–38 dB better than the bare floor F1. As walking on floating floors generated more sound at low frequencies than walking on other floors, it can be concluded that low-frequency impact sound insulation of floors is not well included in the standardized [37] or suggested [6, 19, 20, 28] SNQs.

Floor F6 had clearly lower noise rating values than the other floors (Table VI). When the standardized and suggested SNQs (Table V) of floors F6 and F9 are compared with each other, the difference of the same SNQ is 2,6 dB at highest and 0,3 dB at smallest. The SNQs thus rated these two floors almost equal. In the case of walking with socks, floor F6 had 6–12 dB lower $L_{A,eq}$, 9–13 dB lower $L_{A,F,max}$ and 6–10 phon lower L_N than floor F9 had. On the basis of real walking sounds, floor F6 would obviously be a better structure than the objectively best rated floating floor F9. Thus, the ranking order according to the SNQs based on the tapping machine is incorrect in this respect.

4.3. Correlation between noise ratings and SNQs based on the tapping machine

Table VII describes the coefficients of determination r^2 between the SNQs based on the tapping machine and noise ratings of walking and other impact sound sources. The correlation coefficients might give an impression that the

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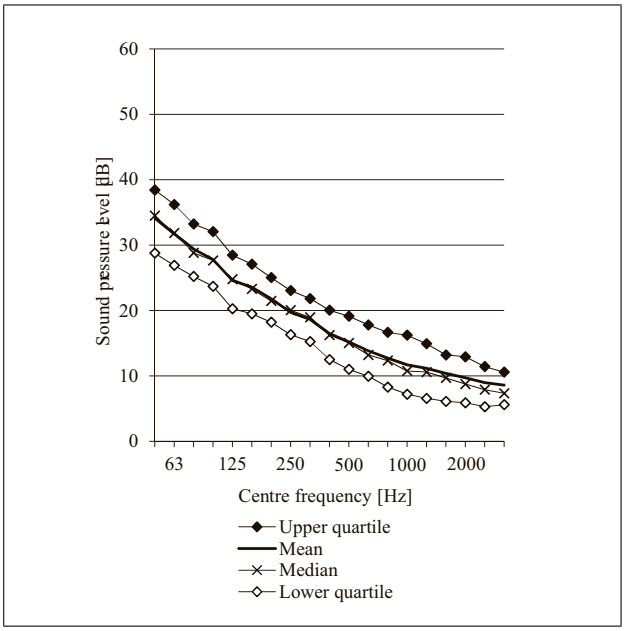


Figure 8. Linear background noise levels at 1/3-octave bands from HVAC systems in Finnish dwellings [47].

SNQs described in the present standard, i.e. $L'_{n,w}$, $L'_{n,w}+C_I$ or $L'_{n,w} + C_{I,50-2500}$, are satisfactory as correlation coefficients between them and the noise ratings of walking with hard-heeled shoes exceed 0,60. $L'_{n,w} + C_I$ or $L'_{n,w}+C_{I,50-2500}$ correlate also well with the walking of W3 with soft-heeled shoes. Widest range of statistically significant correlation coefficients was achieved using $L'_{n,w}+C_I$, $L'_{n,Fas}$ and $L'_{n,Ger}$ which correlated strongly with the superball bouncing in addition to the mentioned sound sources (Figures 6 and 7).

The SNQs based on the tapping machine had, however, mainly a weak correlation with noise ratings of walking with socks. This result supports the earlier researchers' [7, 9, 22, 26, 31, 32] conclusions related to the significance of walking with socks and walking on concrete floors covered with floating floors. Most walkings of walkers W1 and W3 with soft-heeled shoes resulted in statistically significant correlation, but the walking of walker W2 did not. The probable explanation to this is that the sound pressure levels generated by W2 walking with soft-heeled shoes were lowest of the three walkers and W2 did not excite the resonance frequencies of floors F3, F4 and F5 like the other walkers did. This shows that in walking tests, more than one or two walkers are needed in order to avoid false conclusions. Nearly half of the correlation between the objective SNQs and the noise ratings of walking with soft-heeled shoes were, however, weak.

The results described in Table VI indicate that both the standardized SNQs defined in the present standard and the suggested SNQs do not correlate well with the noise ratings of walking with socks or soft-heeled shoes. This means that both standardized and suggested SNQs ignore the meaning of walking with socks as a sound source. There is an obvious need for a new SNQ which would take walking with socks better into account.

4.4. Limitations

The walkers could repeat their walking significantly well (Table IV). It can thus be assumed that there were no such changes in walking that would have affected the measurement results of the actual walking tests and the differences between the nine floors. Furthermore, it is thus clear that the differences between the sound spectra shown in Figure 6 depend on footwear and floor covering as well as on personal walking style. For example, the heaviest walker was not the loudest.

Three walkers were used in the generation of the walking sounds. It was justifiable to use three walkers instead of one or two, because there were differences between the walkers. Even though the SPLs generated by their walking varied, the shapes of the sound spectra of different walkers wearing the same type of footwear were quite similar. All walkers, however, were men between 22 and 40 years. It is possible that female walkers or other walkers might have generated different sound spectra, depending on their walking style.

The bearing floor structure was the same 265 mm thick hollow core slab in all measurements. This has been a typical structure in Finland from the 1970s to the end of the 1990s [35], but other European countries use a wide scale of different concrete slabs [34]. According to the standardized calculation method [48] of impact sound insulation, the higher mass of the slab reduces the impact SPLs generated by the tapping machine. The changing mass and stiffness of the slab also influences the critical frequency of the slab. Both tapping machine and walking on other floors than those studied here might generate sound spectra differing from the spectra presented here. In most countries, however, the thickness, and mass of concrete slabs are quite similar to the one studied here [34].

5. Conclusions

The SPLs generated by the tapping machine and real impact sounds were measured for nine floors having the same bearing concrete slab and different coverings. Eight different single-number-quantities were calculated based on the tapping machine excitation. Three noise ratings, equivalent A-weighted SPL, $L_{A,eq}$, maximum A-weighted SPL, $L_{A,F,max}$ and loudness level L_N, were determined for real impact sounds, which were walking with socks, walking with soft-heeled shoes, walking with hard-heeled shoes, moving a chair and bouncing a superball.

The results indicate that walking with socks generates SPLs which at frequency bands below 100 Hz are higher than the SPLs generated by walking with hard-heeled or soft-heeled shoes. The results also confirm that compared with walking on other floor coverings, walking on floating floors may generate 5–15 dB higher SPLs below 100 Hz. It can thus be stated that impact sound insulation at low frequency range is not related to light-weight structures only but also to concrete floors.

The noise ratings of walking with hard-heeled shoes correlated strongly with the SNQs based on the tapping

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machine. The correlation coefficients between the noise ratings of chair moving and SNQs based on tapping machine were also strong. Walking with soft-heeled shoes correlated strongly with the SNQs only in the case of one walker of three. However, there was no statistically significant correlation between the noise ratings of walking with socks and the SNQs. That is, the standardized SNQs ranked the floor structures in an inadequate way regarding the situation when the impact sound source is walking with socks. In the Nordic countries, walking with socks is the typical behaviour indoors at home.

There is an obvious need for listening experiments where walking sounds generated by different footwear on concrete floors with different floor coverings are investigated. A new objective SNQ based on the tapping machine or other standardized source as a stimulus is obviously also needed in order to improve the correlation between the subjective rating of different walking sounds and the objective rating of floors' impact sound insulation.

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