Study of a new standardized sound source for noise assessment in building gyms

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ABSTRACT

Gyms have become popular in residential and commercial buildings, responding to the demand for convenience. However, the installation of these spaces in buildings has caused an increase in complaints of impact noise, which affects the acoustics of buildings and the well-being of residents. This study approaches the challenges of the variability of impact noise sources, which compromise the repeatability and reproducibility of acoustic test results. The research builds on a previous authored study, which aimed to identify patterns among impact sources. A new heavy impact source with a standardized and automated drop mechanism was investigated, evolving into the analysis of variability through the coefficients of variation among three noise sources: Sphere, Kettlebell, and Slam Ball, with a focus on greater consistency and standardization. The tests were conducted in accordance with ABNT NBR 10152:2017, on multiple floor systems and buildings. The results highlight the Cast Iron Sphere as the most consistent source, due to its geometry and automation, showing less variability and highlighting its potential suitability for simulating standardized noise in gyms. These findings provide a basis for future discussions on standardizing acoustic test methods.

1. INTRODUCTION

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Gyms have become popular in residential and commercial buildings, reflecting the demand for convenience, as many people prefer to have them near work or home. Maintaining a healthy lifestyle is essential, and regular exercise is fundamental for quality of life and longevity [1]. This scenario drives the construction of gyms in various locations, such as residential buildings, clubs, and commercial complexes, highlighting the need to control impact noise and its implications on the acoustic performance of buildings, as well as on people's health and well-being [2]. Laboratory tests are frequently used to simulate these conditions and evaluate the acoustic characteristics of different construction systems. However, a significant challenge in these assessments concerns the variability of signals generated by different impact noise sources, which can compromise the repeatability and reliability of the results.

This study builds on previous research performed by the authors [3], which aimed to identify patterns among various types of impact sources. In the initial study, significant challenges were encountered due to variability in repeated tests. In this context, the present research focused on investigating a new heavy impact source, developed in-house, featuring a standardized and automated drop mechanism. This source represents an innovation in the field and is compared with two other sources that were prominent in a recent study [3]. The consistency of the maximum A-weighted and S-weighted sound pressure level (L_{ASmax}) generated by each source was evaluated through a field case study, using the coefficient of variation (CV) of the test results as the main analysis metric.

2. LITERATURE REVIEW

It is crucial to note that, besides the difficulties in characterizing sound sources in workout spaces, there are technical obstacles to properly evaluating complaints about the noise generated. These difficulties arise from the lack of standardized test methodologies and parameters, as well as assessment criteria listed in national or international standards. The following is a brief contextualization of recent studies in this field of research.

2.1. Brazilian context

In Brazil, the performance standard for residential buildings, ABNT NBR 15575-3:2021 [4], includes a specific note in the chapter on acoustic performance and the subsection on impact noise insulation. This note clarifies that the standard does not apply to noise generated by impacts, such as weights dropping from gym equipment in workout spaces. In such cases, the standard recommends the development of a specific isolation project. Consequently, for sound assessments involving gyms, the ABNT NBR 10152:2017 [5] is being applied.

This standard establishes measurement and assessment procedures for sound levels in indoor spaces within buildings, considering both the function and intended use of the noise-receiving spaces. Reference values for equivalent and maximum noise levels are established. For maximum levels, which are the focus of this study, the standard sets the maximum A-weighted and S-weighted sound pressure level (L_{ASmax}) as a parameter. It is important to highlight that neither of the two Brazilian standards provides a standardized approach for evaluating noise situations in gyms using standardized noise sources. Therefore, studies aiming to propose standardization of sources for studying gym noise are crucial to improve the reproducibility of methods and the metrological reliability of acoustic measurements applied in a national context.

2.2. International guidelines

At the Euronoise 2018 conference [6], a scientific paper was presented suggesting a standardized methodology for testing in gyms, which inspired the formation of a working group of involved parties. Subsequently, the UK institutions, ANC (Acoustics and Noise Consultants), IOA (Institute of

Acoustics), and CIEH (Chartered Institute of Environmental Health), each with a focus on acoustics and/or health, collaborated to produce a guideline that presented a standardized approach to evaluating how gyms and exercise spaces affect noise-sensitive adjacencies. As a result of this collaborative effort, the "ProPG: Gym Acoustics Guidance" guide was published in March 2023 [7] [8] [9]. This guide included the study of existing guidelines, such as BS4142 [10], BS8233 [11], NANR45 [12], LFNR [13], and others, concluding that none were entirely appropriate. This showed the need for adjustments and the development of new specific guidelines for the measurement and acoustic design of gyms and fitness spaces, to mitigate noise effects in adjacent areas.
Another example of a guideline considered in developing acoustic guides for gyms is the "Guideline for Acoustic Measurement of Gymnasiums and Exercise Facilities" [14] from the AAAC (Association of Australasian Acoustical Consultants) in Australia, published in February 2022. This guideline offered guidance on measuring and managing noise originating from physical activity facilities, although it did not specify a standardized approach regarding the impact source, whether in terms of type, weight, or form.
In this context, the ProPG guide presented specific methods for the assessment of noise in gyms. Among these, the guide recommends dropping a heavy weight, with a rubberized finish, as part of an initial assessment. This weight should have adequate mass to excite the structure to the desired response point, usually ranging between 20 to 35 kg, and be released from a height of 0.5 meters. One of the premises of this method is that the weight should have a shape that allows for uniform impact on the floor; for example, a Kettlebell with a rounded base (or partially rounded) can ensure a consistent and repeatable impulsive force. Another method in the guide involves using a Slam Ball weighing up to 10 kg to simulate gym activities, evaluating impact noise from drops from up to 1.5 meters. As mentioned in the previously cited study reference [3] and in this current study, the Slam Ball was designed to simulate soft body (deformable) impacts, thus providing a realistic representation of a common group of physical activities in gyms.

2.3. Research hypothesis

Based on analyses conducted in previous authorial research [3], which identified potential compromise in the repeatability of tests and the reliability of results in simulations of gym noises, the need for research on a prototype of a new standardized impact source was identified, similar to what already exists for other types of acoustic tests [15]. In another study conducted in Australia [16], where the authors aimed to understand the performance of some gym floor systems, they encountered the absence of international standards for heavy rigid impact tests.
At that time, they adopted the Kettlebell source, assuming it would provide a more repeatable localized impact compared to a dumbbell, for instance. In Korea, researchers were interested in evaluating the experimental precision of the rubber ball [17] that can occur during field measurement with different operators, from the aspect of repeatability and reproducibility. The aim of this current research was to propose a prototype source for gym assessment and verify whether the use of a standardized source would reduce the variability of results compared to those obtained with non-standardized sources, representing heavy impacts consistently in standardized acoustic tests.

3. METHOD

To test the research hypothesis, a case study was conducted followed by statistical analysis of data. Field tests were carried out with 3 heavy impact sources, across 11 different floor systems, in 3 distinct buildings, and by 2 technical teams. The methodological steps applied are summarized in Figure 1 and described in the following topics.

Test procedure

- Definition of noise sources and floor systems.
- Definition of the testing methodology and collected variables.

Data treatment and analysis

- Visualization and frequency analysis of data.
- Initial treatment: A-weighting (L_{ASmax}) and calculation of the global value.
- Data grouping (source, floor, team, building).
- Calculation of the average, standard deviation and coefficient of variation.
- Visual analysis.
- Application of statistical tests to verify the research hypothesis.

Figure 1: Methodological Scheme.

3.1. Test procedure

Impact tests were conducted under controlled conditions, using the same floor construction elements and assembly conditions for all noise sources to ensure comparability of results. A total of 3 noise sources and 11 floor systems were selected for the research, as described below. It is important to note that the repetition of tests across different floor systems and with different teams was motivated by the desire to evaluate whether the observations made for each source would hold, regardless of these variables.

3.1.1 Impact sources

To explore the research hypothesis, a standardized and automated drop device was designed as shown in Figure 2. This device was named "Sphere" and consisted of the following components:

– A wooden stand with adjustable-height legs and level adjustment bubbles;
– A sliding horizontal bar with height adjustment for drops up to 50 cm;
– A Cast Iron Sphere, weighing 6.87 kg;
– An electromagnet for the Sphere's magnetization;
– A button for releasing the suspended weight (demagnetization of the system);
– A 5 mm rubber mat: used to protect the floor during Sphere drops.

The descriptions and visualizations of the sources used in the research, including the Sphere, are in Figures 2 and 3. Figure 3 specifies the drop height, corresponding to the height between the source and floor for release and impact noise generation. For the Sphere, the drop was automated; for the other sources, the drop was manual by the operator.

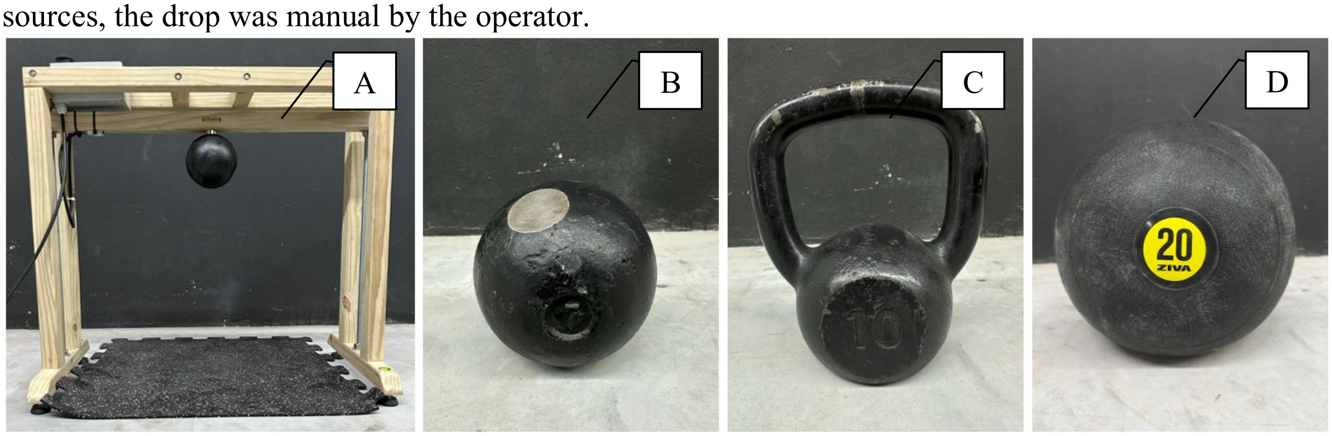

Figure 2: Impact Sources: A) New device; B) Sphere; C) Kettlebell; D) Slam Ball.

Sphere [E]	weight of 6.87 kg, spherical shape, made of cast iron, dropped from a height of 40 cm. Use of a 5 mm rubber mat for floor protection.
Kettlebell [K]	weight between 10 to 12 kg, spherical shape with a handle, made of cast iron, without coating, partially rounded base, dropped from a height of 22 cm. Use of a 5 mm rubber mat for floor protection.
Slam Ball [S]	Weight of 20 kg, spherical shape, made of PVC with an interior of silica sand and metal pellets, internal pressure of 2.5 LBS, dropped from 50-60 cm (operator's waist height).

Figure 3: Description of impact sources and technical characteristics.

Note: The Kettlebell and Sphere sources can be classified as rigid (hard body impact), while the Slam Ball source can be considered deformable (soft body impact) [3].

3.1.2. Floor systems

The tests were conducted in 3 different buildings located in Goiânia-GO, Brasília-DF, and Balneário Camboriú-SC. The floor systems of these buildings consisted of solid reinforced concrete slabs with the following specifications:

– Building 01: 14 cm slab, 3.5 cm screed, ceramic floor covering, and gypsum ceiling lining;
– Building 02: 20 cm slab, 3 to 5 cm screed, ceramic floor coveringg, and gypsum board ceiling (21 cm inter-ceiling;
– Building 03: 20 cm slab and 3 cm screed, no floor finish and no ceiling.

To simulate different floor systems, 11 samples of damping materials were installed in situ on each tested flooring system. The descriptions of the samples are presented in Table 1.

Table 1: Constructive systems subjected to impacts from different sources.

Floor System	ID	Damping Materials
Building 01	011	No damping layers added
	012	50 mm rubber plate (SBR+EPDM) weighing 31 kg/m², underside with damping pockets, top finish focused on damping
	013	34 mm rubber plate + 15 mm rubber floor
	014	15 mm rubber floor
	015	50 mm rubber plate (SBR+EPDM) weighing 34 kg/m², underside with damping pockets, top finish focused on abrasion resistance
Building 02	021	No damping layers added
	022	04 helical springs with a free height of 90 mm under a load of 212 kg/m² (1 Wall Panel plate of 40 mm + 1 person weighing 65 kg)
Building 03	031	04 helical springs with a free height of 55 mm under a load of 187 kg/m² (8 steel plates of 3 mm each, totaling 24 mm)
	032	No damping layers added
	033	34 mm rubber plate + 15 mm rubber floor

034	5 pads [4 microcellular polyurethane pads of 25 mm (open cell) + 1 microcellular polyurethane pad of 25 mm (mixed cell)] under a load of 187 kg/m² (8 steel plates of 3 mm each, totaling 24 mm), with a top finish of a microcellular polyurethane plate of 25 mm (closed cell)

3.1.3. Data collection

The data were collected through tests following the methodology of the standard ABNT NBR 10152:2017 [5]. A total of 615 data points on the maximum sound pressure level in linear weighting (L_{max}) were collected at frequencies from 31.5 to 8000 Hz. The data collection procedure involved 5 repetitions of impact from the source against the floor, conducted at 3 points in the receiving room for Buildings 01 and 02, and at 5 points in Building 03. Class 1 sound level meters and sound calibrators, which were duly calibrated in accredited laboratories, operated under regular environmental conditions, with field adjustments carried out at the beginning and end of the measurements.

3.2. Data processing and initial analysis

The data analysis was conducted using the R programming environment and spreadsheets. Initially, a visual analysis of the data measured by frequency was performed to obtain initial insights. Representative levels of each measurement were determined and expressed by the global maximum value in A weighting and S weighting (L_{ASmax}). Subsequently, for the global L_{ASmax} values per source-floor combination, the average (X), standard deviation (Sx), and coefficient of variation (CV) were calculated. The CV, defined according to Equation 1, is expressed as a percentage and served as a metric for assessing repeatability.

$$CV = \frac{Standard\ derivation}{Mean} = \frac{S_X}{X} \times 100, \qquad (1)$$

By scaling the standard deviations of the results by the magnitude of the different measured averages [18], the CV makes it possible to compare the relative variability between the sources, independently of the magnitude of the absolute values of L_{ASmax}. The use of this coefficient is, therefore, appropriate to the situation under study, as it is expected that different source-floor combinations will generate distinct average noise levels. The coefficients of variation (CV) of the 3 sound sources (E, K, and S) used in the tests were compared with the aim of assessing the uniformity of the results obtained in repeated measurements.

3.3. Statistical data analysis

Initially, a graphical exploration of the variability of the L_{ASmax} results by source-floor combination (bar graph, scatter plot with lines, and boxplot) was performed to obtain an overview of the data and identify trends or potential issues. Subsequently, the normality of the data and the homogeneity of variances between the groups were assessed (using the Shapiro-Wilk test and Levene's test, respectively). Based on these diagnostics, analysis of variance (ANOVA) [19] [20] was chosen to test the hypothesis of a difference between the average CVs of the 3 sources. The analysis was conducted without the removal of outliers to better reflect the natural variability of acoustic phenomena. For performing multiple pairwise comparisons, Tukey's post hoc test [21] [22] was used. Given the presence of potential extreme values in the data sets, the ANOVA was complemented with the non-parametric Kruskal-Wallis test [23], followed by pairwise comparisons using the Wilcoxon test [24] [25], with p-value adjustment using the Benjamini-Hochberg (BH) method.

4. RESULTS

Figures 4 and 5 are examples of peaks (maximum levels) recorded by the sound level meter due to the repetitive dropping of each impact source, highlighting the variability among them. To illustrate the visual analysis of the time history of the maximum sound level, two floor systems were chosen: 031, which has higher damping capacity (Figure 4), and 032, with a lower degree of impact damping (Figure 5). Source E was notable for having the greatest consistency and pattern among the sources studied, independently of the floor system used. In contrast, sources K and S showed less consistency and pattern. Different behaviors were observed: the sources achieved more consistent results in the system with less damping (032, Figure 4) and exhibited greater variations among the repetitions in the system with higher damping (031, Figure 5).

It is worth mentioning that system 031 generates a significant opposing force to the impact caused by the sources. This occurs because the system is composed of helical springs, which exhibit typical elastic behavior according to Hooke's Law, exerting a restoring force to return to their equilibrium position.

In test situations where the impact sources were manually released by the operator (K and S), there was less control and precision, influencing the consistency of the repeatability of the drops. It was observed that the 20 kg weight of source S exerts a substantial impact force. This impact, combined with the high storage of potential energy in the system, caused the release of the opposing force to destabilize the sample.

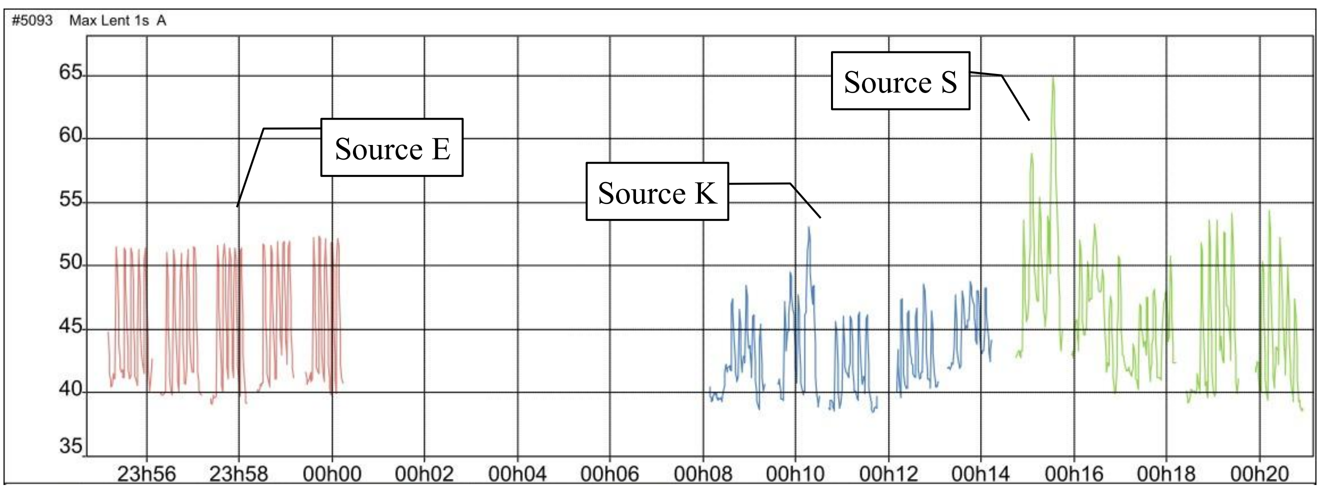

Figure 4: Time history of the maximum sound level, floor system 031 (high damping).

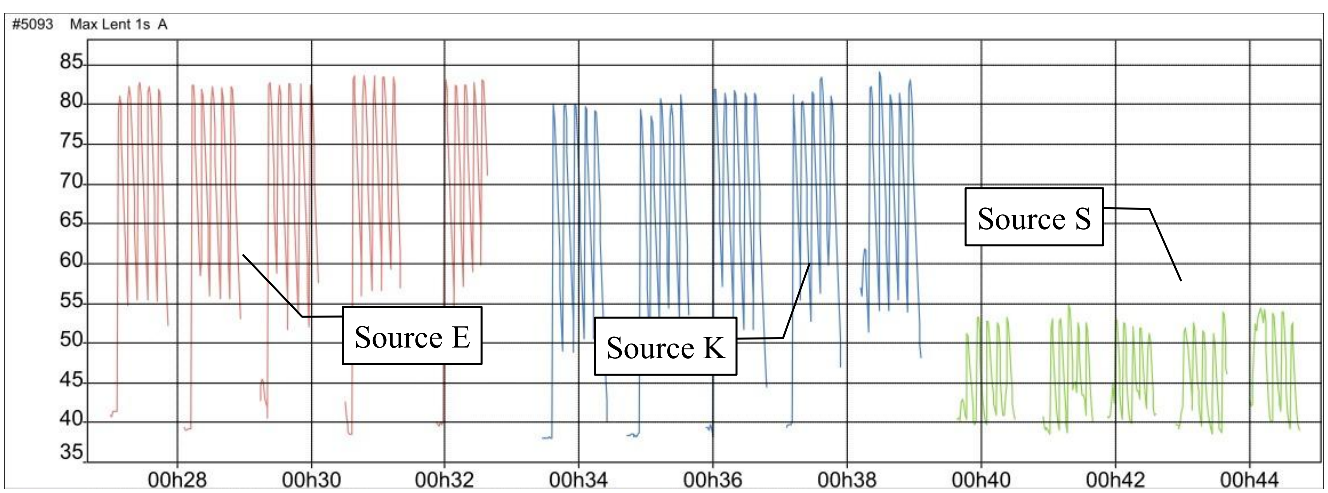

Figure 5: Time history of the maximum sound level, floor system 032 (low damping).

The analysis of Figure 6 corroborates the initial data analysis: the CV values obtained for each noise source appeared visually different for the 3 assessed sources. Furthermore, source E presented the lowest average and dispersion CV values, followed by source K (Table 2), indicating greater uniformity of results, regardless of the type of floor tested.

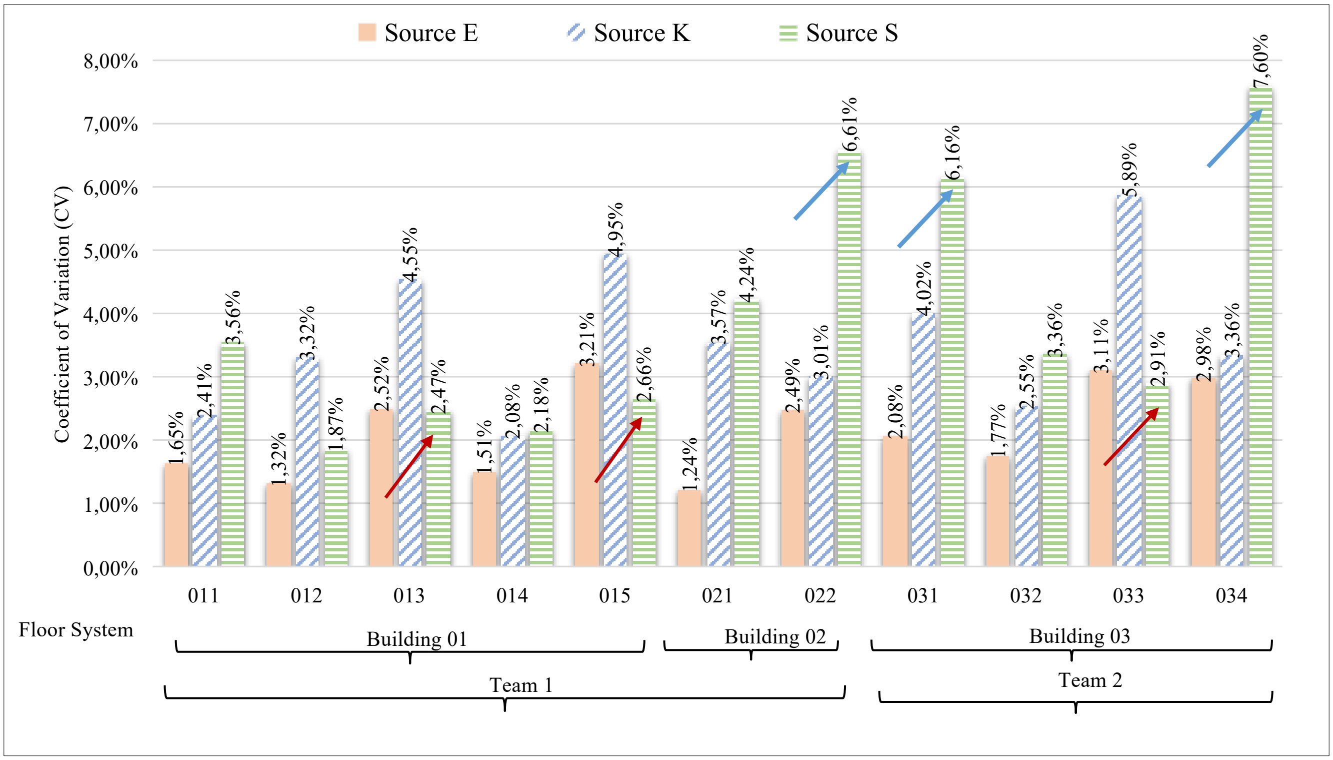

Figure 6: Bar graph of the coefficients of variation (CV) for the source-floor combinations.

In the 11 source-floor combinations analyzed, source K did not achieve the lowest CV in any situation when compared to the other sources. This behavior was to be expected due to its spherical shape with a handle and partially flattened base. With each collision with the floor samples, the object can slightly change its position, altering the contact surface and resulting in less uniformity. Additionally, manual dropping can cause small rotations when the object is let go from the hands.

Table 2: Coefficients of variation (CV) correlated with average, median, and standard deviation.

Source	n	Average CV (%)	Median CV (%)	SD of CV (%)
E	11	2.17	2.08	0.73
K	11	3.61	3.36	1.16
S	11	3.97	3.36	1.96

On the other hand, source E is associated with most of the lowest CVs obtained in the research, achieving this result in 8 of the 11 source-floor combinations. This indicates that, due to its fully spherical shape, combined with standardized drops by the device, the Sphere offers a more uniform and predictable performance, making it a good choice for tests requiring high precision and repeatability. Source S was responsible for 3 of the lowest CVs in the tests conducted but also presented the 3 highest values,

indicating considerable dispersion in the results associated with this source. This performance can be attributed to deformation in systems with a high degree of damping, such as those with springs and elastomers of low natural frequency, due to the high impact energy generated by the 20 kg weight of the Slam Ball and its average drop height between 50 to 60 cm.
Conversely, in systems with a low degree of damping (more rigid), the deformations were significantly smaller, not causing destabilization of the samples and resulting in the 3 lowest CV values. Figure 6 reaffirms these extreme variations, with the 3 lowest CVs represented by floor systems 013, 015, and 033 indicated by red arrows, and the 3 highest CVs represented by floor systems 022, 031, and 034, indicated by blue arrows.
According to Table 2, source S achieved the highest standard deviation of the CV, with an SD of 1.96%, which is more than twice that of source E, which presented an SD of 0.73%. When comparing the average CV, source K showed a variation 66% higher than source E (2.17% versus 3.61%), also indicating less consistency and pattern. This data supports that the Sphere can be a good alternative for tests requiring consistency and uniformity in repeatability.
The boxplot in Figure 7 illustrates the distribution of CVs for the 3 sources: E, K, and S. The analysis shows that source E has the lowest median and the narrowest IQR (interquartile range), indicating greater consistency and uniformity in the results. In contrast, sources K and S show wider IQRs, especially source S, suggesting greater dispersion of results and, consequently, less predictability. These results highlight the Sphere as the most reliable alternative for tests requiring consistency and uniformity in repeatability.

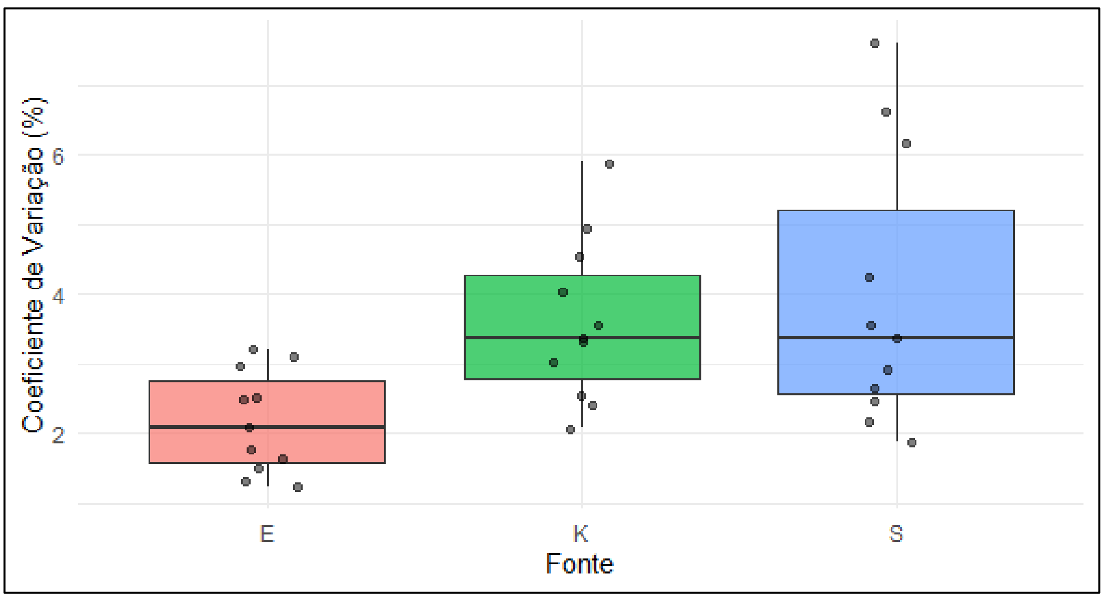

Figure 7: Boxplot of the distribution of the coefficient of variation (CV) by source.

After verifying the assumptions of ANOVA, it indicated a statistically significant difference between the groups of sources, as evidenced by an F-value of 5.23 and a p-value of 0.011. This signifies that at a 95% confidence level (significance level of 0.05), we can assert that at least one of the source groups differs significantly from the others in terms of its impact on the variability of L_{ASmax} measurements (Table 3).

Table 3: ANOVA results for the coefficient of variation (CV) of L_{ASmax}.

Source of Variation	**SS**	**DF**	**F-value**	**p-value**
Between groups	19.86	2	5.225	0.0113
Within groups	57.03	30		

The Tukey post hoc test (Figure 8) revealed significant differences between sources E and S, with a p-value of 0.012, indicating a statistically significant difference ($p < 0.05$). However, no significant differences were found between K and E, reflected by a p-value of 0.82, indicating that these sources produce similar average effects ($p > 0.05$). Additionally, the comparison between K and S showed a borderline result with a p-value of 0.052, suggesting that more in-depth verification may be warranted.

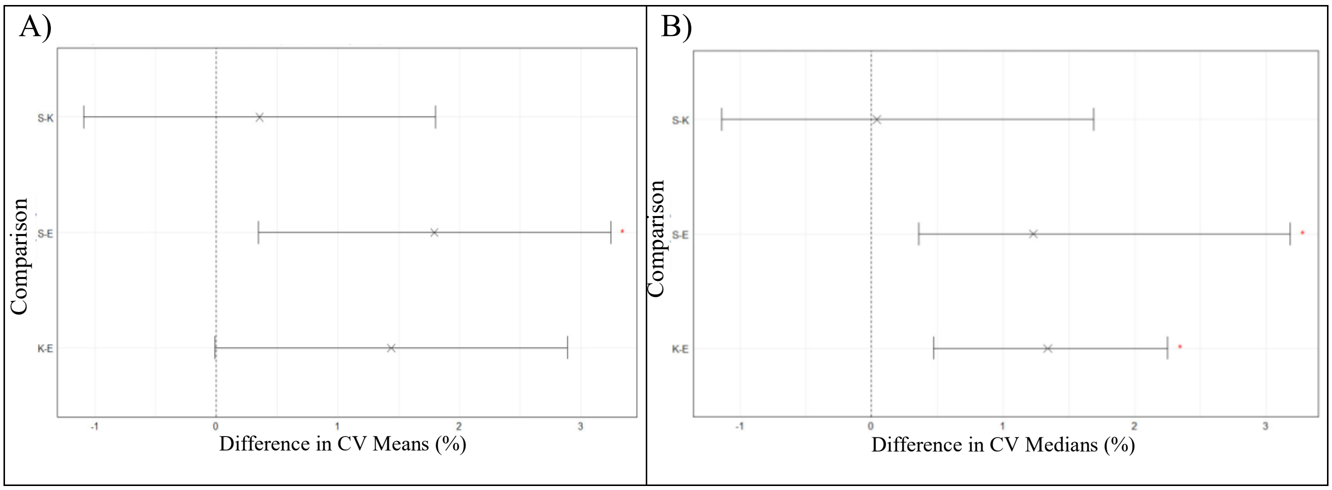

Figure 8: 95% family-wise confidence level: A) Tukey HDS; B) Hodges–Lehmann estimator (adjusted by BH).

The complementary results obtained with the non-parametric Kruskal-Wallis test confirmed the significant effect of the "source" variable on the CV, with a p-value of 0.006 ($p < 0.05$), corroborating the ANOVA findings. This non-parametric method was chosen to validate conclusions without needing to assume normality of the data. Additionally, the multiple comparisons conducted using the Wilcoxon test, adjusted by the Benjamini-Hochberg (BH) method and illustrated in Figure 8 B), revealed statistically significant differences not only between sources E and K ($p = 0.010 < 0.05$), aligning with parametric results, but also between E and S ($p = 0.016 < 0.05$).
These results reinforce the greater repeatability of the Sphere source, indicating its superiority in generating consistent impacts. This characteristic is particularly desirable for standardized tests as it reduces the uncertainty of the results and improves comparability among laboratories, ensuring a more robust and reliable application of testing method.

5. CONCLUSIONS

This study investigated the influence on the variability of tests of maximum A-weighted and S-weighted sound pressure levels (L_{ASmax}), using the coefficient of variation (CV) as a measure of the results. The main objective was to identify which of these sources would be most suitable for simulating the noise associated with the use of gym equipment in laboratory tests with less variability and greater consistency in repeatability.

Among the 3 heavy impact sources selected for the study—namely: Sphere (E), Kettlebell (K), and Slam Ball (S)—the results highlighted the Sphere source as particularly promising, consistently presenting the lowest coefficients of variation for L_{ASmax} results, which indicates greater repeatability and standardization in tests. This positive performance can be attributed to its fully spherical shape, which ensures a uniform distribution of impact, and the automated drop method, which minimizes manual variations during testing.

Both the parametric tests (ANOVA and Tukey) and the non-parametric tests (Kruskal-Wallis and Wilcoxon) confirmed statistically significant differences between sources E and S, highlighting the precision of the Sphere. In contrast, the source K, with its partially rounded surface and the presence of a handle, exhibited the second-highest variation in the coefficients. This instability can be attributed to variations in the contact surface and the rotation of the object during drops, resulting from multiple possible impact points that affect the uniformity of Kettlebell repetition. Lastly, the source S is responsible for the worst variation results in the coefficients calculated for the tested floor systems, and interestingly, it also showed the least variation for 3 of these systems, indicating considerable dispersion in results associated with this Slam Ball source.

This body of evidence suggests that the Sphere (E) has potential and consistency, validating the hypothesis that it is a promising source for laboratory tests. Its ability to generate consistent and high-precision results can significantly contribute to tests that require low variability and high comparability between laboratories, reducing uncertainties and strengthening the reliability of testing methods.

It is clear that the results are associated with the shape of the source, the deformability, and the form of the drop. Having harmonized these 3 factors, it is possible to achieve more standardized and repeatable test results. The study's findings provide a solid basis for discussion among professionals, encouraging in-depth analysis of the applicability of different sound sources in acoustic testing.

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