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Insights into Noise and Vibration stemming from the Gym's heavy lifting

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Abstract: In 2011 the percentage of the American population affected by Noise Induced Hearing Loss (NIHL) was 15.3%. Unlike most forms of hearing loss, this can be prevented by limiting exposure to certain magnitudes of noises for varying amounts of time. The present study aims to assess the sound which can contribute to NIHL given off from dropping free weights using six calibrated smartphones in the gym at the University of Birmingham. This report sets out to measure the noise and vibration given off by dropping loaded barbells at the top of a deadlift. By conducting these tests, it can be assessed whether the sound given off from dropping free weights in the gym could be contributing to NIHL. A relationship between drop weight and the vibration is also be constructed. For vibration, it is found that vibration level (m/s^2) increased with drop weight, whereas the average noise level for each drop weight only varies by a range of 4.4 dB between 102.7 dB and 98.3 dB. There is no correlation shown by these results between sound level and drop weight, however, all the sound levels recorded are over 85 dB leading to NIHL. This study reminds us that measures need to be taken to reduce the sound level from the dropping of loaded barbells in the University of Birmingham Sports and Fitness Centers

Keywords: hearing loss; vibration; sound; noise; drop weight; smartphones;

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1. Introduction

Noise and vibration (N/V) induced by the behaviors in a fitness center is a major problem leading to complaints in commercial, mixed-use, and residential buildings [1]. More importantly, exposure to a high level of noise can be harmful to people's hearing [2]. However, inaudible is not necessary so that the investigation of the acceptable level of N/V can be quantified. NIHL can be prevented by limiting exposure to sounds greater than 85 dB [3]. The Squat, Deadlift and Bench Press are widely accepted to be the 'Big Three' powerlifting exercises by strength and conditioning experts[4]. Of these three the deadlift is found to have the highest one repetition maximum for the majority of people [5] and due to this reason, it is one of the most common exercises to be performed in gyms with the available equipment. According to the rules set out by the International Powerlifting Federation, returning the weight to the platform without maintaining control with both hands is a disqualifiable offence in competition [6]. However, both professional and amateur weightlifters frequently drop the weight to the platform at the completion of the exercise. Such uncontrolled release of the weight and contact with the platform results in noise and vibration which may lead to NIHL in people close to the event.

To determine the effectiveness of different types of damp-poof flooring, Hayne carried out an in-situ floor impact isolation testing on a gym floor and concluded that most of the damping effect of noise when weights were dropped came from the type of structure that was underneath the vibration absorbing flooring, comparing floating floor to a concrete slab. Different materials were tested for their noise dampening properties and concrete slabs were used as a reference level [7]. This is useful for deducing the effect of the current flooring by replicating the experiment on the flooring at the University of Birmingham Fitness Centre's gym. In our previous report [8], we have conducted an experiment measuring noise and vibration given off from deadlifts with varying weight but keeping the contact area of the drop weight constant. We found that noise levels are above 85 dB for all drops from 20 kg – 75 kg but there was a drop in the dB level at 70 kg. As an improvement of our former report, we set up a more rigorous experimental procedure. Regarding the noise induced by background music and the vibration caused by other gym users in [8], access is given to the Sports and Fitness Centre's performance gym where there would be no other gym users and the ability given to mute the usual music speakers. The performance gym consists of the same damp-proof flooring as the main gym and sits on the same floating concrete slab. These were the two main concerns for sources of background noise and vibrations in [8], which were eliminated. More importantly, the weight range goes higher, up to 130 kg in this work since the average one repetition maximum weight in deadlift of 67 untrained college students were measured to 107 kg in [9] so that the relationship between weight and noise, and vibration can be plotted over a wider range of weights. McNulty produced the noise and vibration patterns of cardio machines but did not conduct any experiments that weightlifting exercise could have, although it was mentioned that they will be a factor[10].

In this study, we have proposed mobile phones as an experimental tool to detect noise and vibration level. There are still some concerns that reveal if the quality of the sensors installed in a smartphone is capable to meet the demand of the measurement as Sachs has depicted the worries of the accuracy that the phone can reach due to the size and low price of the sensors in the phones[11]. Previous researches [12,13] have established the reliability of the accelerometer housed in cell phones. Two phones and a sophisticated accelerometer were used to acquire train carriage vibrations in [12], and the feasibility was proven by the comparison of the data from phone-based accelerometer and the sophisticated accelerometer. Similar to [12], the vibrations collected by smartphones worn on 31 participants were compared to the same data from a validated physical activity monitoring system and the results implied the performance of the accelerometer embedded in phones is accurate and precise [13]. Eric et.al proposed a microphone-based application SpiroSmart performing spirometry sensing. 5.1% mean error was achieved by the SpiroSmart compared to a clinical spirometer [14]. Multiples research and government institutes have adopted the microphone of phones to monitor noise pollution monitoring [15-18] leading to the growing development of many mobile apps for measuring sound levels such as NoiseSPY [19], EarPhone [20] and NoiseTube [21]. The reliabilities of these applications have been assessed outside and inside a laboratory [22-26].

The findings in this report can be used to ensure that the gym is a safe place for those attending the gym, or to indicate what action can be taken to better protect the longevity of hearing for these attendees. Besides, the procedure in this study outline how we can use our phones to evaluate the noise and vibration in a gym. Many different sources in daily life may emit a sound level that can lead to NIHL. This report does not set out to present the argument that the gym is the sole factor in causing NIHL but instead it aims to present findings that demonstrate how powerlifting exercises, in particular the deadlift, can be a contributory factor in NIHL.

2. Methods

2.1 experimental procedure

The testing is conducted in a certified gym and the activities are performed by one of the gym instructors. To complete a deadlift, the subject starts with the feet width just beyond shoulder-width apart, and hands gripping the bar at shoulder width. The bar is pulled upwards using hip and knee joint extension until it reaches upper thigh level and the spine is fully erect, and the subject's shoulders are pulled back. The bar is then dropped back to the floor [27]. Figure 1 shows the deadlift form that will be tested. The key element about the lift for this investigation is the finishing height, which as illustrated in this figure is an upright body posture pulling your shoulders back and locking your hips forward, leaving the bar to rest against the lower hips or pelvic area (dependent on arm length). The impact noise produced by the dropping of the bar is also dependent on attributes like the height between the bar and the floor. In the UK, the average height of a male and a female is 175.3 cm and 161.6 cm respectively according to the Office of National Statistics. The gym instructor is 179.0 cm who is higher than the average standard which means that the distance between the instructor's hands and the floor exceeds most of the people in the UK. The distance is measured to 85.0 cm when the performer fully erects during a complete deadlift.

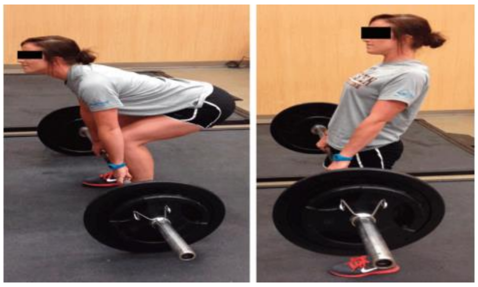


Fig. 1 An example of deadlift technique (Source: authors)

2.2 Noise and Vibration recording applications used

The robustness of the microphone, accelerometer and the applications used to acquire sound and vibration has been proven by previous researches [11-25]. At the same time, we also evaluated the measuring instruments to accommodate the British standard BSEN 61672 in our previous study [8] by comparing the six sound measurement applications and six vibration measurement applications yielding that the DecibelX for sound measurement is outperforming other applications. However, in this study, we instead the app Vibsensor in place of the app Accelerometer since the more user-friendly service has been achieved. The reason being ease of use during the experiment as it only requires a double-tap of a button to start recording a new result. This enables quicker testing in the gym as there is only limited time when access is given for the testing. The accuracy of the metering is distinct depending on the brands of mobile phone. Murphy and King have investigated and concluded that Apple phones provide surpassed accuracies compared to Android phones in general [28]. The applications chosen are both available on the IOS 'App store'. Six different iPhones are used in the tests listed in table 6 in the appendix as there is a limitation to get six identical iPhones.

2.3 Testing Area

Access is given to the Sports and Fitness Centre's performance gym. The performance gym consists of the same damp-proof flooring as the main gym and sits on the same floating concrete slab. This is arranged with the gym staff as access can be granted at a time where there will be no other gym users and the ability given to mute the usual music speakers. These are the two main concerns for sources of background noise and vibrations, which are eliminated. Figure 3 shows the floor layout of the powerlifting stations in the performance gym. Testing is conducted at the middle station on the top line. The location of measurement is governed by BS ISO 2631 – 1. The position of the phone should be able to demonstrate the vibration at the interface between the origin of the source of vibration and the performer. For deadlift, the measurement should be taken on the surface that supports the feet most often where are tagged to three and four in Figure 4 as suggested by the procedures in BS ISO 2631 – 1.

The position of the smartphones is indicated by the numbers in Figure 4 according to the literature on an overview of sound measurement which has highlighted the location of sound measurement should be placed around the source of the sound [29].

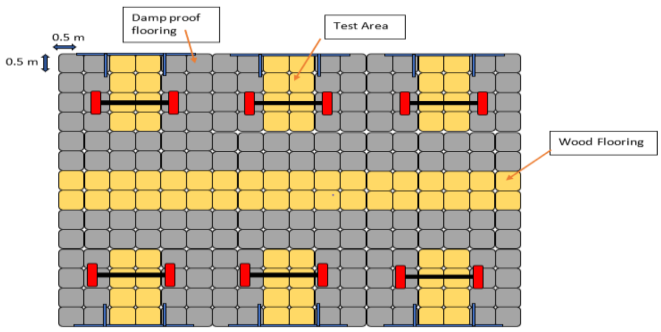


Fig. 3 Floor layout of powerlifting stations in performance gym (Source: authors)

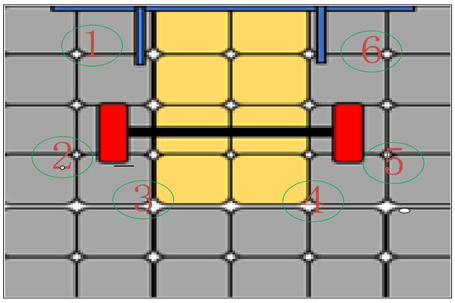


Fig. 4 Test area with phones laid out in positions 1 – 6 (Source: authors)

2.4 Calibrating mobile phone for vibration measurements

As specified in figure 4, six smartphones are being used as recording devices. A test is carried out to ensure that they are calibrated accurately, and this requires the use of an accelerometer. The accelerometer used is ‘Brüel & Kjær’s’ type 4533-B-002 with a range of ±140 m/s^2 peak.

A signal conditioner is used to convert the accelerometer’s signal to a voltage with a relative amplitude. The signal conditioner used is ‘Brüel & Kjær’s’ Type 1704-A-001. The software, LabView, converts the voltages to presentable data of vibration in m/s^2. Figure 5 demonstrates the circuit created in LabVIEW to collect the readings from the signal conditioner.

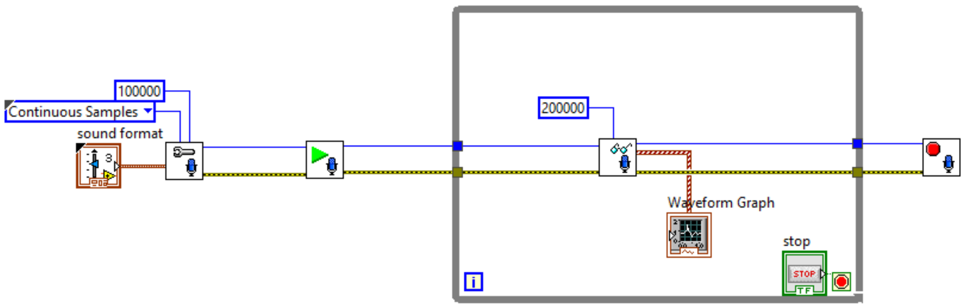


Fig. 5 LabVIEW circuit to read accelerometer readings (Source: authors)

The accelerometer and one phone (referred to as ‘reference phone’) are laid 0.5 m on the floor away from the weight. Both devices then begin measuring vibrations, the weight is dropped, and the peak vibration level is recorded on each device. The calibration settings of the phone are then changed by the difference in peak vibration level from the phone to the accelerometer. Subsequent readings from the phone will then match the accelerometer. This is repeated several times until the phone’s readings are consistently equal to that of the accelerometer as access to the other smartphones is limited, calibration is not able to be carried out at the same time or with the accelerometer. For the calibration of the other phones, the above procedure is carried out but instead using the reference phone in place of the accelerometer.

2.5 Calibrating mobile phones for sound measurements

To ensure the sound measurements of the phones are accurate and calibrated together a similar test is carried out to that described in section 2.4. Instead of using an accelerometer to ensure accuracy of reading, a separate reference phone is used to generate a 70 dB sound level. Each phone is, in turn, placed 20 cm away from the reference phone and its sound recording level is set to 70 dB within the ‘DecibelX’ application.

2.6 Deadlift weight combinations

The design of A-J aims to recreate common gym practice. As stated earlier in [9], the average weight to be expected is 107 kg and 130 kg has been chosen as the maximum as it is 120% of the expected average.

Table 1. Deadlift weight combinations (Source: authors)

	Combination of weights	Weight (kg)
A	Barbell (20kg) + 2x10kg rubber covered plates	40.0
B	Barbell (20kg) + 2x15kg rubber covered plates	50.0
C	Barbell (20kg) + 2x20 rubber covered plates	60.0
D	Barbell (20kg) + 2x25kg rubber covered plates	70.0
E	Barbell (20kg) + 2x20kg + 2x10kg rubber covered plates	80.0
F	Barbell (20kg) + 2x20kg + 2x15kg rubber covered plates	90.0
G	Barbell (20kg) + 4x20kg rubber covered plates	100.0
H	Barbell (20kg) + 2x20kg + 2x25kg rubber covered plates	110.0
I	Barbell (20kg) + 4x20kg + 2x10kg rubber covered plates	120.0
J	Barbell (20kg) + 4x10kg + 2x15kg rubber covered plates	130.0

2.7 Data post-processing

The most common measurement of sound level is decibels (dB). Hall suggested that defining decibels is not achievable unless in terms of power and its immediate related quantities such as current and voltage[30]. However, Horton presented a solution to this by using 'Logit' to compare ratios of different physical quantities. A ratio of one Logit being a ratio of 10(0.1)[31]. A sound is usually considered to have four main attributes, a decibel is a measure of the sound pressure created from different amplitudes and frequency of waves [32]. Sound pressure cannot be directly converted into effect on humans and their hearing. Given the above information when judging the effect of decibel level on people reference will be made to the 85dB limit stated previously. Equation (1) allows the conversion of a given sound level in decibels into its matching eight-hour level when its duration is known [30].

$$L_R = L_M - 10\log_{10}\left(\frac{T_R}{T_M}\right) \quad (1)$$

Where:

L_R= Eight-hour equivalent level (dB)
L_M= Recorded Level (dB)
T_R= Seconds in eight hours (S)
T_M= Time duration decibel level recorded (s)

With the combined noise of powerlifting stations and cardio machines such as treadmills, which McNulty's report modelled as cyclic impact loading, there is a danger that all the different sources of noise are superimposed to create more constant noise, and if each source is emitting a decibel level that is above 85 then NIHL can be contributed towards.

The relationship between the acceleration caused in the human skeletal system and the magnitude and frequency of vibrations is non-linear [33]. Defining a set level of tolerable vibration is very difficult. Therefore, for guidance on what magnitude and frequencies of vibration are acceptable, reference will be made to British Standards BS 6472:2008 [34], where acceptable vibrations come from a structural point of view, whilst also making considerations for human vibration interactions. Transmissibility is the ratio of the outputted vibration compared to the inputted vibration. In a report by McNulty the transmissibility in large structures is given by the following equation (2)[10]:

$$T = \sqrt{\frac{1+4\psi^2(\frac{f}{f_0})^2}{\left[1-(\frac{f}{f_0})^2\right]+4\psi^2(\frac{f}{f_0})^2}} \quad (2)$$

Where:

T= Transmissibility
f= forcing frequency (Hz)
f_0= The natural frequency of the isolator
ψ = Damping ratio

These factors can be obtained for the current flooring from ‘Pullum’, the company that designed the existing vibration-absorbing flooring. From the testing carries out and analysis of the results, it can then be decided if a material with lower transmissibility will need to be installed in the gym.

3. Results

The current section presents the results acquired from the experimental and analysis of the wide range of the weight changed inducing different sound and vibration levels. The outcomes are demonstrated in the two tables and figures in the following.

3.1 Sound level

Table 2 shows the averaged values of sound levels from the three repeats of each weight dropped, for reference table 4 in the appendix has the raw data that these averages are calculated from.

Table 2. Measured sound levels average for each phone from deadlift drops (Source: authors)

	Sound level (dB)							
Weight (kg)	Phone 1	Phone 2	Phone 3	Phone 4	Phone 5	Phone 6	Average	Critical
40	103.2	104	101.5	102.1	102.8	102.7	102.7	104
50	102.3	99.6	97.9	99	97.7	97.4	99	102.3
60	99.8	101.7	100.9	101.3	99.5	98	100.2	101.7
70	98.3	98.3	99.8	99.1	100.4	96.2	98.6	100.4
80	101.4	100.3	97.8	99	99.3	97.6	99.2	101.4
90	99.4	98.6	97.8	99.2	95.4	102.5	99.1	102.5
100	98.4	102.2	99.8	97.9	95.9	95.8	98.3	102.2
110	100.9	104	97.9	99.2	99.2	97.8	99.8	104
120	101.1	100.4	98	98.3	98	98.4	99	101.1
130	98.6	100.6	98.4	98.9	100.5	97.4	99.1	100.6

For the calculation of the equivalent eight-hour average the largest average decibel level recorded from Table 2 is to be used, therefore using the most critical case to show the maximum effect that these drops can have. The average selected is the 40 kg drop at 102.7 dB. In the example, the duration of the sound around peak level is conservatively taken as 0.5 seconds regarding Figure 9 appendix.

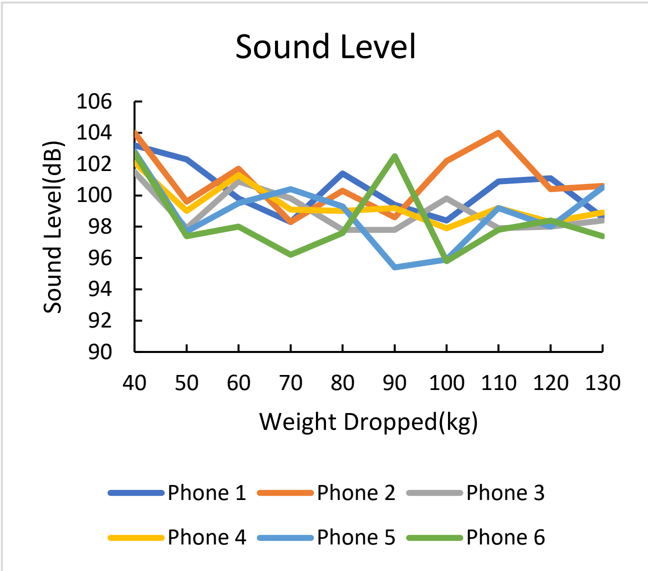
$$L_R = L_M - 10 \times \log_{10}\left(\frac{T_R}{T_M}\right)$$

LR = 102.7 – 10 x Log10((80 x 60 x 60)/ (0.5))

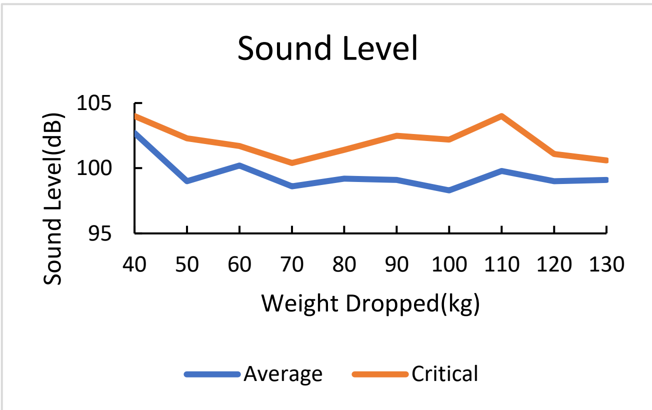
LR = 45.01 dB over 8 hours

3.1.2 Average sound levels against weight

Figure 6(a) reveals that the sound levels collected by six experimental phones commence with a relatively high level (all above 85 dB) with fluctuations settling at a smaller point than the starting point from weight range from 40 kg to 130 kg. Figure 6(b) presents the average and critical sound levels from table 2 columns eight and nine against the weight dropped.



(a)



(b)

Fig. 6 Sound level against weight dropped. (a) Sound level against each phone; (b) Average and critical sound level against each phone (Source: authors)

3.2 Vibration levels

Phones three and four are employed to evaluate the vibrations impact on the deadlift performer. Table 3 shows the average vibration among three repeats that phones three and four recoded at a given weight, also with column four being the average of phones three and four and column five being the highest recorded value for a given weight.

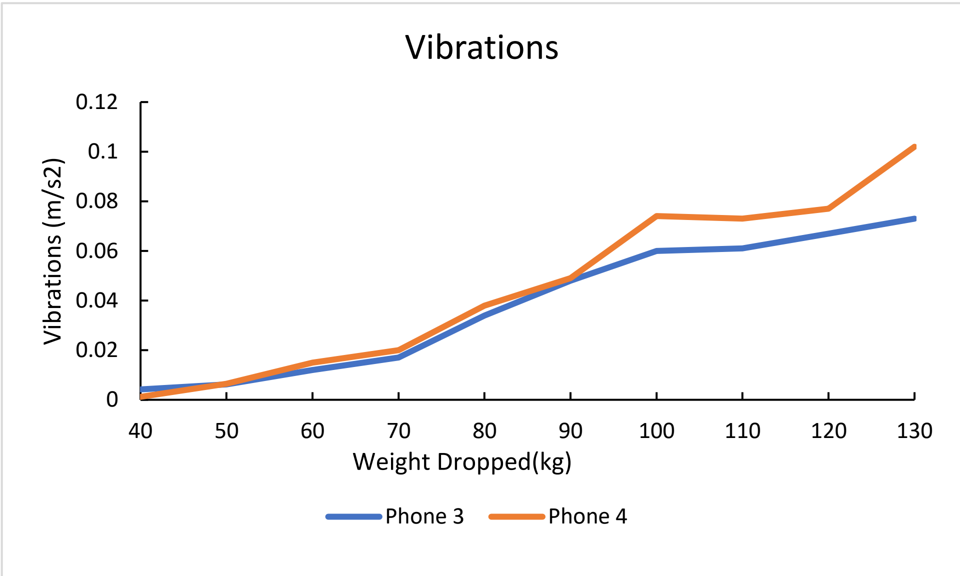
Table 3. Measured vibration level average for phones three and four from deadlift drops (Source: authors)

	Vibration level(m/s^2)			
Weight (kg)	Phone 3	Phone 4	Average	Critical
40	0.0042	0.0012	0.0027	0.0042
50	0.0062	0.0065	0.00635	0.0065
60	0.012	0.015	0.0135	0.015
70	0.017	0.02	0.0185	0.02
80	0.034	0.038	0.036	0.038
90	0.048	0.049	0.0485	0.049

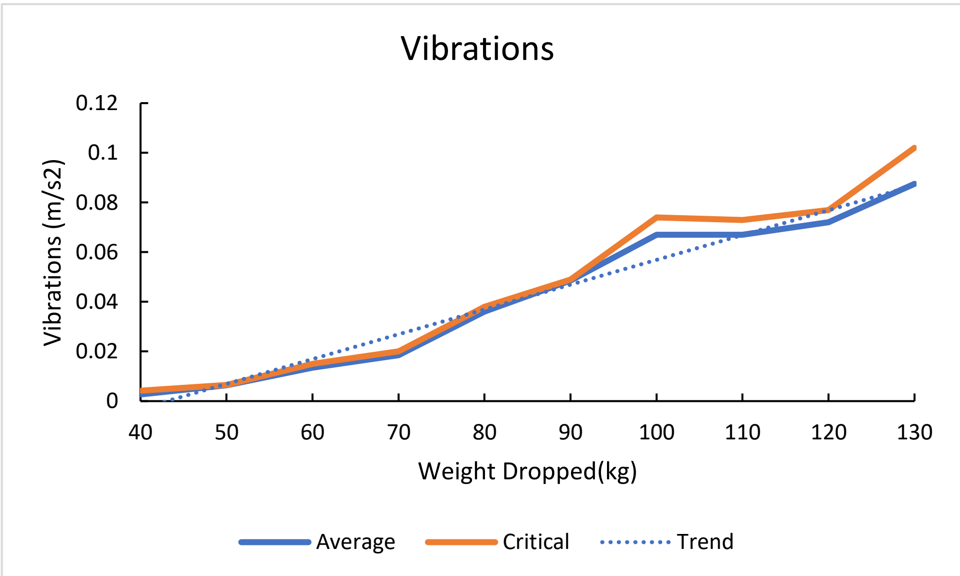
100	0.06	0.074	0.067	0.074
110	0.061	0.073	0.067	0.073
120	0.067	0.077	0.072	0.077
130	0.073	0.102	0.0875	0.102

3.2.1 Average vibration vs Weight

The vibration for phones three and four is averaged out for each drop of a given weight and then again averaged between the phones for each weight. Figure 7(a) demonstrates the weight against the vibration collected by the two phones. The two lines are almost overlapping showing that they have close values. While, Figure 7(b) shows the relationship between average vibration and weight, critical vibration and weight.



(a)



(b)

Fig. 7 Measured Average Vibration Level against Weight. (a) Vibrations against weight dropped; (b) Average and critical vibrations against weight dropped (Source: authors)

4. Discussion

Most of the previous researches that have evaluated the usefulness of lightweight floating floor to mitigate vibration and noise from activities [35-37] or how the vibration and noise transmit along with the structure of the buildings [38,39]. However, very little of the relationship between the varied weight drops and the induced N/V is analyzed. In [10], the major focus is the N/V induced by aerobic machines and there was no evaluation of the impact of weight-based activities on N/V.

As shown by Figure 7 vibration level increases as weight increases. Figure 7(b) shows the trend as, unlike the sound levels these points do show a correlation between weight and vibration level. The trend line commences with 0.0027 m/s^2 at the weight drop of 40 kg and reaches the peak of 0.0875 m/s^2 at the weight drop of 130 kg. The noise level drops sharply from 40 kg to 50 kg and tends to stay stable although it suffers from a small fluctuation. For this reason, a line of best fit has not been plotted. It is expected that the noise would have followed a similar relationship with weight as vibration does, being that vibration level increases as weight increases however this is not the case. The greatest average sound level is at 40 kg of dropped weight. Weight combinations between 40 kg and 70 kg are made up of just one rubber bumper plate on each side of the bar. An evident during the experiment is that having one rubber bumper plate on each side of the barbell, allows the plate to move against the clip and the bar plate stop when dropped. This movement that is caused by the impact of the plate with the floor created noise itself. This noise created from the plate hitting the bar is not dampened by the flooring as it has no contact with the damp proof flooring. This can explain the weight combinations of 40 kg – 70 kg being similar magnitudes of the heavier weights. Combinations E to J include weights 80 kg to 130 kg. Each of these combinations has multiple rubber bumper plates, therefore, eliminating the effect of the bumper plate hitting the bar plate stop. The highest average sound level recorded in this given range is at 110 kg at 99.8 dB, the lowest average sound level at weight 100 kg being 98.3 dB. The jump from highest to lowest sound level values is made in just a 10 kg interval. A possible reason for this can be that the dampening properties of the flooring are most effective at the specific weight of 100kg. However, this hypothesis is not supported by the value of sound levels produced by the surrounding weights. Instead, this small interval from highest to lowest (in the range of 80 kg -130 kg) can further highlight the lack of correlation of the data, possibly caused by limitations highlighted in section 5. Every average from Table 2 is above 85 dB which highlighted in the literature review [3] is the minimum value for when NIHL can begin to occur. These are impulse sounds measured with very little duration however NIHL is caused by many different scenarios and situations in daily life. A reduction in any of these noises above 85 dB should be achieved where possible. It is the responsibility of the gym to ensure that their environment does not contribute towards this. As can be seen in section 3.1, the eight-hour energy for an individual drop is low. However, in a busy gym environment, there will be multiple drops happening simultaneously, therefore, increasing the duration of these sounds giving a larger eight-hour equivalent energy value. Besides, there will be background noise such as music and also noise and vibration from cardio machines such as treadmills.

5. Conclusions

Ensuring a healthy gym environment is critical to sustainable development. As the large fitness market in the UK, it highlights the importance of our study to address the critical issue induced by the vibration and noise in the gym at the University of Birmingham. By fostering on providing the gym with a safe place to excise, this study offers guidelines to test the vibration and noise with a convenient tool a smartphone. The adoption of the smartphone provides the benefit that the prevalence of the mobile phone allows the gym members to test the noise and vibration in their daily lives.

Further investigation should also be undertaken to investigate how impulse sounds from the dropping of loaded barbells are affected by the other sounds in the gym environment. The frequency domain of sound and vibration can be studied in the future. There is no mechanism used to ensure connection where vibrations are measured accurately. In future studies, the use of specialized gels can be used between floor and accelerometers or accelerometers with floor clips and mounts. The bar is dropped from the top of a deadlift by a weightlifter. The lack of precise mechanical controls means that the weights at the bar ends may hit the ground at different times. This can affect the amplitude of the noise given off at the initial contact of the barbell with the ground, as one side of the bar connects with the ground first. Another limitation is the degree of measurement of the smartphones as when it comes to calibration the phones can only be calibrated in measurements of 0.1 dB. In the future devices with a higher level of precision should be used. Due to having limited access to smartphones at the same time, calibration is done at separate times. A possible improvement to the calibration process will be to ensure all devices are calibrated under the same conditions by having them all present together. Besides, the same models of the smartphone should be used.

6. Conflict of Interest

The authors declare there is no conflict of interest.

7. Appendix

7.1 Recorded data

7.1.1 Table of peak sound

The data for peak sound level recorded on each phone for each performed drop is shown in table 4. The results here are used to calculate the averages forming the data for each cell in Table 2.

Table 4. Peak sound level recorded for each drop weight (Source: authors)

Sound Level (dB)																		
	Phone 1			Phone 2			Phone 3			Phone 4			Phone 5			Phone 6		
Weight	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
40	105.8	100.8	102.9	103.4	104.6	103.9	99.5	102.1	102.9	98.5	102.8	104.9	100.3	104.6	103.4	103.7	100.1	104.3
50	99.4	101.2	106.4	98.6	102.6	97.7	98.6	96.4	98.6	99.8	97.4	99.7	99.6	95.4	98.2	98.5	96.2	97.6
60	99.6	98.3	101.6	101.9	100.3	103	101.6	98.8	102.2	102.4	98.8	102.7	99.1	97.8	101.5	96	97.3	100.8
70	98.1	100.4	96.5	96.1	101.8	96.9	97.5	103.1	98.8	97.8	102.4	97.2	101.8	101.4	97.9	95.1	98.6	95
80	101.3	100.5	102.4	101.9	98.8	100.3	97.5	97.1	98.7	98.5	99.4	99	98.9	99.2	99.8	96.4	99.8	96.6
90	98.1	102.3	97.7	98.3	100.8	96.6	97.6	99.9	95.8	98.7	102.5	96.3	94.1	99.9	92.2	104.7	101.8	101.1
100	101.9	97.5	95.7	102.8	103.7	100	102	97.7	99.6	98.4	97.3	98.1	97.6	97.6	92.6	97	94.3	96
110	101.4	99	102.4	100.8	105.1	106	96.1	98.8	98.7	100	98.3	98.7	96.3	100.4	100.8	98.3	97.8	97.3
120	100.5	103.3	99.5	97.8	102.6	100.9	95.7	99.9	98.3	96.6	98.9	99.3	96.6	99.3	98	97.5	98.8	97.8
130	100.3	98.2	97.4	105.8	98.1	97.9	101.6	97.5	96	103.1	97.1	96.6	102.8	101	97.5	99.2	97.3	95.6

7.1.2 Table of vibration levels

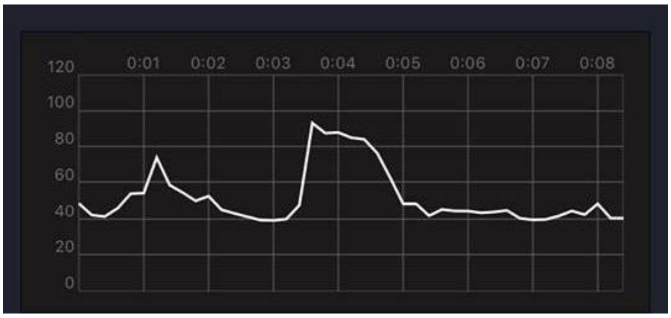
This data is then used to calculate the average for phones three and four at each drop weight, hence forming the data presented in table 3.

Table 5. Vibration level recorded for each drop weight (Source: authors)

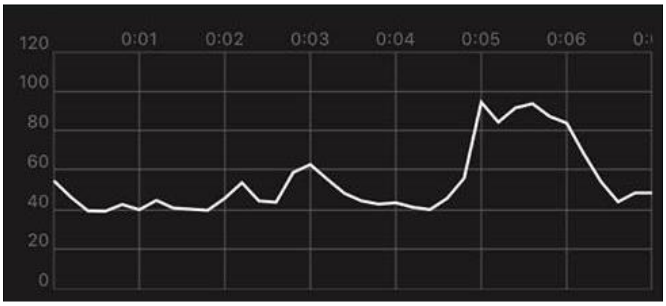
Weight (kg)	Vibration Level (m/s²)																	
	Phone 1			Phone 2			Phone 3			Phone 4			Phone 5			Phone 6		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
40	N/A	0.029	0.012	N/A	0.0038	N/A	0.0045	0.0035	0.0047	0.0014	0.00093	0.0012	0.0069	0.004	0.0028	0.003	0.00087	0.0012
50	0.035	0.046	0.061	0.0091	0.0095	0.015	0.0066	0.0043	0.0078	0.0058	0.0073	0.0065	0.012	0.0047	0.012	0.0046	0.0027	0.0027
60	0.042	0.033	0.051	0.019	0.06	0.016	0.012	0.016	0.0091	0.014	0.021	0.0087	0.0082	0.012	0.016	0.0031	0.0037	0.0035
70	0.04	0.15	0.046	0.024	0.026	0.02	0.018	0.021	0.013	0.013	0.022	0.026	0.016	0.023	0.0036	0.012	0.018	0.0082
80	0.088	0.045	0.048	0.054	0.025	0.062	0.033	0.033	0.035	0.034	0.041	0.038	0.014	0.035	0.045	0.041	0.015	0.046
90	0.11	0.11	0.097	0.083	0.082	0.58	0.057	0.055	0.031	0.045	0.025	0.076	0.04	0.018	0.049	0.055	0.062	0.035
100	0.01	0.099	0.15	0.034	0.14	0.18	0.04	0.095	0.045	0.084	0.066	0.073	0.07	0.021	0.041	0.047	0.094	0.088
110	0.085	0.18	0.13	0.1	0.19	0.16	0.035	0.075	0.073	0.084	0.039	0.096	0.082	0.051	0.045	0.75	0.095	0.078
120	0.11	0.081	0.12	0.13	0.13	0.084	0.064	0.07	0.067	0.056	0.077	0.098	0.1	0.12	0.09	0.1	0.067	0.083
130	0.14	0.073	0.081	0.13	0.079	0.044	0.072	0.075	0.072	0.13	0.085	0.091	0.079	0.09	0.13	0.14	0.098	0.11

7.1.3 Raw data for impulse duration

Below are figure 9 showing the impulse duration of sound recorded from phone 1, showing that roughly the impulses last at a similar level to peak for a conservative estimate of 0.5 seconds.



(a)



(b)

Fig. 9 Impulse duration of sound recorded from phone 1 (a) Sound level (dB) against time Phone 1 Drop 16; (b) Sound level (dB) against time. Phone 1 drop 14 (Source: authors)

7.2 Table of Phones used

Table 6 shows the make and model of each of the phones used for the measurements in the experiment.

Table 6. Phone Models used (Source: authors)

Phone number	Make and Model
1	iPhone 6
2	iPhone 7 plus
3	iPhone 7
4	iPhone 6s
5	iPhone 6 plus
6	iPhone 7

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