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Improved Accuracy in Determining the Acceleration Due to Gravity in Free Fall Experiments Using Smartphones and Mechanical Switches

Supakorn Harnsoongnoen ^{1,*} , Saksun Srisai ¹, Pongsathorn Kongkeaw ² and Tidarat Rakdee ¹

¹ The Biomimicry for Sustainable Agriculture, Health, Environment and Energy Research Unit, Department of Physics, Faculty of Science, Mahasarakham University, Kantarawichai District, Maha Sarakham 44150, Thailand; 64010262001@msu.ac.th (S.S.); 63010212039@msu.ac.th (T.R.)

² Program of Physics, Faculty of Science and Technology, Rajabhat Maha Sarakham University, Muang Maha Sarakham District, Maha Sarakham 44000, Thailand; pongsathorn.ko@rmu.ac.th

* Correspondence: supakorn.h@msu.ac.th

Abstract: This study presents an innovative methodology to augment the accuracy of gravitational acceleration (g) measurements in free fall experiments. Employing smartphones and integrating mechanical switches, our approach utilizes a built-in microphone for precise time measurements during the initiation of free fall. A meticulously designed mechanical switch controls the release of a steel sphere, triggering the timer upon the initiation of descent. Our experimental outcomes showcase a commendable congruence between the calculated g value and the locally accepted reference value, pinpointing g at $9.8274 \pm 0.01 \text{ m/s}^2$. A salient feature of our method is the utilization of the smartphone's onboard microphone sensor, offering superior convenience to conventional sensor-based methodologies that require additional equipment. Additionally, our study introduces the seamless integration of open-source software on smartphones, facilitating the direct display and analysis of sound parameters. This integration streamlines the experimental process, contributing to the ongoing endeavors aimed at enhancing accuracy in free fall experiments. Our findings underscore the potential of smartphones and mechanical switches as accessible and effective tools in advancing physics education and scientific investigations.

Keywords: gravitational acceleration; free fall; acoustics; smartphone; laboratory tool; physics teaching



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1. Introduction

The scientific exploration of gravity began in the 16th century with Galileo Galilei, who demonstrated that objects of varying mass experience the same acceleration due to gravity [1]. Isaac Newton developed the mathematical framework for gravity in 1687, followed by Henry Cavendish's experimental measurement of gravity in the 18th century, which helped determine Earth's density. Albert Einstein's general theory of relativity in 1915 revolutionized the understanding of gravity, portraying it as the curvature of spacetime by massive objects. Experimental validations of Einstein's theory, such as the gravitational deflection of light by Arthur Eddington and the gravitational redshift by Robert Pound and Glen A. Rebka, further confirmed his predictions. Gravitational waves, a consequence of general relativity, have been detected [2,3]. There is currently a collaboration between several organizations aimed at studying this phenomenon. Notably, LIGO, Virgo, and KAGRA comprise the advanced gravitational wave detector network. LIGO is operated by the National Science Foundation, Virgo by the European Gravitational Wave Observatory, and KAGRA by the Ministry of Education, Culture, Sports, Science and Technology-Japan (MEXT). Standing at the forefront of gravity research, their collaborative endeavor aims to delve deeper into the nature of gravity while also striving to detect gravitational waves [4–7]. However, understanding basic gravitational acceleration (g) at

the high school and university level within the domain of classical mechanics is considered very important because gravitational acceleration quantifies Earth's gravitational influence on objects in close proximity to its surface, dictating their descent. With a fixed value of approximately 9.81 m/s^2 near the Earth's surface [8–12], this gravitational constant forms the cornerstone of fundamental physical principles, including Newton's law of gravitation and Einstein's theory of relativity and extends its utility across scientific and engineering domains. This value of g plays a central role in the kinematic description of free-falling objects, elucidating their velocity changes over time under the influence of Earth's gravitational field, thereby providing profound insights into the predictability of falling bodies. In sum, gravitational acceleration g is an indispensable concept in physics, bridging historical and contemporary frameworks and serving as a crucial tool in diverse scientific and engineering applications.

The experimental determination of g assumes a pivotal role in introductory physics and mechanics courses at school and college. It not only imparts fundamental principles but also cultivates scientific methodology and an appreciation for historical scientific achievements. This experiment serves as a cornerstone in nurturing critical thinking and quantitative skills among students. The most common and well-known techniques for measuring g experimentally in class is free fall. In 1969, Oliver and Pirie introduced a methodology for gauging g through free fall, employing a photodiode to trigger and cease the timing of a Panax transistorized scaler [13]. Subsequently, in 1974, Ferlen and Eaton devised a straightforward release mechanism for quantifying g in free fall experiments utilizing a photocell unit [14]. Similarly, Walton, D. S. proposed a basic apparatus for g determination via free fall in the same year, integrating a timer-counter circuit [15]. Further advancements were made by Blackburn and Koenig in 1976, who proposed a meticulous falling-body experiment employing TTL logic gates within the timing circuit [16]. Edgar, in 1991, suggested a cost-effective timer for free fall investigations, utilizing the lab timer [17]. In 1994, Childs proposed an expedited determination of g employing photogates [18]. Wick and Ruddick, in 1999, presented a method for precise g measurement utilizing falling balls [19]. Moving into the digital era, in 2011, Vogt, Kuhn, and Müller proposed a computer-aided approach for g determination [20]. Vogt and Kuhn, in 2012, advocated for the analysis of free fall phenomena utilizing smartphone acceleration sensors [21]. Expanding these methodologies, Schwarz, Vogt, and Kuhn put forth the proposition of employing acoustic measurements on bouncing balls as a means to determine gravitational acceleration [22]. Subsequently, in 2015, AbdElazem and Al-Basheer introduced an alternative method utilizing an IR transceiver for the same purpose [23]. Building upon these advancements, Fontana, Yeung, and Hall in 2020 advocated for the utilization of the ticker tape timer method to not only ascertain gravitational acceleration but also account for the effects of friction [24]. Another popular technique for measuring g in the classroom is the pendulum [25–29]. Both of these techniques are popular because they are both directly influenced by the gravitational acceleration and they offer straightforward and accessible ways to measure the acceleration due to gravity in a classroom setting. This makes both experimental methods become standard laboratory practices in school and college.

The free fall experiment necessitates precise time interval measurements at sub-second scales, posing challenges for conventional handheld stopwatch devices. This is a key driver behind the widespread adoption of photogate timers in educational laboratory settings. In contemporary contexts, smartphones equipped with a plethora of sensors offer a versatile platform for accurate time measurement and data acquisition, as documented in recent literature [20–23,26–30]. A compelling alternative to conventional stopwatch and photogate methods emerges through the utilization of readily accessible smartphones equipped with sound-recording capabilities. In numerous mechanics experiments, sound emissions can serve as a precise timing mechanism, and in such instances, direct audio recording offers a means to obtain accurate measurements of the pertinent time intervals [31–38]. Within this scholarly exposition, researchers expound upon a methodological approach that employs smartphone audio recording as a means of precisely timing the descent of steel balls. This

technique leverages the acoustic signals generated by the switch activation at the initiation of the experiment and the subsequent auditory cues of the steel ball impacting the ground to establish the start and end times of free fall, respectively.

2. Theoretical Background

In the modern era, our understanding of gravity has evolved significantly, propelled by advancements in theoretical physics and observational evidence. At the heart of this understanding lies Albert Einstein's general theory of relativity (GR), which revolutionized our conception of gravity by proposing that massive objects warp the fabric of spacetime, causing curvature and influencing the motion of other objects. However, in this research, we focus on explaining the classical foundations of gravity as the main focus. We begin by revisiting Newton's law of universal gravitation, which states that the gravitational force between two point masses is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. Mathematically, this can be expressed as

$$F = G \frac{m_1 m_2}{r^2} \quad (1)$$

where F is the gravitational force between the two objects, G is the gravitational constant ($6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$), m_1 and m_2 are the masses of the two objects, and r is the distance between the centers of the two objects. On the surface of the Earth, the object's mass (m_2) does not affect the value of g because it cancels out when considering the force experienced by an object of mass m_2 . Therefore, we usually consider m_2 to be the mass of a test object experiencing gravity, and for simplicity, we can take m_2 to be 1 kg. On the surface of the Earth, the distance (r) from the center of the Earth to the object's surface is approximately equal to the Earth's radius (R). Now, considering a test object with mass $m_2 = 1 \text{ kg}$, the gravitational force experienced by it near the surface of the Earth is

$$F = G \frac{m_1 m_2}{r^2} = G \frac{m_1}{R^2} \quad (2)$$

Now, according to Newton's second law of motion, the force F acting on an object of mass m_2 is equal to the mass times the acceleration ($F = m_2 g$). So we have

$$G \frac{m_1}{R^2} = m_2 g \quad (3)$$

$$g = G \frac{m_1}{R^2} \quad (4)$$

Given that $G = 6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$, $R \approx 6.371 \times 10^6 \text{ m}$ (radius of the Earth), and m_1 is the mass of the Earth, which is approximately $5.972 \times 10^{24} \text{ kg}$, we can calculate $g = 9.81 \text{ m/s}^2$. So the acceleration due to gravity on the surface of the Earth is approximately 9.81 m/s^2 . However, when the elevation of the Earth's surface changes, the gravitational value (g) will also change.

A solid body is permitted to fall freely over a fixed distance, denoted as H , and the time taken to cover this distance is observed. The formula for a body, initially moving at a velocity of $u \text{ m/s}$ and traversing a distance H under free fall for a time t , is as follows:

$$H = ut + \frac{1}{2}gt^2 \quad (5)$$

When a solid body is released from rest, with $u = 0 \text{ m/s}$, Equation (5) can be rewritten as

$$H = \frac{gt^2}{2} \quad (6)$$

The calculation of g via the free fall method entails the precise measurement of the time (t) required for a steel ball to descend a defined vertical distance (H). The determination

of g is derived through the application of the following mathematical relationship in Equation (6). In the context of this experiment, where H represents the falling height and t denotes the time of descent, the calculation of g is achieved by employing the following formula:

$$g = \frac{2H}{t^2} \quad (7)$$

3. Materials and Methods

Figure 1 illustrates the schematic representation of the researchers' experimental setup. A retort stand, affixed with a clamp, is positioned on the laboratory table. An electromagnetic solenoid, fastened securely with another clamp, is connected to a switch via a direct current (DC) power supply. The electromagnetic solenoid serves the function of capturing and subsequently releasing a steel ball, which has a diameter of 9.53 mm and a mass of 3.52 g. In the course of the experiment, the steel ball is affixed to the electromagnetic solenoid at varying heights and is then released to undergo vertical free fall, ultimately striking the ground. In the pursuit of precision, a retort stand was meticulously marked to ascertain the precise height of the steel ball's descent relative to the laboratory table using a tape measure. This endeavor revealed a meticulous arrangement comprising five distinct levels: 0.60, 0.80, 1.00, 1.20, and 1.40 m. The lowest point of the steel sphere was installed and adjusted to a predetermined height on a retort stand, as depicted in Figure 1. During the experiment, all windows, doors, fans, and air conditioners are closed to prevent drafts inside the room during the experiment. In adherence to a rigorous methodology, the test was meticulously repeated three times at each height of the steel sphere launch. Prior to the experiment, it was imperative to position both the mechanical switch and smartphone in close proximity to the anticipated trajectory of the metal sphere's descent. This strategic placement was implemented with the specific intention of minimizing the distance between the sound source, represented by the metal sphere's impact and switch contact, and the recording device, the smartphone. During this descent, the time it takes for the steel ball to traverse this vertical trajectory is meticulously measured, while concurrent audio recording of the event is facilitated using a smartphone.

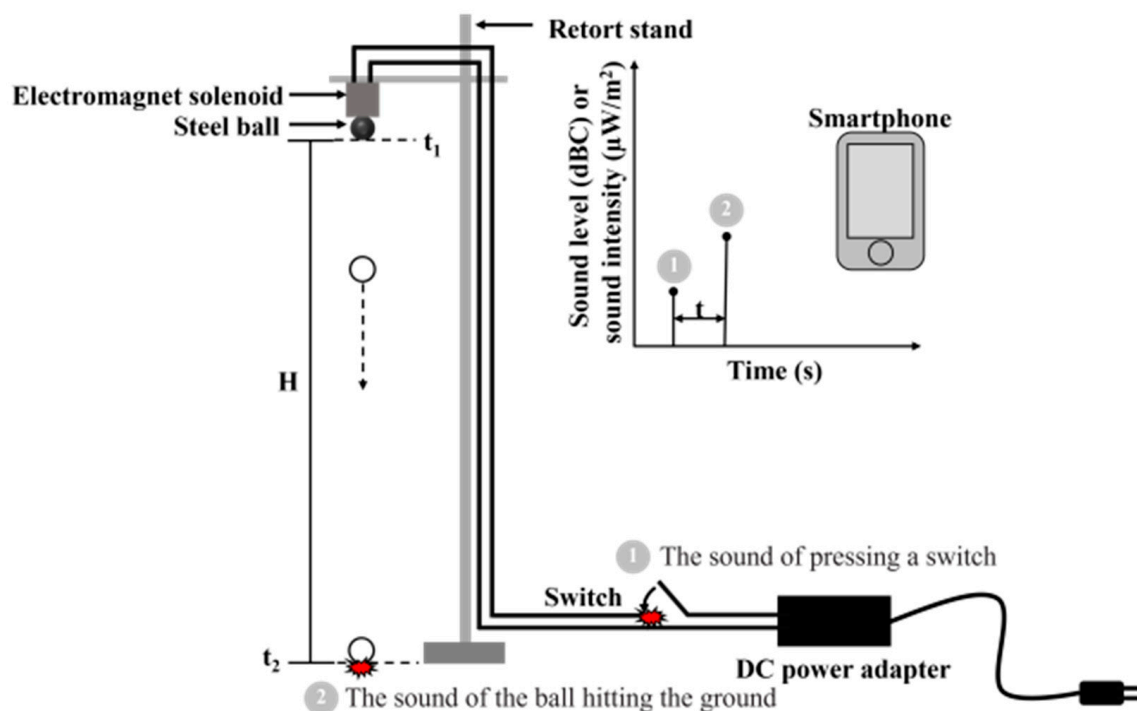


Figure 1. The schematic of the experimental setup.

Figure 2 depicts the setup of the experimental system developed and utilized in this study. In the experimental setup, careful attention was paid to the positioning of the smartphone, mechanical switches, and nearby ball drop points to minimize the speed limit of sound. Furthermore, during the experiment, the wind must be controlled to ensure its absence, and the temperature in the room must be maintained at a constant value throughout the experiment.

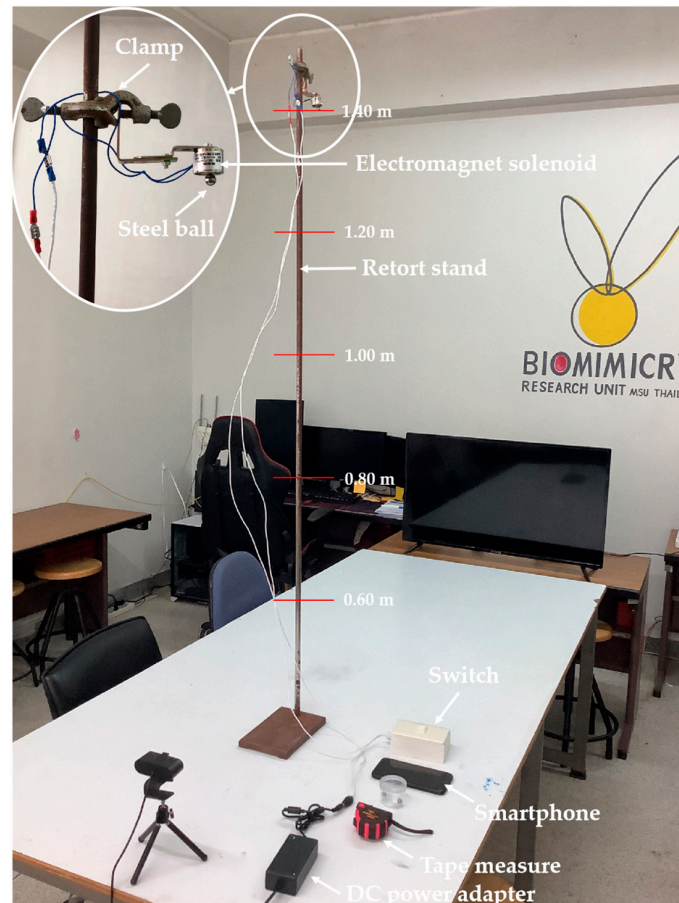


Figure 2. Experimental setup.

Figure 3 shows the smartphone screen where the sound level and intensity were recorded by the SPARKvue App in each experiment. SPARKvue is available free of charge on all devices as a browser-based application. It is available for both Android and Apple iOS devices, making it accessible across a wide range of mobile devices commonly used in educational settings [39]. In the audio recording, the initial peak corresponds to the moment the switch is pressed, while the subsequent peak signifies the instance when the steel ball impacts the ground, indicated by the red box as shown in Figure 3. The time difference between these two events can be directly monitored on the application screen or recorded for later analysis and integration with other software programs.

In this experimental investigation, the research team systematically partitioned the release heights for the steel ball into five distinct levels. Commencing from an initial height of 1.40 m, they methodically reduced the drop height by 0.20 m increments. At each designated level, the experiment was meticulously repeated three times, and the resultant data measurements were subjected to rigorous averaging procedures prior to subsequent analysis and graphical representation.

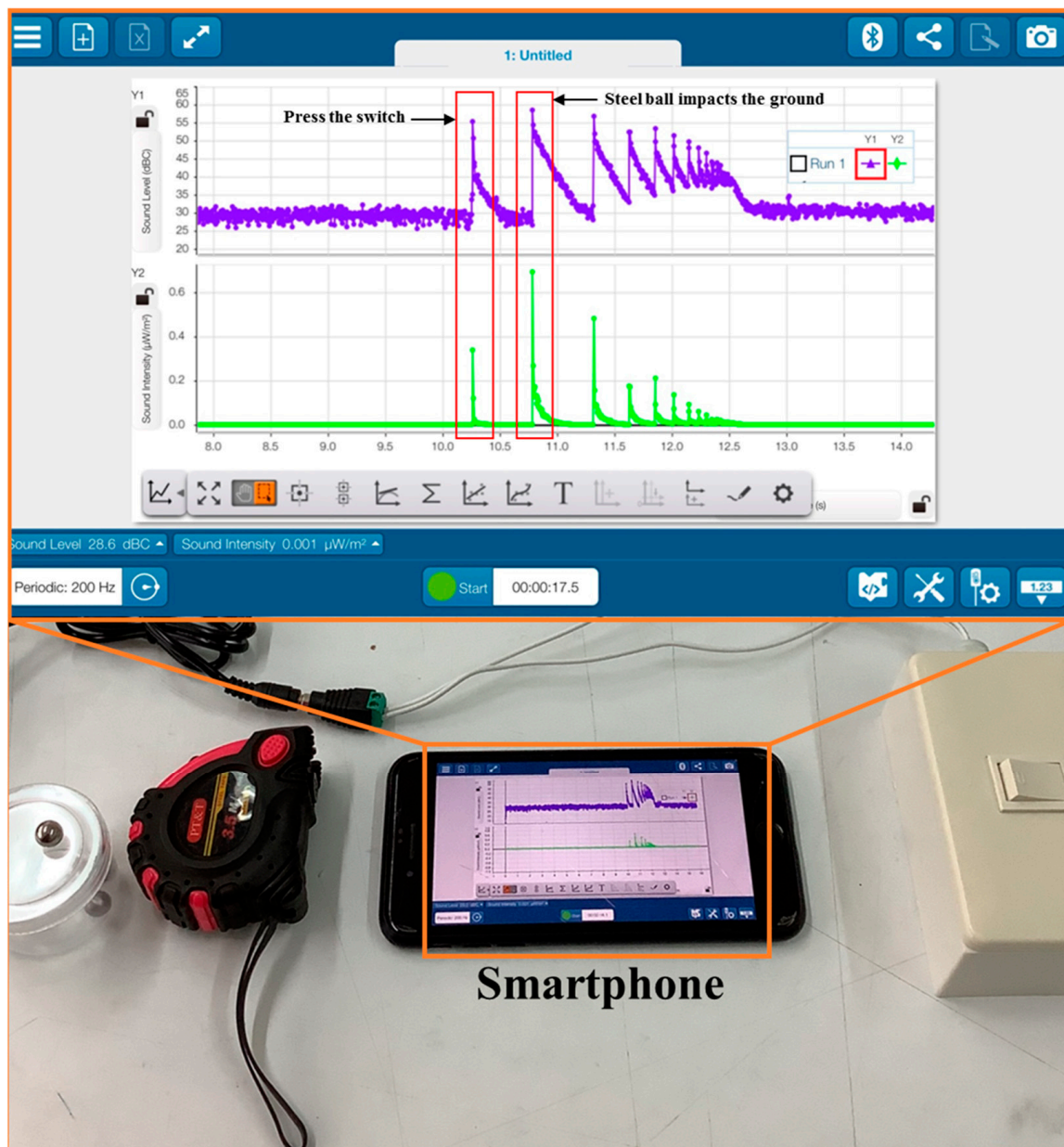


Figure 3. Recording sound level and intensity using the smartphone with an iPhone 8 Plus model.

4. Results

Figure 4a,b aptly illustrate the recorded sound data, incorporating both sound level and sound intensity. Within these recordings, Peaks 1 (t_1) and 2 (t_2) correspond to discernible acoustic events, signifying the actuation of the switch and the subsequent impact of the steel ball with the ground, respectively. Subsequent peaks capture the acoustic signature of the restitution bounce exhibited by the steel ball, characterized by a gradual diminishment in amplitude. The time data for a steel ball falling from varying heights, acquired through both theoretical calculations and experimental measurements, are presented in Table 1. The time period obtained at each altitude consists of three values. All three values are used to calculate the average and standard deviation (S.D.) in order to analyze the distribution of the data around the average. The experiment's results revealed that the time intervals obtained from measuring the sound level and intensity between the pressing of the mechanical switch and the steel ball hitting the ground were consistent. Hence, we have the flexibility to analyze the results using data from either source.

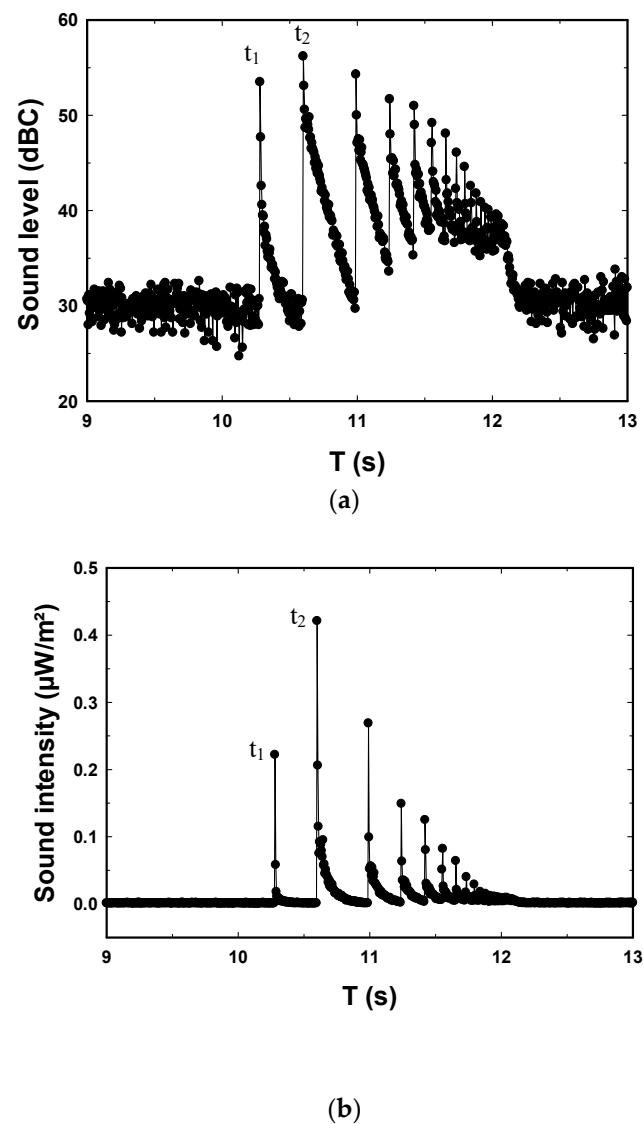


Figure 4. Sound signals corresponding to the pressing of a switch and the impact of a steel ball with a table at different time intervals, showcasing (a) sound level and (b) sound intensity.

Table 1. Time measurements for the descent of a steel ball from different heights: theoretical calculations versus experimental observations.

H (m)	Theory		Experiments	
	T (s)	T (s)	T ² (s ²)	S.D.
0.60	0.350	0.330	0.109	0.011
0.80	0.404	0.392	0.153	0.005
1.00	0.452	0.448	0.201	0.012
1.20	0.495	0.482	0.232	0.002
1.40	0.535	0.522	0.272	0.002

The theoretical time calculations presented in Table 1 are derived by substituting the altitude and gravitational acceleration values into Equation (6), using $g = 9.81 \text{ m/s}^2$. In Figure 5a, researchers present the correlation between T_{theory} and $T_{\text{experiment}}$. The empirical findings indicate that the time measurements obtained through the proposed research method exhibit a relative error of 3.27% when compared to theoretical values. In Figure 5b,

researchers illustrate the correlation between T^2 and H , revealing a slope of 4.9137 m/s^2 and an R^2 coefficient of 0.9952 .

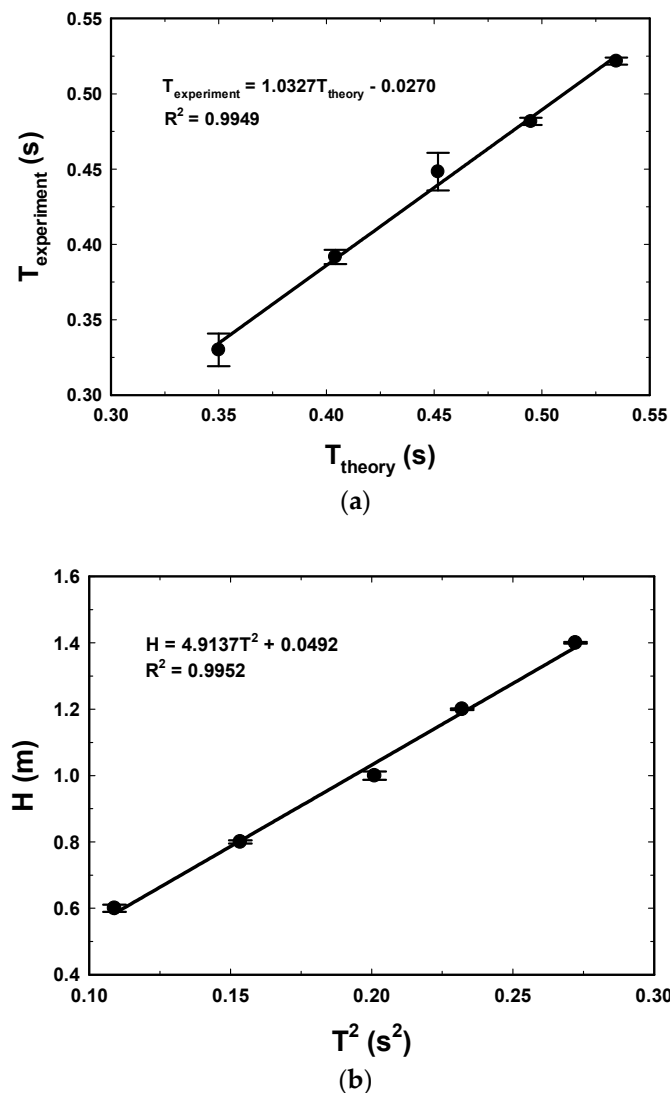


Figure 5. Correlation between T_{theory} and $T_{\text{experiment}}$ (a) and T^2 and H (b).

This derived slope is then employed to calculate the g using Equation (7), yielding a value of 9.8274 m/s^2 . Remarkably, this calculated g exhibits a mere 0.17737% relative error when juxtaposed with the theoretical value. Furthermore, the propagated uncertainty, denoted as ± 0.01 , underscores the precision of using smartphones for the meticulous measurement of time intervals pertinent to gravitational experiments.

5. Discussion

5.1. Accuracy and Consistency of Results

The primary objective of this study was to employ smartphone audio recording as a means to determine g via the free fall method, aiming for accuracy and reliability comparable to established reference values. The calculated value of g from our experimental setup, accounting for associated uncertainties, yielded a precise measurement of $9.8274 \pm 0.01 \text{ m/s}^2$. Notably, this value demonstrated a remarkable alignment with the locally accepted reference value. The acceleration due to gravity by an altitude calculator

estimates the approximate acceleration due to gravity on the surface of the Earth based on the altitude [40]. The equation for the acceleration due to gravity based on altitude is:

$$g_{alt} = g \times \left(\frac{r_e}{r_e + h} \right)^2 \quad (8)$$

where h is the altitude above mean sea level (AMSL), g_{alt} is the acceleration due to gravity at a specific altitude, r_e is the mean radius of the Earth (6371.009 km), and g is the acceleration due to gravity at sea level (9.80665 m/s²) [41]. To measure the height of the experimental location, it was found that the altitude above mean sea level was 176 m. When calculated using Equation (8), we obtained g_{alt} is 9.80611 m/s². This was found to be close to the nominal “average” value at the Earth’s surface, known as standard gravity, which is, by definition, 9.80665 m/s² [41], which results in a minimal relative error of 0.0055%. A review of research articles and textbooks revealed that the standard reference g value is 9.81 m/s² [8–12,21,25]. The congruence between our calculated g and the established g value near the Earth’s surface, which stands at approximately 9.81 m/s², and the experimental location is 9.80611 m/s², and the methodology presented here yielded results within accuracy levels of 99.8226% and 99.7829%, respectively. This underscores the accuracy achieved through the utilization of smartphone audio recording, despite inherent challenges in precise time measurement at sub-second scales, with the smallest relative error amounting to 3.27%. This small margin of error is indicative of the reliability and precision of the experimental setup. The consistency of our results was evident through systematic experimentation, varying the release heights of the steel ball in controlled increments. Through meticulous data collection and averaging procedures, the time measurements acquired via audio recording consistently aligned with theoretical calculations. The comparison between theoretical and experimental time measurements provides strong evidence of a high degree of correlation, further supporting the accuracy of the obtained results across varying experimental conditions. Moreover, the propagated uncertainty of ± 0.01 emphasizes the precision achieved using smartphones for time interval measurements pertinent to gravitational experiments. This level of precision is notable considering the simplicity and accessibility of the method, underscoring the potential of smartphone technology in facilitating accurate scientific measurements. The above discussion clearly shows that the results obtained through smartphone audio recording demonstrated not only accuracy but also commendable consistency in determining gravitational acceleration via the free fall method. These findings validate the feasibility and reliability of utilizing smartphone onboard microphones as a convenient and precise tool in experimental physics, particularly in educational settings aiming to enhance students’ understanding of fundamental physical principles.

5.2. Comparison with Alternative Methods

The traditional experimental determination of g often relies on specialized equipment like photogate timers or handheld stopwatches, posing challenges in achieving precise time interval measurements, especially at sub-second scales. In contrast, the methodology presented in this study leverages the built-in microphone of a smartphone for precise time measurements during free fall experiments. Comparison with conventional sensor-based methods reveals distinctive advantages of utilizing smartphone audio recording. The smartphone’s ubiquitous presence and integrated capabilities offer a more accessible and convenient approach to experimental physics, particularly in educational settings where accessibility to specialized equipment might be limited. This method obviates the need for additional costly equipment, streamlining the experimental setup and reducing resource constraints in educational laboratories. Furthermore, the integration of SPARKvue, facilitating real-time display and analysis of sound parameters like sound level, sound intensity, and period values, enhances the experimental process. This seamless integration provides a user-friendly interface, enabling direct and accurate time measurements through sound recordings, eliminating the complexities associated with traditional sensor setup and

calibration. Moreover, while traditional methods require specific equipment calibration and meticulous setup, the smartphone-based approach offers a more straightforward setup process. The smartphone's capability to capture and analyze audio signals associated with the initiation and termination of free fall events simplifies the experimental procedure, making it more accessible to a wider spectrum of learners without compromising on accuracy. However, it is essential to acknowledge that this method might present limitations in certain experimental conditions or environments where ambient noise or variability in sound emissions could affect the accuracy of time measurements. Additionally, while our study exhibits promising results, further comparative studies across diverse experimental scenarios could provide a comprehensive evaluation of its efficacy in various contexts. Therefore, it is sufficient to conclude that while traditional sensor-based methods have long been the cornerstone of experimental physics, the adoption of smartphone audio recording represents a novel and accessible alternative. The comparison highlights the advantages of smartphone-based methodologies, showcasing their potential to revolutionize experimental setups, particularly in educational environments, by offering a balance between accessibility, accuracy, and simplicity. Table 2 delineates the prevailing methodologies employed in gauging the g , notably through free fall and pendulum experiments. These methods deploy a spectrum of sensors—acceleration, microphone, IR, ultrasonic, proximity, magnetometer, and ambient light sensors—integrated within contemporary smartphones or interfaced with external apparatus such as personal computers and Arduino boards. Our conducted experiment yields a remarkable relative error of merely 0.18%, a notable achievement eclipsing the majority of scholarly references in this domain. Notably, Reference [32] reports a marginally lower value of 0.10%. Nevertheless, our proposed approach heralds greater adaptability and elegance in execution. The uncertainty range of our experiment, $\pm 0.01\% \text{ m/s}^2$, stands narrower than that of Reference [32], signifying heightened precision in delineating gravitational acceleration. This affirms the constricted scope around the computed value, thereby augmenting the accuracy and trustworthiness of our proposed framework. Our methodology stands out for its precision and adaptability in ascertaining gravitational acceleration. While Reference [32] marginally reduces relative error, our approach distinguishes itself through its simplicity and a narrower uncertainty range, indicative of heightened precision. This accentuates the potential superiority of our suggested methodology for precise and straightforward gravitational assessments.

Table 2. Performance comparisons used to determine gravitational acceleration (g).

Method	Sensor	Accuracy	Uncertainty	References
Free fall and acoustical Doppler effect	Microphone with a personal computer	99.08%	$9.90 \pm 0.2 \text{ m/s}^2$	[20]
Free fall	Smartphone acceleration sensor	98.06%	$10.00 \pm 0.2 \text{ m/s}^2$	[21]
Free fall	Smartphone's onboard microphone	99.99%, 97.45%, and 99.59%	9.82, 10.06, and 9.77 m/s^2	[22]
Free fall	IR transceiver	99.8063%	$9.8092 \pm 0.0384 \text{ m/s}^2$	[23]
Free fall	Ticker tape timer	90–95%	$9.82 \pm 0.04 \text{ m/s}^2$	[24]
Pendulum	Ultrasonic sensor and arduino	99.60%	$9.82 \pm 0.10 \text{ m/s}^2$	[25]
Pendulum	Smartphone's proximity sensor	99.99–99.46%	$9.75 \pm 0.02 \text{ m/s}^2$	[26]
Pendulum	Smartphone magnetometer	98.98%	$9.8 \pm 0.1 \text{ m/s}^2$	[27]
Pendulum	Piezo buzzer and smartphone's onboard microphone	99.39%	$9.72 \pm 0.15 \text{ m/s}^2$	[28]

Table 2. Cont.

Method	Sensor	Accuracy	Uncertainty	References
Pendulum	Smartphone ambient light sensor	99.215%	$9.729 \pm 0.01 \text{ m/s}^2$	[28]
Free fall	Microphone and sound card of a personal computer	99.90%	$9.82 \pm 0.03 \text{ m/s}^2$	[32]
Falling ball with the pendulum	Microphone and sound card of a personal computer	99.75%	$9.776 \pm 0.005 \text{ m/s}^2$	[34]
Free fall	Smartphone's onboard microphone	97.50%	9.57 m/s^2	[38]
Free fall	Smartphone's onboard microphone	99.82%	$9.8274 \pm 0.01 \text{ m/s}^2$	This work

5.3. Variability in Time Measurements

One of the notable aspects encountered during the experimental procedure was the observed variability in time measurements recorded through smartphone audio recordings. While the methodology utilizing the smartphone's onboard microphone for time measurements proved effective, some degree of variability was evident across the conducted experiments. Several factors could contribute to this variability in time measurements. Ambient noise, variations in the smartphone's microphone sensitivity, and the inherent limitations of audio-based time measurement systems might have influenced the accuracy and consistency of the recorded time intervals. Additionally, variations in the acoustic signals generated by the switch actuation and the impact of the steel ball on the ground could have contributed to the observed variability. Despite this variability, it is crucial to note that the overall trend and consistency in the time measurements remained within an acceptable range across the experimental trials. Rigorous data-collection procedures and averaging methodologies were implemented to mitigate individual inconsistencies and fluctuations, resulting in reliable averaged data used for analysis and calculation of g . Furthermore, the small magnitude of variability observed in the time measurements did not significantly impact the final calculated g value. The methodology's robustness was evident in the consistent alignment between theoretical and experimental values, showcasing a high degree of correlation despite the observed variability in individual time measurements. To address and potentially minimize this variability in future experiments, the standardization of experimental conditions, such as controlling ambient noise levels and optimizing smartphone recording settings, could be considered. Additionally, exploring advanced signal processing techniques or utilizing external microphone accessories to enhance signal clarity and precision might offer avenues for reducing variability in time measurements.

5.4. Comparison of Theoretical and Experimental Values

A fundamental aspect of our investigation involved comparing the theoretical values of time measurements with the experimental data obtained through the smartphone audio recording methodology. Theoretical calculations based on the principles of classical physics provided expected time intervals for the free fall of a steel ball from varying heights, while experimental measurements using the smartphone's onboard microphone recorded the actual time intervals during the descent. The comparison between the theoretical and experimental time measurements revealed a consistent trend and a high degree of alignment across varying experimental conditions. The table of results exhibits this alignment, indicating that the measured time intervals closely corresponded to the theoretical predictions for the descent of the steel ball from different heights. While a slight discrepancy between theoretical calculations and experimental measurements was evident, the relative error remained within a narrow margin. The observed relative error ranged between 2%

and 3.27% across different experimental trials. This discrepancy could be attributed to factors such as minor variations in the experimental setup, imperfections in the timing of the switch actuation and the steel ball's impact, or inherent limitations in the audio-based time measurement system. However, it is noteworthy that despite this minor discrepancy, the calculated value of g derived from the experimental time measurements exhibited a remarkably small relative error when compared to the theoretical g value. The experimental g value of 9.8274 m/s^2 evidences a mere 0.17737% relative error when juxtaposed with the theoretical value, emphasizing the accuracy and reliability of the smartphone-based methodology in determining g . The consistency in the correlation between theoretical and experimental values further validates the efficacy and precision of the smartphone audio recording method in capturing accurate time intervals during free fall experiments. Despite the minor variations observed, the overall agreement between theoretical predictions and experimental measurements underscores the methodology's robustness and reliability in determining gravitational acceleration.

5.5. Applicability and Significance

The findings of this research hold significant implications, particularly in educational settings and broader scientific applications, owing to the demonstrated efficacy and accessibility of the smartphone-based methodology in determining g through free fall experiments. In educational contexts, where the understanding of fundamental physics principles is paramount, the utilization of smartphones equipped with built-in microphones presents a practical and accessible means to engage students in experimental physics. This methodology not only simplifies the experimental setup but also fosters hands-on learning experiences, enhancing students' comprehension of gravitational concepts while nurturing critical thinking and quantitative analysis skills. Moreover, the adaptability and simplicity of this approach make it accessible across diverse learning environments, regardless of resource constraints. By obviating the need for specialized equipment and leveraging commonly available smartphones, this methodology democratizes experimental physics education, ensuring broader inclusivity and participation. Beyond educational settings, the significance of this research extends to scientific and engineering domains where accurate measurements of gravitational acceleration are crucial. The demonstrated precision and reliability of the smartphone-based methodology highlight its potential for applications in fields requiring portable and accessible measurement tools for gravitational studies, such as geophysics, civil engineering, and materials science. Furthermore, the integration of SPARKvue for the real-time display and analysis of sound parameters enhances the methodology's practicality and usability, providing a user-friendly interface for data collection and analysis. This feature augments the methodology's value in both educational and research settings, streamlining experimental processes and facilitating accurate data acquisition.

5.6. Limitations and Future Directions

While the smartphone-based methodology for determining g via free fall experiments showcased promising results, several limitations were identified during the course of this study that warrant acknowledgment and opportunities for future exploration.

5.6.1. Limitations

Variability in time measurements, stemming from factors such as ambient noise and fluctuations in acoustic signals, presents a significant challenge to achieving absolute precision within methodologies. Mitigating these variations holds promise for enhancing the reliability of the methodology. Moreover, the accuracy of audio-based measurements is subject to potential inaccuracies due to environmental noise interference or limitations in the sensitivity of smartphone microphones. Exploring improvements in audio signal processing or alternative validation methods could effectively address these concerns. Additionally, while this study was conducted under controlled laboratory conditions, extending the methodology to real-world environments introduces additional variables that may impact

measurement accuracy. Thus, it is imperative to carefully consider these external factors to ensure broader applicability and robustness of the methodology. Furthermore, it is imperative to consider that sound waves possess a finite velocity and are subject to variation with temperature, pressure, and humidity. Under standard conditions, typically defined as at sea level with a temperature of 20 °C or 68 °F, the speed of sound in dry air is approximately 343 m per second. This velocity exhibits an upward trend with elevated temperatures and conversely declines at greater altitudes. Consequently, there may exist temporal disparities between the occurrences of actual events and the instances of the corresponding sound waves recorded by the smartphone. These temporal disparities are anticipated to escalate with increasing distances between the ball, mechanical switches, and the smartphone. To mitigate this issue, meticulous attention should be directed toward aligning the positions of the smartphone, mechanical switches, and the point of ball descent in close proximity.

5.6.2. Future Directions

Comparative studies play a pivotal role in elucidating the advantages and limitations of smartphone-based methodologies vis à vis traditional sensor-based techniques, employing quantitative evaluations to furnish a comprehensive understanding of their efficacy. Furthermore, advanced signal processing techniques, including advanced algorithms or machine learning methods, could be explored to refine the accuracy and reliability of time measurements gleaned from smartphone audio recordings. Moreover, this study in part paves the way for advancements in smartphone-based measurement techniques and their broader integration into scientific research and educational settings.

6. Conclusions

The utilization of a smartphone's onboard microphone for determining g via the free fall method has proven to be successful, showcasing a noteworthy alignment between the calculated g and the locally accepted reference value for g . The time measurements exhibited some degree of variability, with the smallest relative error amounting to 3.27%. The experiment's reported value of g , accounting for associated uncertainty, is $9.8274 \pm 0.01 \text{ m/s}^2$, with an accuracy of 99.82%. The proposed method can enhance the accuracy of gravitational acceleration measurements in free fall experiments in various ways, building upon previous presentations. Additionally, the method is simple to implement, with the system being easily installed at a low cost. Moreover, it offers flexibility to adjust the experimental design according to the specific environmental conditions. This versatility makes it suitable for various applications, including educational purposes, research, and practical experimentation. Notably, the approach employing the smartphone's onboard microphone sensor yielded favorable outcomes, offering enhanced convenience compared to alternative sensor-based methods, as it obviated the need for supplementary equipment. Additionally, the integration of SPARKvue streamlined the process by directly displaying sound level, sound intensity, and period values. In summation, this study represents a valuable contribution to the refinement of current methodologies for the analysis of mechanics, particularly in the context of the free fall phenomenon, and is applicable across educational institutions at both university and secondary levels.

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