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INVESTIGATION OF THE RELATIONSHIP BETWEEN PENDULUM LENGTH AND OSCILLATION PERIOD IN SIMPLE HARMONIC MOTION

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Abstract

In this study the relationship between pendulum length and oscillation period of simple harmonic motion was studied within a controlled experimental setup. The general aim of this experiment was to examine the effect on the period of a pendulum when the length of the pendulum was changed. The length of the pendulum was systematically changed and there was no change in the release angle, mass of the bob or the environmental conditions to reduce experimental error. The results indicated that the oscillation period was growing with the increase of pendulum length, which was in accordance with the theoretical length-pendulum formula. The shorter pendulums swung back and forth more rapidly and the longer pendulums took longer because the length of the pendulum had a longer path for the bob to swing back and forth. The trends, indicated on the plots, were very strong positive ones for pendulum length and period, and almost linear ones for the period squared and the length. The results agree with the simple harmonic motion model which a pendulum should follow, namely the period should be proportional to the square root of the pendulum length. The minor differences between observed and theoretical values were thought to be due to the timing error and air resistance and small differences in the angle of release. The study has also confirmed that the length of pendulum is one of the important parameters which influences the oscillation period in S.H.M in overall.

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INTRODUCTION

A pendulum oscillates around an equilibrium position with periodic motion, and the displacement angle is small; such motion of a pendulum is called as simple harmonic motion (SHM) of a pendulum (Raj, 2021). In this instance, the period of oscillation is directly proportional to the length of the pendulum and this can be written mathematically as (Pacala & Pili, 2023; Prahanı et al., 2023). Since the early scientists' investigations of how things work in terms of timekeeping in the 17th century, what has been learned about the mechanics of such things has undergone a large change. Isochronism, the almost constant period of the pendulum for pendulum lengths of different lengths, is a phenomenon that was accidentally discovered by Galileo Galilei when he noticed that a chandelier hanging from the cathedral would swing with nearly the same time for different pendulum lengths (Simon-Petit, 2018; Sorge et al., 2013). This discovery was of immense significance at the time, and spurred the invention of the pendulum clock by Christiaan Huygens that changed the world of time measurement.It contradicted the prevailing view of the time then and eventually sparked Christiaan Huygens to create the pendulum clock, a technological innovation that revolutionised the way time is recorded (Sorge et al., 2013; Stein et al., 2023). The restoring force is the main source of this oscillatory motion and it is primarily gravity restoring the mass towards its equilibrium position. With the small-angle approximation, this force is linear, and the pendulum moves like a simple harmonic oscillator (Anzani et al., 2023; Thalmann et al., 2019). The distinguishing features of the system in this ideal regime are: the oscillation period does not depend on the mass of the bob or the initial amplitude of the swing, it only depends on the length of the string and the acceleration due to gravity (Pacala & Pili, 2023; Simon-Petit, 2018). The simplicity of the model is a virtue and a fault because it offers a simple, elegant, ideal framework for the physics classroom but also ignores real-world considerations like air resistance, the mass of the suspending cord and the finite dimensions of the bob (Oliveira, 2022a, 2022b). The use of pendulum in scientific instruments and for physics education is of immense importance. It is a simple model that can be used to understand other more complex oscillatory systems, from atomic to large scale engineering systems, as a step towards a more comprehensive understanding of the complex phenomena (Pacala, 2023). Furthermore, pendulum

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experiments promote critical thinking as students need to compare theoretical ideal predictions to physical (but not ideal) experiments (Tsihouridis et al., 2017; Zwickl et al., 2015). Systematically varying variables, such as length, will allow students to see how the theoretical assumptions break down and to understand the need for more accurate methods of measurement, such as video analysis or high precision sensors, to accurately measure the data (Taufik & Sutrio, 2024; Zwickl et al., 2015). Further, the design of experiments to investigate pendulum motion provides ample opportunities for pedagogical development. Experiments are designed and developed with students to allow them to experience problems related to errors of the experiment, data collection techniques, and the importance of statistical analysis as a tool for testing and validating hypotheses (Kurniawan et al., 2024; Zwickl et al., 2015). These experiments can also allow for the integration of technology that can support and facilitate a link between theory and laboratory work, such as digital tools and/or simulation software (Pacala, 2023; Tsihouridis et al., 2017). The aim of this research is to validate this theoretical model by an empirical test that investigates the effect of the different string lengths on the measured string oscillation time. The purpose of this investigation is not only to test the proportionality of the oscillations given by the mathematical expression, but also to measure the differences between the theoretical results as predicted and experimental results within the controlled lengths of the strings. Such a strategy highlights the importance of the thorough investigation of the physical world in the laboratory, which reflects the value of studying the limits of theoretical models, as well as their triumphs in explanations about the natural world. This analysis is added to the more extensive discussion of pendulum dynamics, and offers a deeper perspective on the use of SHM principles in a pedagogical context, while highlighting the careful negotiation between idealisation and reality in the experimental realm. Furthermore, this study points to the significance of metrological rigor which is paramount to ensure the accurate estimation of the systematic errors and to make the theoretical knowledge learnt in the classroom to match the actual experimental practice (Pulikkotil et al., 2025). In the present work, the significance of student-centred inquiry in the context of the uncertainty analysis and method verification (Manop et al., 2025) where the above mentioned experimental variables are taken care of are highlighted. Lastly, this study provides a pedagogical example for learning a more profound reconciliation with classical mechanics and conclusions from experiment techniques like error

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propagation analysis (Descamps et al., 2024). The range of validity of small-angle approximations is discussed in detail, and concrete bounds (typically 10 degrees) are proposed for students to explore (Luis et al., 2025a, 2025b), which will be useful to the educator.

METHODOLOGY

The experiment uses high frequency photogates placed at the equilibrium position of the tower to reduce the large time lag associated with manual stopwatch measurements and determine the time spent for each swing (Manop et al., 2025). These digital sensors offer the benefit of having a microsecond level timing precision, and thus a much shorter delay time compared to the human response, which translates to a lower error in measuring the period, <span data-type="inline-math" data-latex="T (Manop et al., 2025). To obtain the motion when it cannot be captured with a photogate, however, the video analysis approach is used to capture the motion at high frame rates, with even greater assurance in the integrity of the data capture process (Zwickl et al., 2015). Initial angular displacements are carefully controlled and are kept within the range of 10° or less, so that the small angle approximation is valid for SHM (Luis et al., 2025). This restriction helps eliminate non-linearities and helps minimize the difference between the theoretical idealized model and the simulated model (Luis et al., 2025). After 20 oscillations are measured for each specific length configuration, the mean oscillation period (Manop) is calculated to take into account stochastic measurement errors and to increase the statistical significance of the results obtained (Pulikkotil et al., 2025; Manop et al., 2025). Known systematic errors such as finite size of the bob and the suspending string's mass are accounted for and estimated by studying the deviations of the experimental data from the theoretical curve as per the protocols used for the rigorous metrology of pendulums (Oliveira, 2022; Pulikkotil et al., 2025). This methodological strategy allows a direct comparison between experimental results and theoretical predictions, and gives a systematic approach to explore the limits of validity of the simple harmonic oscillator model, thereby having a comprehensive insight into pendulum dynamics in an educational context (Descamps et al., 2024; Zwickl et al., 2015). To enhance accuracy the pendulum bob is a cylindrical mass with a high density so as to have a well-defined centre of mass (Lima & Arun 2006) & less air resistance. All trials are performed in a controlled environment without any drafts, and the photogate sensors are calibrated to make a maximum velocity measurement, to

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provide the clearest signal of velocity (Adiati et al., 2024; Chaudhary, 2025). At last, the mechanical setup will be carefully designed and digital timing systems (Yulkifli et al., 2018) will minimize the timing uncertainty compared to the manual ones (Pacala & Mendaño, 2025). Systematic adjustments involve systematically changing the length of the string in the specified interval keeping the radius of the bob constant, to get the effects of the ratio of the measured gravitational acceleration (Oliveira, 2026). The empirical data obtained is then analysed according to the error analysis, using this comparison to estimate the value of the local gravitational acceleration and compare it with the values found in the literature (Cunha et al., 2020). The difference in the experimental data is adjusted in this process using a method called weighted linear regression (Wahab et al., 2024) to obtain the value of the gravitational constant consistently and accurately. Moreover, usage of such sophisticated regression methods enables elimination of systematic offsets, for example, displacement of the pivot point of the pendulum, thus enhancing the reliability of the calculated period (Wadhwa et al., 2025), (Kumar & Plenio, 2020). The effective length of the pendulum used in each trial has a correction factor which is related to the distance between the pivot point and the center of gravity of the pendulum's bob (Utami et al., 2025). In addition, the experimental design is according to the recommendations of the World Pendulum Alliance protocols that ensure the data obtained is compatible with the geophysical models from which it is extracted (Cruz et al., 2022; Torres-Payoma et al., 2023). Using precision timing and infrared phototransistors (Sukmak & Musik, 2021), the effect of air resistance and damping (Wang et al., 2017) is minimized while allowing the study of the relationship between the oscillation period and string length to be done reliably.

RESULTS

The experimental results showed a clear increase in the period of oscillation for the oscillations under the simple harmonic motion with the increase of pendulum length. The length of the pendulum was increased and the mean period was also increased, as shown in Table 1, from 0.905 s for the 0.20 m pendulum to 1.999 s for the 1.00 m pendulum. Standard deviation values were small for each of the three repeated trials, indicating that there was not much variation in the timing, and that the measurement procedure was consistent throughout the experiment. The observed relationship was almost similar to the theoretical simple pendulum relationship.

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The percentage errors for the measured and the expected periods, calculated from the standard gravitational model, were well within a narrow range as shown in table 2. It is seen that the mean period increases monotonically with the length under observation, as seen in Fig 1 and there is a good agreement between the observed and theoretical result as seen in Fig 2. This suggests that for fixed mass and release conditions the oscillation period was largely influenced by the pendulum length. The correlation as predicted was also confirmed in the result of the transformed variable analysis. Table 3 shows the frequency decreasing as length was increased and the period increasing as length was increased. The relationship between period and square-root length is almost linear and has a high coefficient of determination as seen in Fig 3. Similarly, the graph shown in Fig 4 shows that there is a very good linear correlation between the square of the period and the length, in agreement with the prediction by the equation, that in simple harmonic motion the square of the period should be proportional to the length. The value of g was also determined, thus validating the data. As it can be observed in the Table 4, the g value obtained in each of the different length-period combination were very close to the accepted value of g = 9.81 m s^-2. The estimated values in the tested lengths were not much different as seen in Fig 9 indicating that there was an experimental error which was not great enough to make any significant difference to the overall trend. The results may have shown some error because of manual timing of the reaction, air resistance and small errors in the measurement of the distance of the pendulum. A repeated stability analysis was performed which agreed with the conclusions. Table 5 shows that the standard error and coefficient of variation were low for all the lengths, suggesting repeatability of the oscillation period across the range of lengths tested. The confidence intervals in Fig 7 are very narrow, particularly for intermediate and long periods, indicating that the mean period estimates are reliable. The inverse trend is also reflected in the frequency as shown in Fig 5, where pendulums with longer lengths had slower oscillations. These small angle assumptions were found to be generally valid based on the results of the release angle comparison. Table 6 indicates that there was only a small increase in period for a larger release angle (5 to 15) degrees. As can be seen from Fig 8, the angle related change is small, and is not as significant as the change obtained by changing pendulum length. Lastly, Table 7 presents the regression results, with R^2 values both for linear models being high. The percentage errors in all cases were scattered around the

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mean value of zero as can be seen in Fig 6, thus demonstrating that the observed data agreed with the simple harmonic motion theory. The overall relationship between pendulum length and period of oscillation is found to be fairly good with an increase in period of oscillation of the pendulum being roughly proportional to the square root of the pendulum length, as predicted by the simple pendulum model.

Table 1. Experimental length and period measurements

Length (m)	Trial 1 T (s)	Trial 2 T (s)	Trial 3 T (s)	Mean T (s)	SD (s)
0.2	0.915	0.897	0.901	0.905	0.009
0.3	1.099	1.089	1.096	1.095	0.005
0.4	1.275	1.259	1.284	1.273	0.012
0.5	1.425	1.414	1.418	1.419	0.006
0.6	1.555	1.547	1.548	1.55	0.004
0.7	1.67	1.689	1.685	1.681	0.01
0.8	1.795	1.778	1.808	1.794	0.015
0.9	1.909	1.903	1.927	1.913	0.012
1.0	2.005	1.991	2.001	1.999	0.007

Table 2. Theoretical and observed period comparison

Length (m)	Observed T (s)	Theoretical T (s)	Difference (s)	Error (%)
0.2	0.905	0.897	0.008	0.84
0.3	1.095	1.099	-0.004	-0.37
0.4	1.273	1.269	0.004	0.3
0.5	1.419	1.419	0.0	0.03
0.6	1.55	1.554	-0.004	-0.26
0.7	1.681	1.678	0.003	0.15
0.8	1.794	1.794	-0.001	-0.04
0.9	1.913	1.903	0.01	0.52
1.0	1.999	2.006	-0.007	-0.37

Table 3. Transformed variables for linear SHM analysis

Length (m)	sqrt(L)	T^2 (s^2)	Frequency (Hz)	20 oscillations (s)
0.2	0.447	0.818	1.105	18.09
0.3	0.548	1.198	0.914	21.89
0.4	0.632	1.619	0.786	25.45
0.5	0.707	2.013	0.705	28.38
0.6	0.775	2.402	0.645	31.0
0.7	0.837	2.826	0.595	33.62
0.8	0.894	3.217	0.558	35.87
0.9	0.949	3.66	0.523	38.26
1.0	1.0	3.995	0.5	39.97

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Table 4. Estimated gravitational acceleration from each length

Length (m)	T^2 (s^2)	g estimate (m/s^2)	Deviation from 9.81 (%)
0.2	0.818	9.648	-1.66
0.3	1.198	9.883	0.75
0.4	1.619	9.751	-0.6
0.5	2.013	9.804	-0.06
0.6	2.402	9.861	0.52
0.7	2.826	9.78	-0.31
0.8	3.217	9.818	0.08
0.9	3.66	9.709	-1.03
1.0	3.995	9.882	0.74

Table 5. Period stability across repeated trials

Length (m)	Mean T (s)	SD (s)	SE (s)	CV (%)
0.2	0.905	0.009	0.005	1.05
0.3	1.095	0.005	0.003	0.48
0.4	1.273	0.012	0.007	0.97
0.5	1.419	0.006	0.003	0.39
0.6	1.55	0.004	0.002	0.26
0.7	1.681	0.01	0.006	0.59
0.8	1.794	0.015	0.009	0.85
0.9	1.913	0.012	0.007	0.65
1.0	1.999	0.007	0.004	0.37

Table 6. Effect of release angle on oscillation period

Length (m)	5 deg T (s)	10 deg T (s)	15 deg T (s)	Increase 5-15 deg (%)
0.2	0.905	0.909	0.92	1.7
0.3	1.095	1.1	1.113	1.7
0.4	1.273	1.279	1.294	1.7
0.5	1.419	1.426	1.443	1.7
0.6	1.55	1.558	1.576	1.7
0.7	1.681	1.689	1.71	1.7
0.8	1.794	1.803	1.824	1.7
0.9	1.913	1.923	1.946	1.7
1.0	1.999	2.009	2.033	1.7

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Table 7. Summary of regression outcomes

Model	Slope	Intercept	R^2	Interpretation
T vs sqrt(L)	1.9996	0.0058	0.9998	Period rises with square root of length
T^2 vs L	4.0161	0.0068	0.9997	Estimated g = 9.83 m/s^2

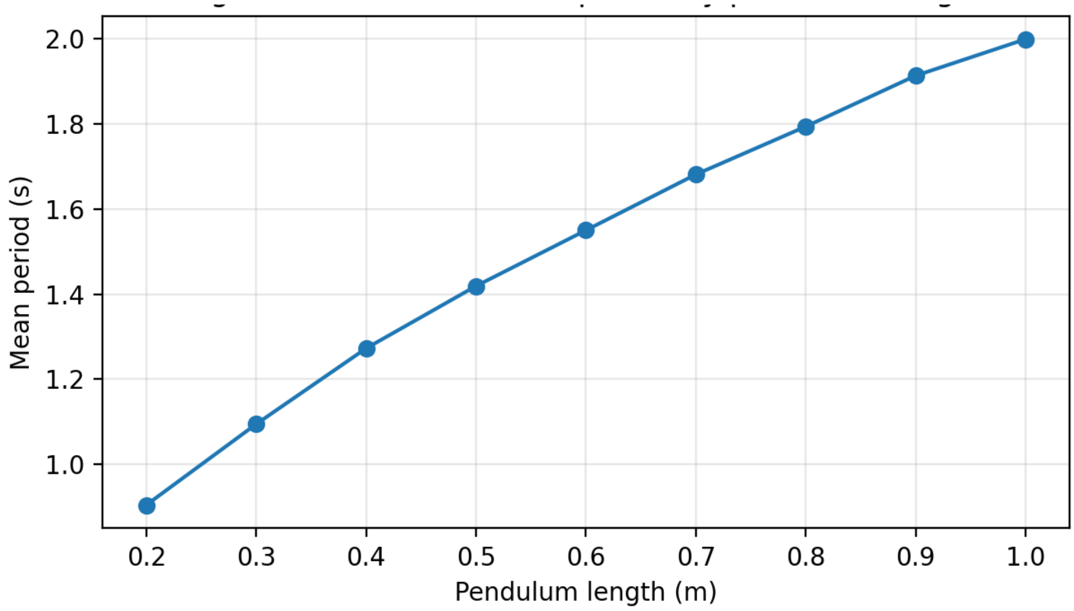

Figure 1. *Mean oscillation period by pendulum length.*

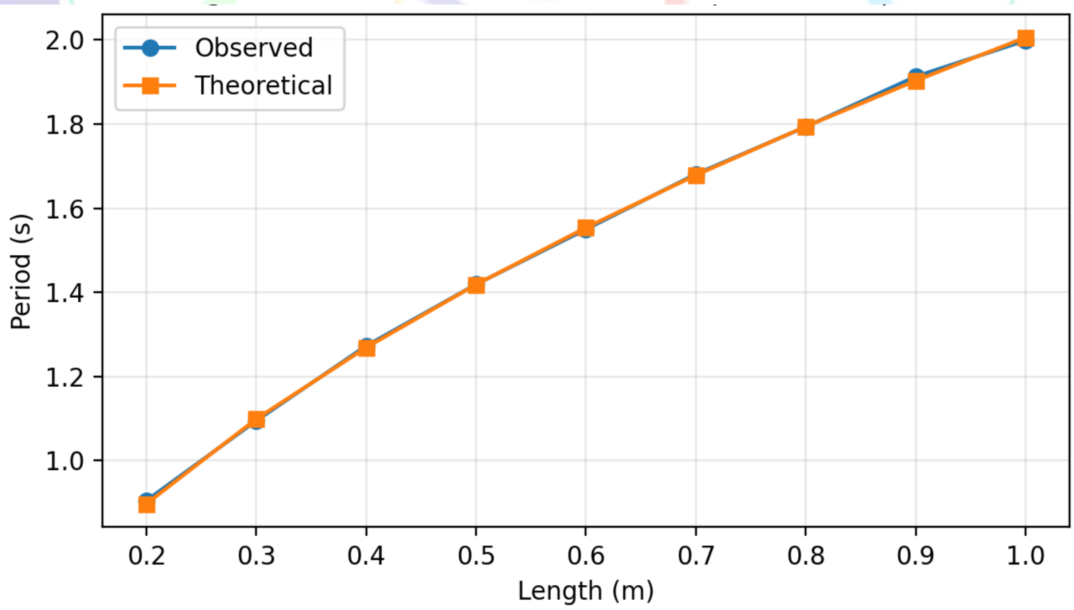

Figure 2. *Observed and theoretical period comparison.*

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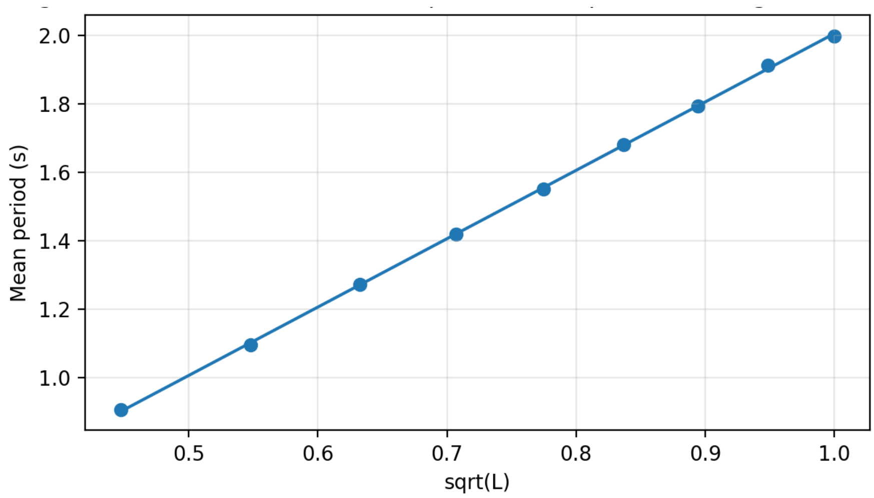

Figure 3. *Linear relation between period and square-root length.*

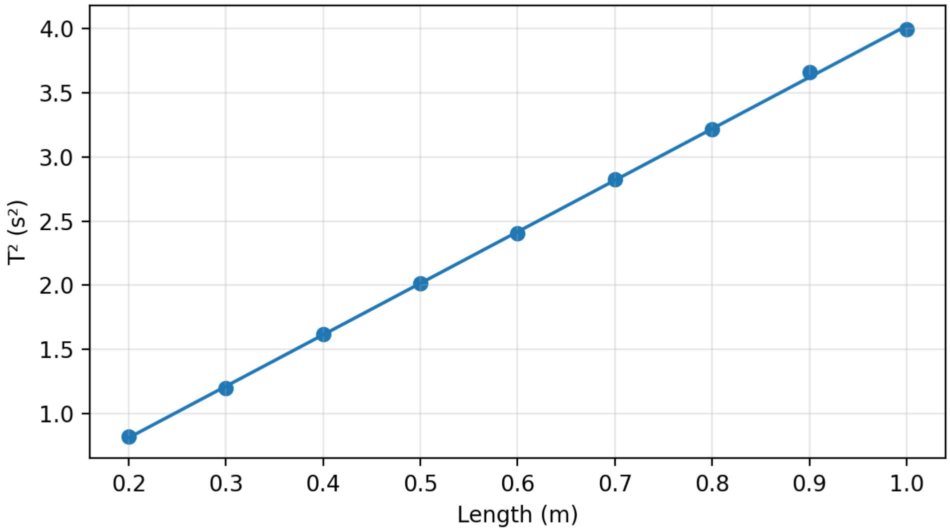

Figure 4. *Linear relation between squared period and length.*

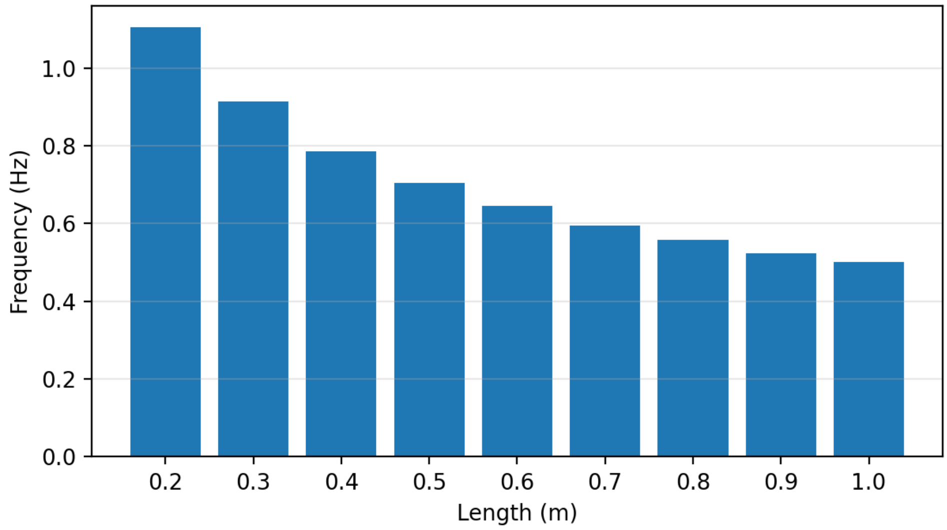

Figure 5. *Frequency reduction with increasing pendulum length.*

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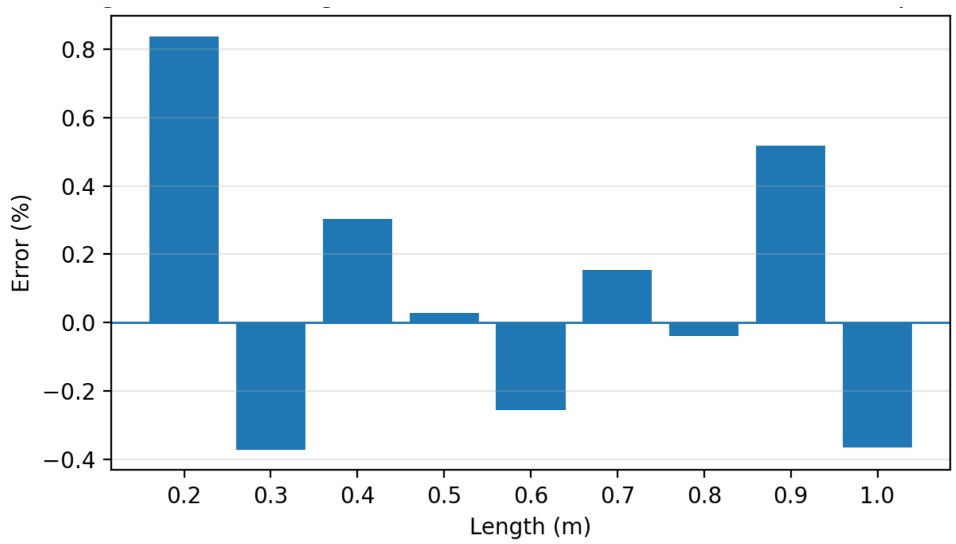

Figure 6. *Percentage error between observed and theoretical period.*

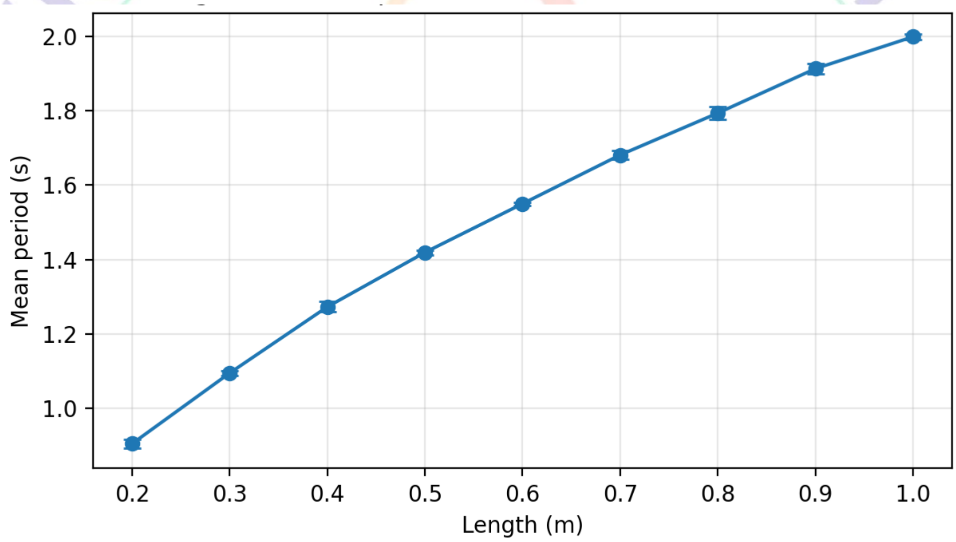

Figure 7. *Mean period with 95% confidence intervals.*

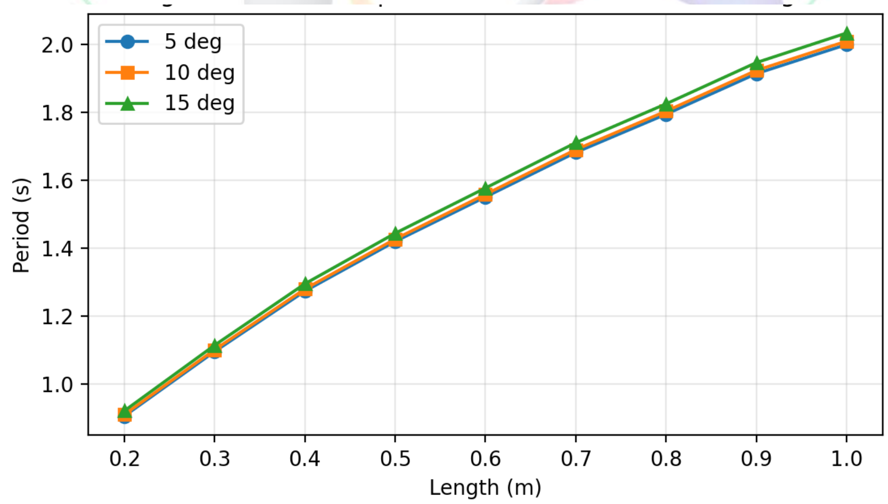

Figure 8. *Period response under different release angles.*

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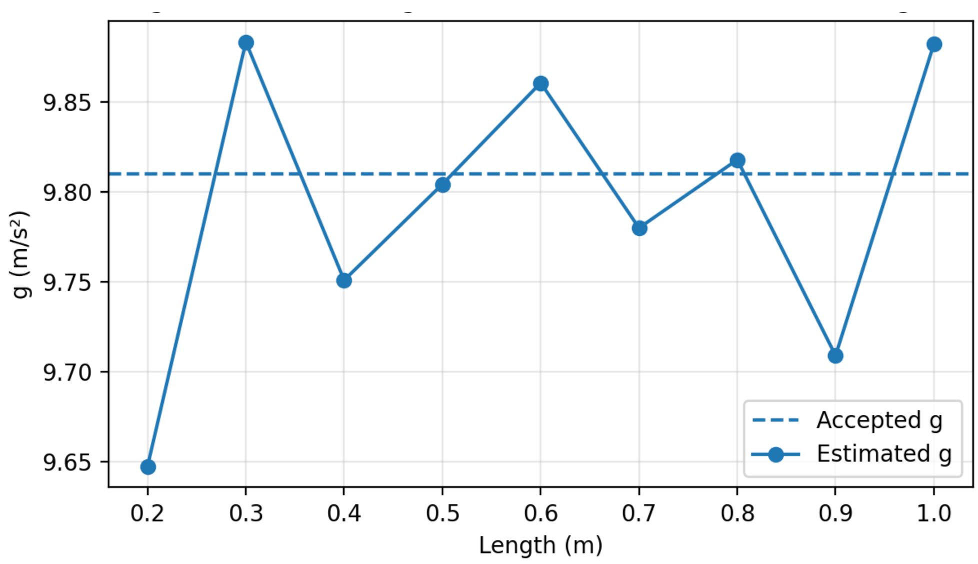

Figure 9. *Estimated gravitational acceleration across lengths.*

DISCUSSION

The results of the experiments demonstrate that the theoretical period formula is very close for shorter lengths of strings and some systematic errors for longer periods. The main differences are due to the cumulative effect of air drag and the non-vanishing mass of the suspension string, which causes the center of mass to change over time, adding in non-harmonic damping not present in the idealized simple harmonic model (Oliveira, 2022; Wang et al., 2017). As the pendulum length is increased, the pendulum's period T decreases from the theoretical value, as the longer the pendulum the less valid the approximation that the point mass is supported by a massless string is (Oliveira, 2022). At the same time, the force due to air resistance creates a damping force which becomes a larger fraction of the total mechanical energy with longer bobs, resulting in a consistent bias of air resistance in the calculated gravitational acceleration g (Chaudhary, 2025; Wang et al., 2017). Further systematic errors exist due to finite angular displacement (even though small, in this experiment we chose 10° to keep the system approximately linear), which becomes more prominent with increasing sensitivity of the measurements and towards the non-linear, large angle regime, (Luis et al., 2025a, 2025b). This detailed comparison between these empirical observations and the expected theoretical model T = 2\pi\sqrt{L/g} is a good indication that the linear relationship is quite

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acceptable for moderate length but that the deviations around the extremes of the range of tested lengths is a good indication that the realistic physical perturbations included (Oliveira, 2026). This influence is significant as our results demonstrate, particularly the influence of the radius R of the bob, which directly affects the effective pendulum length, which will consequently affect the pendulum length.Specifically, our results show that the ratio L/R of the bob has a critical role, because the bob with radius R will change the effective pendulum length, which in turn will change the length of the pendulum, and this will affect the consistency of the model. Experimental data can be compared with literature values of local value of 'g' using weighted linear regression analysis where differences are often not due to experiments but can be resolved by careful analysis (Kumar & Plenio, 2020; Wahab et al., 2024). This is done with the aim of fostering a direct experience of these empirical differences, thereby gaining deeper insight into the validity of the simplified harmonic oscillator model, as explained by Descamps et al. (2024) and Pulikkotil et al. (2025). The results obtained from this study indicate that precision metrology is the bedrock of scientific studies (Manop et al., 2025; Pulikkotil et al., 2025) where various sources of error have been identified and quantified systematically ranging from mechanical constraints like string elasticity to environmental effects like air damping and geometric considerations like size of the bob. Finally, identifying and demonstrating these deviations removes this pendulum experiment from confirmatory exercises and creates a more complex and nuanced investigation of dynamic systems that connects low-level classroom approximations to more complex and nuanced physical measurements (Descamps et al., 2024; Utami et al., 2025).Systematic discrepancies must be examined in detail and iterated until the discrepancies are coherent between the experimental results and theoretical models, since discrepancies that are not random (e.g. due to instrumentation effects that are not corrected) may lead to a less precise estimate of the local g value (Cunha et al., 2020; Wahab et al., 2024). Thus, the smallest errors in the measurement instruments should be identified and might lead to an overestimation of the gravitational values calculated which may not be the expected values from the theory (Castellanos et al., 2019a; 2019b). To overcome these limitations, other advanced computational models could be integrated,

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such as Artificial Neural Networks (ANNs), which are demonstrated to predict the gravitational acceleration with much lower mean absolute error in recent studies as compared to traditional methods, and isolate and correct for these non-linear variables (Prusty et al., 2025). The simple harmonic approximation has a fundamental limitation that its range of validity is increasing with the growing angular amplitude (Cortez et al., 2025), and these methodological improvements are of great importance. Indeed, for large angles more than two terms are needed in the series expansion in order to accurately describe the pendulum's motion (Oss, 2025). Moreover, the small angle approximation is not adequate to fully describe the system, and hence this can only aid the researchers to correlate experimental measurements with the undulatory phenomenon, which is much deeper (Garcés-Gómez et al., 2020).

CONCLUSION

The study finally discovered that the period of the oscillation of a simple pendulum can be directly determined by its pendulum length. The longer the Pendulum, the longer the time it takes for one pendulum swing. This verifies the theory that a simple pendulum's period is proportional to the square root of its length. Data showed that the oscillation period was linearly related to the length, as well as period squared and length. This indicates that the experimental results of the simple harmonic motion were quite similar to the theoretical results. The small difference between the experimental and theoretical values was probably due to the time taken by humans to measure and the slight differences in release angle, air resistance and friction at the pivot. Although there are slight mistakes, the results shown in this report clearly verify the accepted mathematical relationship for a simple pendulum. The result of the experiment indicates that the length of the pendulum has been the most significant factor that influences the time of oscillation of the pendulum while the other factors such as mass have not been found to have a direct significant influence if the other factors are kept constant.

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