Smartphone as monitor of the gravitational acceleration: A classroom demonstration and student experiment

A Kittiravechote* and T Sujarittham
Program of General Science, Faculty of Education, Bansomdejchaopraya Rajabhat University, Bangkok, 10600, Thailand

*Corresponding author’s e-mail: aungtinee.ki@bsru.ac.th

Abstract. As the development of technology, smartphones today come with various sensors to mediate a nicer customer use. This paves the way for new perspectives on using smartphones as the laboratory tools. Accordingly, this paper presents how smartphone determining of the magnitude of gravitational acceleration (g) may be made, describes a classroom demonstration, cites a reported experiment designed to obtain the necessary data, and suggests a student experiment to calculate the magnitude of g. The depth of the mathematical analysis of the data can easily be adjusted to the level of the class such as arithmetic mean, slope of graph plotted by hand, and slope of graph plotted by excel. After conducting the experiment with 33 students, major in program of general science, faculty of education, Bansomdejchaopraya Rajabhat University (BSRU), the students report the magnitude of gravitational acceleration nearly the theoretical value (g = 9.78 m/s² at Bangkok; provided by the National Institute of Metrology (Thailand)) with a percentage difference less than 2%. We highlight the advantage of this experiment with the use of low-cost means and everyday devices in the classroom as a way of gathering empirical data about moving objects.

1. Introduction

It has been realized for a long time that a hands-on experiment is considered to be one of the teaching and learning approaches to foster the development of students who are confident in their ability to accomplish real achievements with direct practical experience on doing [1]. Consequently, this approach is mostly conducted to promote the practical skill and scientific reasoning skill of the students in science classroom [2], especially in physics [3], chemistry [4], and biology subjects [5].

For the physics classroom, one of the important experiments is the measurement of the gravitational acceleration using ticker timer [6]. However, due to the development of technology, smartphones today come with various sensors in order to facilitate a nicer customer use. This paves the way for new perspectives on using smartphones as the laboratory tools to collect the data [7-9]. Toward this end, we arise the question of whether the smartphone can be used to monitor the acceleration of gravity in physics classroom or not. Yes, it can. Publications have recently shown how to convert the smartphones into the laboratory tools to measure the acceleration of gravity. Patrik Vogt and Jochen Kuhn directly measured the acceleration of gravity through the smartphone sensors called micro-electro-mechanical systems (MEMS) [10] as well as they determined this magnitude on the basis of the resulting Doppler shift of sound, which increases with the velocity of the fall, via the microphone port [11]. Unofre Pili et al. found the acceleration due to gravity via measurement of the period of oscillations of a simple pendulum through the smartphone magnetic field sensor [12].
Although the methods to observe the gravitational acceleration have been known, the classroom demonstration and student experiment have not been pursued yet. This paper presents how smartphone determining of the magnitude of gravitational acceleration (g) may be made, describes a classroom demonstration, cites a reported experiment designed to obtain the necessary data, and suggests a student experiment to calculate the magnitude of g. The depth of the mathematical analysis of the data can easily be adjusted to the level of the class such as arithmetic mean, slope of graph plotted by hand, and slope of graph plotted by excel.

2. Experimental method
2.1. Participants
The participants comprising the sample used in this study consisted of 33 undergraduate students, enrolled in program of general science, faculty of education, Bansomdejchaopraya Rajabhat University. All of the students were required to work as groups of 5 to 6 members.

2.2. Recording the time of free fall experiment
We performed an experiment following the procedure described before [13]; figure 1 displayed the way to record the time of free fall experiment. Briefly, to set the height of experiment, four or five unused A4-sized papers were taped together and folded into a shape such that any object could place on top; figure 1 (A). The height for this experiment was simply set to 0.100 – 1.500 meters, which started at the maximum height and then shortened it by cutting papers out or folding papers one by one. To convert the smartphone into time recorder, the application namely “Phyphox” operating in the “Timer” mode with the “Acoustic Stopwatch” function was selected, the threshold was then set to be above the environmental noise level (slightly over 0.3 arbitrary units), and the “Play” button shown by the triangle symbol was finally pressed. To record the time of free falling, it was started by the first jingle from flicking the folded paper and it was later stopped by the second jingle from hitting to the ground of the object; figure 1 (B). To increase accuracy from measurement, the above procedure was repeated for 3 times and an average value of time was reported.

Figure 1. Time recording of the free fall experiment. (A) Setting the height of the object by folding the unused A4-sized papers. (B) Example of images represent the time series of the free fall experiment.

2.3. Data analysis
As the time recording of the free falling depends on the height of the object, a student experiment may be hence performed to discover the relationship between the height and time. Accordingly, the average value of time of free falling should be reported at the different height. In this work, we assigned the students to write down the average time at the 5 different heights into the given table and then calculate the average of magnitude of the gravitational acceleration through (i) the arithmetic mean, (ii) the slope of graph plotted by hand, and (iii) the slope of graph plotted by excel.
We noted that the arithmetic mean is defined as
\[ \bar{g} = \frac{\sum_{i=1}^{n} g_i}{n}, \]
where the magnitude of the gravitational acceleration of the object \( g \) is
\[ g = \frac{2H}{t^2}, \]
when \( H \) is the height of the object above the ground and \( t \) is the travelling time.
Likewise, the magnitude of \( g \) can be identified from plotting the linear graph such that
\[ H = \frac{1}{2} gt^2, \]
which is equivalent to the linear equation,
\[ y = mx + c, \]
where \( H \) and \( t^2 \) represent the \( y \)- and \( x \)-axis, respectively, the value of \( y \)-intercept \( c \) is vanished, and the term of \( \frac{1}{2}g \) becomes the slope of the graph \( m \).

Moreover, to facilitate the data prediction, the excel program is introduced to the student for plotting the graph and providing the equation of the line of best fit via the following commands: Layout, Analysis, Trendline, More Trendline Options, choose Linear, tick Set Intercept = 0.0, and tick Display Equation on chart.

3. Result
The time recording of the free fall experiment at the 5 different heights together with its averaged magnitude of acceleration of gravity were presented in table 1. The students reported their magnitude of \( g \) as 9.90, 9.64, 9.79, 9.36, 9.54, 10.11 m/s\(^2\) with the percentage difference of 1.43, 1.23, 0.31, 4.10, 2.25, 3.59%, respectively. We noted that the theoretical value of \( g \) at Bangkok was 9.76 m/s\(^2\); provided by the National Institute of Metrology (Thailand).

As we mentioned before, the averaged magnitude of acceleration of gravity from experiment was further obtained through plotting the graph from the above data using hands drawing and excel program. The relationship between the height in meter (\( y \)-axis) and the squared time in second\(^2 \) (\( x \)-axis) gave a linear line which the twice of its slope was equal to the magnitude of the gravitational acceleration. We presented the students’ result in figure 2. When using the hands drawing (left figure shown in each group), the slope of graphs were reported as 4.95, 4.69, 4.77, 6.09, 4.44, and 4.88 m/s\(^2\) which resulted in the magnitude of the gravitational acceleration of 9.90, 9.38, 9.54, 12.18, 8.88, and 9.76 m/s\(^2\) with the difference of 1.43, 3.89, 2.25, 24.80, 9.02, and 0.00%, respectively. It seem to be disappointed for the magnitude of \( g \) of 12.18 m/s\(^2\) in group 4, however, when we looked at the graph plotting by hands we found that this incorrect value was caused by repeating numbers on the \( y \)-axis (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, …). To validate the students’ results and also to reduce the uncertainty made by human error, the graph plotting through excel program were conducted (right figure shown in each group). The slope of graphs were 5.01, 4.89, 4.87, 4.80, 4.83, and 4.89 m/s\(^2\) which provided the magnitude of \( g \) of 10.02, 9.78, 9.74, 9.60, 9.66, and 9.78 m/s\(^2\) with the difference of 2.66, 0.20, 0.20, 1.64, 1.02, and 0.20%, respectively. In comparison with the standard value of \( g \) at Bangkok (9.76 m/s\(^2\)) measured by the National Institute of Metrology (Thailand), students reported the experimental results for gravity in accordance with the theory.
Table 1. The time recording of the free falling at different heights with its averaged magnitude of acceleration of gravity.

| Group | Height $H$ (m) | Time $t$ (s) | $g = \frac{2H}{t^2}$ (m/s$^2$) | Group | Height $H$ (m) | Time $t$ (s) | $g = \frac{2H}{t^2}$ (m/s$^2$) |
|-------|----------------|--------------|-------------------------------|-------|----------------|--------------|-------------------------------|
| 1     | 0.782          | 0.396        | 9.97                          | 4     | 1.080          | 0.463        | 10.08                          |
|       | 0.569          | 0.335        | 10.14                         |       | 0.800          | 0.415        | 9.29                           |
|       | 0.456          | 0.289        | 10.92                         |       | 0.540          | 0.349        | 8.87                           |
|       | 0.360          | 0.278        | 9.32                          |       | 0.270          | 0.242        | 9.22                           |
|       | 0.215          | 0.217        | 9.13                          |       | 0.140          | 0.173        | 9.36                           |
|       | $g = 9.90$ m/s$^2$, difference = 1.43 % | $g = 9.36$ m/s$^2$, difference = 4.10 % |
| 2     | 1.080          | 0.465        | 9.99                          | 5     | 0.297          | 0.248        | 9.66                           |
|       | 0.553          | 0.341        | 9.51                          |       | 0.145          | 0.172        | 9.80                           |
|       | 0.297          | 0.250        | 9.50                          |       | 1.110          | 0.465        | 10.27                          |
|       | 0.149          | 0.173        | 9.96                          |       | 0.805          | 0.420        | 9.13                           |
|       | 0.430          | 0.305        | 9.25                          |       | 0.540          | 0.349        | 8.87                           |
|       | $g = 9.64$ m/s$^2$, difference = 1.23 % | $g = 9.54$ m/s$^2$, difference = 2.25 % |
| 3     | 0.297          | 0.242        | 10.14                         | 6     | 1.335          | 0.535        | 9.33                           |
|       | 0.149          | 0.174        | 9.87                          |       | 1.082          | 0.470        | 9.80                           |
|       | 1.082          | 0.470        | 9.80                          |       | 0.835          | 0.347        | 13.87                          |
|       | 0.553          | 0.341        | 9.51                          |       | 0.410          | 0.325        | 7.76                           |
|       | 0.433          | 0.300        | 9.61                          |       | 0.220          | 0.212        | 9.79                           |
|       | $g = 9.79$ m/s$^2$, difference = 0.31 % | $g = 10.11$ m/s$^2$, difference = 3.59 % |

Figure 2. Experimental results to measure the acceleration of gravity ($g$) for classroom demonstration. The relationship between the height in meter (y-axis) and the squared time in second$^2$ (x-axis) presented a linear line with its slope of half of the magnitude of $g$. Noted for each group: The graph plotting by hands and by excel were shown on the left and on the right, respectively.
4. Discussion

We have presented the classroom demonstration how converting the smartphone into a tool to determine the gravitational acceleration. After conducting the experiment, the students have reported that the magnitude of \( g \) agrees well with the standard value which offers very good accuracy as shown in the table 2.

Table 2. Comparison of the magnitude of gravitational acceleration (g) based on the free-falling experiment through the use of 3 mathematical analyses of the data including arithmetic mean, slope of graph plotted by hand, and slope of graph plotted by excel.

| Group | Arithmetic mean | Slope of graph plotted by hands | Slope of graph plotted by excel |
|-------|-----------------|---------------------------------|---------------------------------|
|       | \( g \) (m/s²)  | Difference (%)                  | \( g \) (m/s²)                  | Difference (%)                  | \( g \) (m/s²)                  | Difference (%)                  |
| 1     | 9.90            | 1.43                            | 9.90                            | 1.43                            | 10.02                            | 2.66                            |
| 2     | 9.64            | 1.23                            | 9.38                            | 3.89                            | 9.78                             | 0.20                            |
| 3     | 9.79            | 0.31                            | 9.54                            | 2.25                            | 9.74                             | 0.20                            |
| 4     | 9.36            | 4.10                            | 12.18                           | 24.8                            | 9.60                             | 1.64                            |
| 5     | 9.54            | 2.25                            | 8.88                            | 9.02                            | 9.66                             | 1.02                            |
| 6     | 10.11           | 3.59                            | 9.76                            | 0.00                            | 9.78                             | 0.20                            |
| Average| 9.72            | 0.38                            | 9.94                            | 1.84                            | 9.76                             | 0.03                            |

To illustrate and summarize the students’ result, we have calculated an averaged magnitude of \( g \) taken from all groups of students. We found that the averaged magnitude of \( g \) depended on the calculation methods: \( g = 9.72 \text{ m/s}^2 \) with 0.38% difference from arithmetic mean, \( g = 9.94 \text{ m/s}^2 \) with 1.84% difference from the slope of graph plotted by hands, and \( g = 9.76 \text{ m/s}^2 \) with 0.03% difference from the slope of graph plotted by excel. With 3 different analysis methods, our result suggested that the magnitude of \( g \) from the slope of graph plotted by excel was the most reasonable tool for conducting the analysis in terms of ease, accuracy, validity, and reliability. The second choice for data analysis would be calculating the value of \( g \) directly from the formula at the different height and then finding the averaged magnitude of \( g \) from the arithmetic mean. The last choice was determining \( g \) from the slope of graph plotted by hands. In addition, although students clearly observe that the data points on the graph do not lie on a straight line, they learn that this is caused by the human error and the experiment error in every measurement. Accordingly, students should recognize that every point on the graph represent an honest measurement.

In fact, the relationship between the height \( H \) and the time \( t \) was described by the quadratic equation. Therefore, assigning the students to plot a graph of \( H \) versus \( t \) would show them to see the parabola curve with an intercept passing through the origin. With this idea, to ask the students which one of the mathematical functions could be described these data points is very interesting. Students might feel that these data points could not be explained by a linear function as they observed the obvious upward curve of points at higher values of time. The different discussion among the students must be taken seriously in a science or physics class. It is hence provided an opportunity for teaching students about the uncertainties in scientific experiments and the statistical treatment of data.

5. Conclusion

We have presented the classroom demonstrations of smartphone to determine the magnitude of gravitational acceleration (\( g \)) based on the free-falling experiment through the use of 3 mathematical analyses of the data including arithmetic mean, slope of graph plotted by hand, and slope of graph plotted by excel. After conducting the experiment with 33 students, we found that our method offers very good accuracy as the students report the magnitude of \( g \) nearly the true value with the difference less than 2%. To the best of our results, the magnitude of \( g \) at Bangkok analyzed by calculation from the twice of the
The slope of the graph plotted by Excel is found to be 9.76 m/s² with its difference of 0.03%. We highlight the advantage of this experiment, e.g., Program of General Science, Faculty of Education, Bansomdejchaopraya Rajabhat University has partnered with secondary and high schools in our region to pilot our hands-on experiments enables with the use of either low-cost materials and equipment or everyday devices in the classroom as a way of gathering empirical data about moving objects.

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