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A physical pendulum experiment with Lego, Phyphox and Tracker

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Abstract

In this study, a physical pendulum experiment, which is one of the basic experiments at the high school level, was carried out using Lego bricks and smartphones (Phyphox application) that students are familiar with in their daily lives. In this way, it is aimed to provide an example to students and teachers about low-cost, theory-compatible experiments that students can perform on their own in out-of-school environments, especially in mechanics. In addition, another aim of the study was to record the experiment on video and analyse it with a video analysis program (Tracker) and to compare the two methods (using a smartphone application and a video analysis program) in terms of results and usability.

Keywords: Lego, Phyphox, Tracker, smartphone, physical pendulum

1. Introduction

The Covid-19 pandemic has had a deep impact on education globally and has forced us to rethink the way we teach and learn physics, as well as all other subjects [1, 2]. Distance education becomes quite challenging, especially in laboratory courses [3]. Laboratory courses are very important in understanding basic physical concepts and establishing the connection between concepts and real situations [4]. However, the fact that students do not perform hands-on experiments in the lessons makes them passive learners and it is much more difficult for them to understand physics phenomena or topics without experiments [5]. One of the solutions that allowed students to continue their experiments during this period was to set up experiments at home with simple materials and use a smartphone as a measuring device [6]. As a result, home-based activities have become more important than ever before [1]. With the accelerating effect of the pandemic, the use of smartphones as digital measurement and experimentation media in physics has become a part of modern physics teaching and learning [7]. Studies have shown that such 'do it at home' experiments can be used not only in the context of distance

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education but also during periods of normal access to the school physics laboratory [6].

Smartphones play an important role in the physics lab because of their embedded sensors. The data obtained from these sensors are read by different applications (Phyphox, etc.) that can be downloaded to mobile devices and used in experiments [8]. Studies on the use of smartphones in physics education have a wide range in parallel with the variety of sensors [9]. Although the studies generally focus on mechanics [10–13], there are also studies on optics [14, 15], magnetism [16, 17] and radioactivity [18] in the literature. One of the difficulties that arise in experiments using smartphones is that the smartphone is part of the experimental setup and therefore not accessible during the experiment. However, the data is not meaningful until it is analysed on a computer. The Phyphox application aims to eliminate these two difficulties that arise in practice in experiments using smartphones [19].

Apart from the experiments carried out with smartphones, one of the technologies that made it possible for students to make some experiments on their own at home during the pandemic was video analysis and modelling programs such as Tracker [20]. Performing some experiments with the help of video analysis programs was one of the methods frequently used in physics education before the distance education process. One of the main reasons for the use of video analysis programs is that sometimes students/teachers need to perform experiments in conditions that cannot be created at home or in the laboratory. The main reasons for these conditions are that some of the experimental equipment is expensive and some experiments are dangerous in terms of safety.

In order for students to perform experiments at home and analyse and interpret them, they first need to physically set up their experiment sets. In particular, it is important for students to use rigid materials in experiments related to mechanics and to determine the variables such as the mass and the length of these materials correctly. As is well known, Lego is a toy brand with a huge fan base around the world. In addition to all this popularity, Lego also offers different products in the field of education (Lego Education Spike, Mindstorm, etc.), especially in the field of robotics, for the use of students [21, 22]. Also, there are studies carried out using Lego products in the field of STEM/STEAM [23, 24]. When the use of Lego in the field of education is examined in detail, apart from mechanical experiments, there are also experiments related to Mach–Zehnder interferometer [25], Michelson Interferometer [26] and Czerny–Turner spectrometer [27]. In most of these and similar studies, bricks and bases are used as holder/fixing parts, but in some studies [4, 28] Lego pieces are used directly as an active element of the experiment.

In this study, a physical pendulum experiment, which is one of the basic experiments at the high school level, was carried out using Lego bricks and smartphones (Phyphox application) that students are familiar with in their daily lives. In this way, it is aimed to provide an example to students and teachers about low-cost, theory-compatible experiments that students can perform on their own in out-of-school environments, especially in mechanics. In addition, another aim of the study was to record the experiment on video and analyse it with a video analysis program (Tracker) and to compare the two methods (using a smartphone application and a video analysis program) in terms of results and usability.

2. Theoretical framework

If a hanging object oscillates about a fixed axis that does not pass through its centre of mass and the object cannot be approximated as a point mass, we cannot treat the system as a simple pendulum. In this case, the system is called a physical pendulum [29].

Consider a uniform, rigid object of length L with its centre of mass at $L/2$, pivoted at one of its ends (figure 1). The gravitational force provides a torque about an axis through the pivot point, and the magnitude of that torque is,

$$mg\,(L/2)\sin\theta.$$

We can model the object as a rigid object under a net torque and use the rotational form of Newton's 2nd law, $\sum\tau = I\alpha$. I is the moment of inertia of the object about the axis through the pivot point. So,

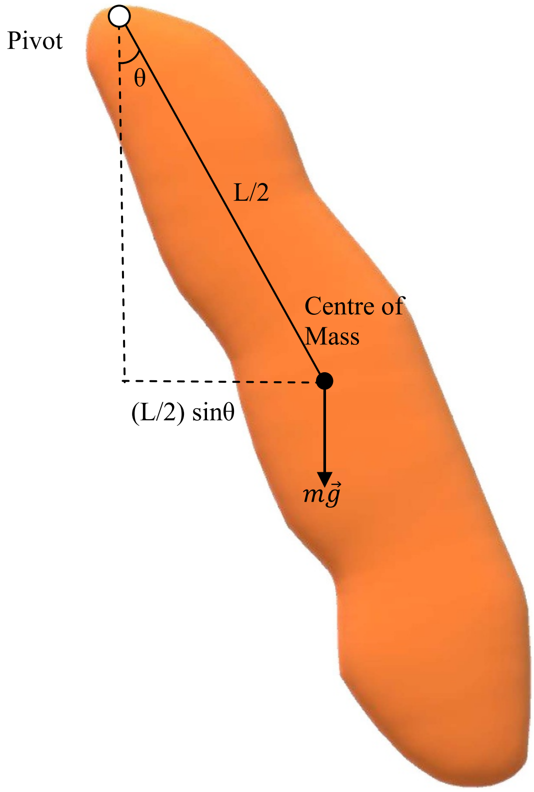


Figure 1. Physical pendulum.

$$-mg\left(\frac{L}{2}\right)\,\sin\theta = I\frac{d^2\theta}{dt^2}. \quad (1)$$

If we assume θ is small (less than about 10°), however, we can use the small angle approximation, in which $\sin\theta \approx \theta$, where θ is measured in radians. As long as θ is less than 15°, the angle in radians and its sine are the same to within an accuracy of less than 1.2% [29]. Therefore, for small angles, the equation of motion becomes

$$\frac{d^2\theta}{dt^2} = -\left(\frac{mgL}{2I}\right)\theta = -\omega^2\theta \quad (2)$$

$$\omega = \sqrt{\frac{mgL}{2I}}. \quad (3)$$

Here ω is the angular frequency (rad s^{-1}) and the solution of the equation (2) is given by

$$\theta = \theta_{max}\cos(\omega t + \varphi) \quad (4)$$

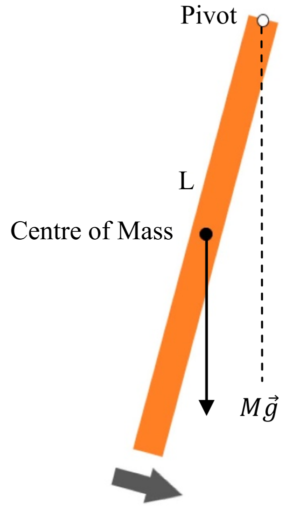


Figure 2. An oscillating uniform rod.

where θ_{max} is the maximum angular position and φ is the phase constant So, the period is,

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{I}{mg\left(\frac{L}{2}\right)}}. \quad (5)$$

In figure 2, a uniform rod of length L and mass M is pivoted about one end and oscillates in a vertical plane.

We know the moment of inertia of a uniform rod about an axis through one end is $\frac{1}{3}ML^2$. The distance between the pivot and centre of mass is $L/2$. So, equation (5) becomes,

$$T = 2\pi\sqrt{\frac{\frac{1}{3}ML^2}{Mg\frac{L}{2}}} = 2\pi\sqrt{\frac{2L}{3g}}. \quad (6)$$

Equation (5) can be used to measure the moment of inertia of a flat rigid object. If the location of the centre of mass is known, the moment of inertia can be obtained by measuring the period. Also, if the period and location of the centre of mass are known, the value of free-fall acceleration or gravity (g) can be calculated.

3. Experimental setup

In this study, the pieces from the 'Lego Classic Bricks Plates' set coded 11717 were used to construct the experimental setup. The pieces in this

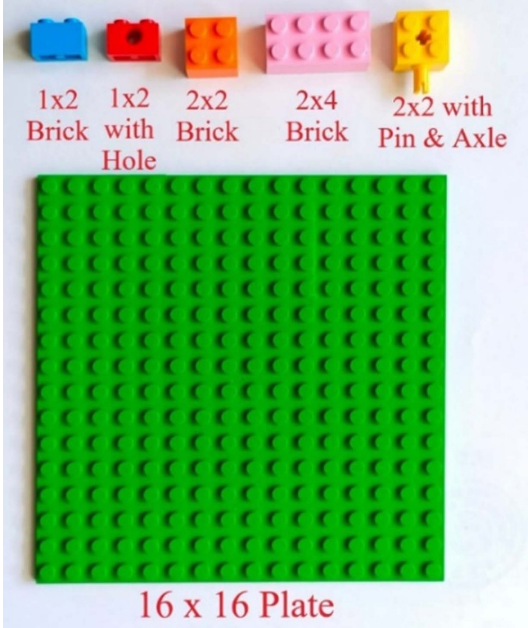


Figure 3. Types of Lego pieces used in the experimental setup.

set are generally similar to the pieces in Lego Classic sets and are easily available. A detailed photo of the pieces used to construct the physical pendulum in the experimental setup is given in figure 3.

There are two different smartphones in the experiment. The first of these smartphones was used for video recording. The camera of the phone that took the video recording was positioned at the middle height of the equilibrium position of the physical pendulum, that is, at the same height as the centre of mass. The most important variable to be considered when analysing with video analysis programs is the frame per second (fps) value. A higher fps value allows more accurate analysis. For this reason, the fps value of the video recording made during the experiment was set to 60 fps, which is the highest value for the smartphone used.

The purpose of the second smartphone in the experimental setup is to receive data from the physical pendulum with the Phyphox. Different sensors in the smartphone can be used for data acquisition. In this study, the data was taken using the magnetometer. For this purpose, a cylindrical neodymium magnet was placed under the brick in the lowest position in the pendulum. The magnet has a diameter of 5.00 mm, a thickness of 1.00 mm and a mass of 0.15 g. However, before the experiments were carried out, the position of the magnetic sensor of the smartphone was determined by using a ferrite magnet with low magnetic field strength. After that, the smartphone was placed on the table so that the sensor of the smartphone was directly under the magnet in the equilibrium position of the physical pendulum. The experimental setup and its SketchUp drawings are given in figure 4.

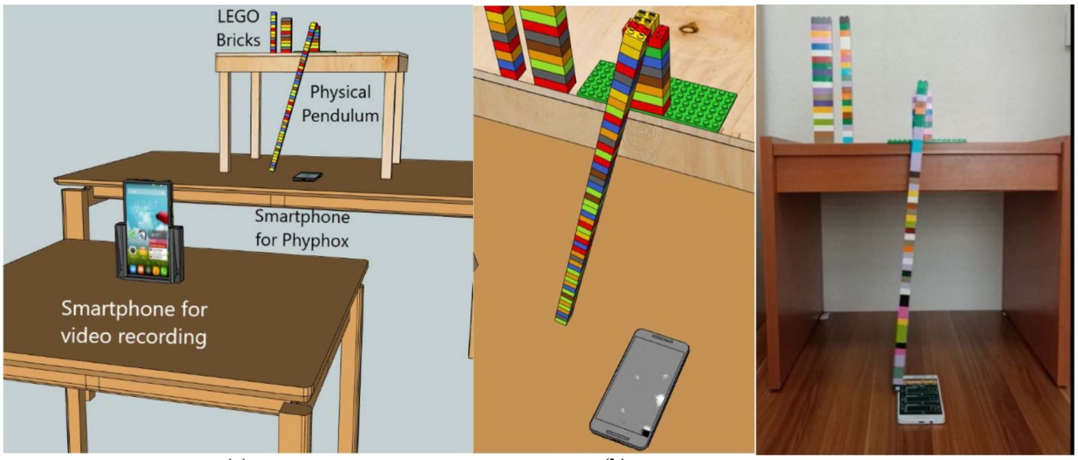
The size information of each of the 2×2 bricks forming the physical pendulum is given in figure 5. In this way, students do not need to measure the length of the physical pendulum before each experiment. Only the number of bricks should be counted and multiplied by 9.60 mm.

4. Experimental data

The experiments to determine the period of the physical pendulum were analysed with two different methods. In the experiments, 5 different lengths of physical pendulum constructed with Lego bricks were used (table 1). In addition, small angle approximation was used to obtain equation (6). For this reason, the experiments were carried out at angles of 15.5° and smaller. The reason for performing each experiment at different angles is that it is not possible for students to perform the experiments at the same angle when performing these experiments at home. In this way, it is thought that the real situation is better reflected. In addition, each experiment was repeated five times and average values were taken.

After the experiments given in table 1 were performed, they were analysed using two methods respectively. Figure 6 shows a screenshot of the video analysis of the first trial of experiment no. 1 performed using Tracker.

Figure 6 shows the position of the physical pendulum consisting of 50 bricks and having a length of 48.00 cm on the x-axis and the variation of the x component of the velocity with time. When the graphs are analysed in detail, it



(a) (b) (c)

Figure 4. (a)–(b) SketchUp drawing and detail of the experimental setup (c) experimental setup.

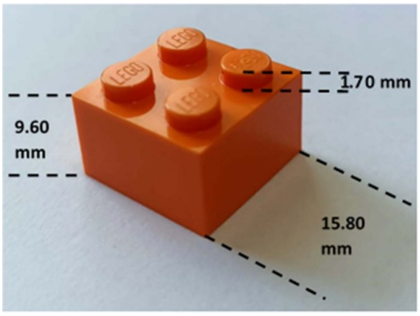


Figure 5. 2×2 Lego brick dimensions.

Table 1. Variables related to the experiments performed.

Exp. no	Number of repeats	Number of brick	Total length (cm)	Angle
1	5	50	48.00	13.8°
2	5	55	52.80	15.5°
3	5	60	57.60	12.8°
4	5	65	62.40	9.4°
5	5	70	67.20	9.5°

is seen that the relationship between the x component of the velocity and the position is obtained in accordance with the theory. When the physical pendulum is at the extreme positions, the x component of the velocity is 0 m s^{-1} and the velocity takes its maximum value (0.619 m s^{-1}) as the pendulum passes through the equilibrium position.

The simultaneous Phyphox data were obtained by measuring the time difference between the points where the magnetic field magnitude was maximum. During this analysis, no additional program was used, only readings were made on the graph in the application (figure 7). The data can also be transferred to the computer.

Figure 7 shows the magnetic field magnitudes measured by the magnetometer on the z-axis. The first peak values on the graph obtained by using the 'pan and zoom' feature in the program were

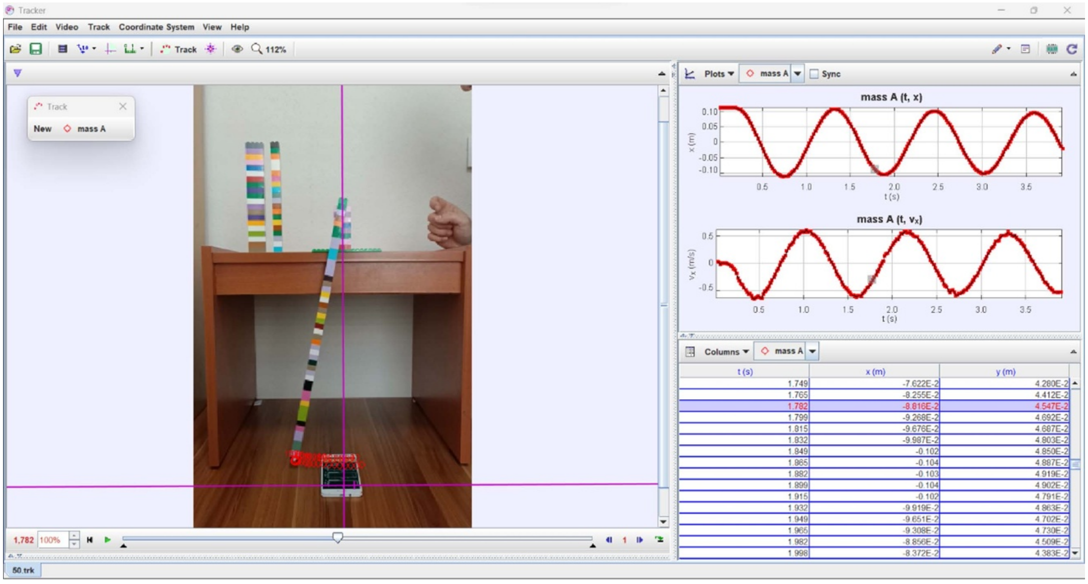
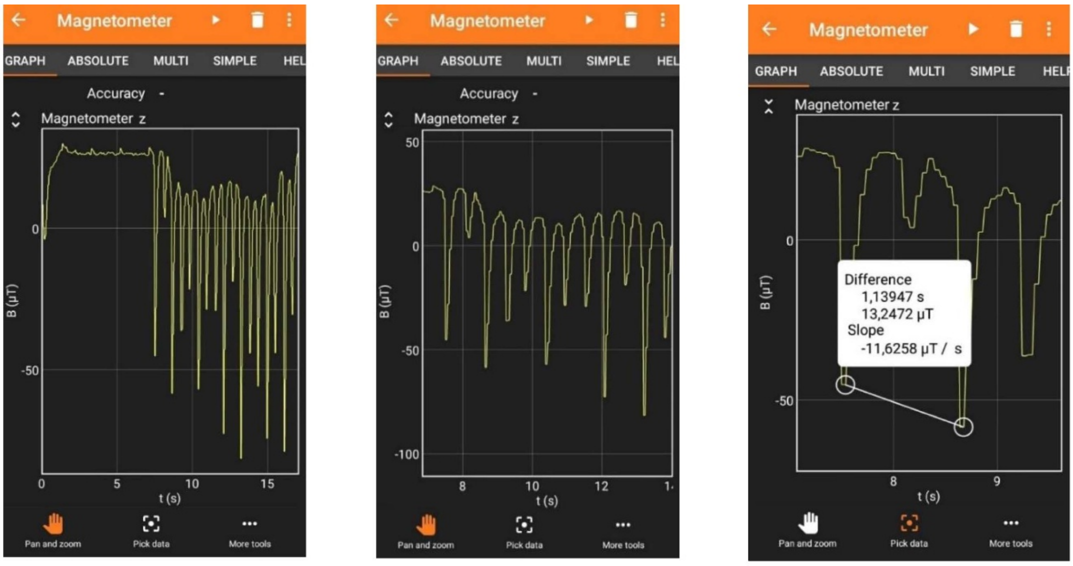


Figure 6. Tracker analysis of physical pendulum (the first trial of experiment no. 1 with 50 bricks).



(a) (b) (c)

Figure 7. (a)–(c) Phyphox analysis of physical pendulum (the first trial of experiment no. 1 with 50 bricks).

focused on. However, the time difference between consecutive peaks does not represent a period but half a period. For this reason, the time between the first and third peaks should be read. Figure 7(c) shows that the period value obtained from the first experiment with 50 bricks is 1.139 s.

As given in table 1, the experiments were repeated 5 times for each length. Average period values are given in table 2.

Table 2 shows that the period values obtained by both methods are close to each other. The period values obtained, and the length information

Table 2. Experimental data.

Exp. no	Total length (cm)	Angle	Tracker	Phyphox
			Period (s)	
1	48.00	13.8°	1.139	1.140
2	52.80	15.5°	1.199	1.199
3	57.60	12.8°	1.249	1.258
4	62.40	9.4°	1.300	1.300
5	67.20	9.5°	1.349	1.340

Table 3. The g values obtained from experiments.

Exp. no	Tracker	Phyphox
	Gravitational acceleration (m s^{-2})	
1	9.728	9.711
2	9.656	9.656
3	9.708	9.569
4	9.708	9.708
5	9.709	9.839

of the physical pendulums used in the experiments were written in equation (6) and the gravitational acceleration (g) was calculated for each experiment (table 3).

When both tables are evaluated together, it is seen that values close to the actual value of gravitational acceleration, approximately 9.80 m s^{-2}, are obtained for different initial angle values and different lengths of physical pendulums. So, it is seen that both methods can be used to determine both the period and the gravitational acceleration.

5. Results and discussion

In this study, data for a physical pendulum experiment using Lego bricks were collected using Phyphox, a smartphone application, and Tracker, a video analysis software. A neodymium magnet placed under the physical pendulum and the magnetometer feature of the Phyphox were used for data collection using the smartphone. In the analyses performed with Tracker, simultaneously recorded videos of the experiment were used.

When the obtained results are analysed, it is seen that both methods can be used to find the period and gravitational acceleration of the physical pendulum. When the results are evaluated by considering the experimental setups, it is thought that the friction at the connection point of the physical pendulum is the main reason for the difference between the experimental results and the theoretical results. The contact between the '2 × 2 with Pin & Axle' and '1 × 2 with Hole' (figure 4) parts is the source of this friction. In order to reduce this friction, applying some machine oil between the two parts can reduce the frictional losses in the experiment.

Neodymium magnet and magnetometer used for data collection in the experiment can only be considered as an alternative. It can be considered that the experimental setup in this study can be repeated using different sensors other than magnetometer. For example, the light sensor can be an alternative for this experiment. Time-dependent changes in illuminance can determine the period of the physical pendulum. There are studies in the literature [30] in which the period of a spring is determined in a similar way.

The opinions of the students about the application were also taken during and after the experiment. Students especially described the experiment with their smartphones as enjoyable. In addition, some of the students made suggestions about performing different experiments using Phyphox after the experiment.

Furthermore, we observed that the use of Lego as part of the experiment increased the students' motivation for the lesson and the experiment. In addition to this, the students reported that they felt comfortable with Lego bricks in experiments than with typical physics laboratory equipment [31]. The students created physical pendulums of different shapes other than the one used in the experiment and determined their periods.

The students' opinions about the experiment with the Tracker were generally positive, similar to those of the smartphone. However, we observed that their motivation was lower in the video-only analysis than in the case where they were actively involved in the experiment and created the pendulum from Lego bricks.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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