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Calculation of kinetic friction coefficient with *Phyphox*, *Tracker* and *Algodoo*

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Abstract
In this study, the kinetic friction coefficient for a block moving on an inclined plane was determined with the help of three different methods (a smartphone application, *Phyphox*, a video analysis program, *Tracker* and a simulation program, *Algodoo*) which can be performed easily using simple materials by the students. The results obtained from the experiments were compared with the theoretical results and each other. As a result, the advantages and disadvantages of three methods were evaluated and several recommendations were presented.

Keywords: kinetic friction coefficient, Tracker, Algodoo, Phyphox

1. Introduction

Friction is a phenomenon that everyone frequently encounters in daily life [1]. Hence, the subject of friction keeps its significance in each grade level of science and physics curriculum [2]. Students have difficulty in understanding friction and its associated phenomena [3]. The literature indicates that students carry misconceptions concerning friction in middle school [4], high school [5] and university level [6]. When the research conducted in university level is considered, it is seen that students possess misconceptions concerning friction in high percentages [7, 8]. The main method preferred in the teaching of the subjects related to friction can be specified as supporting the theoretical knowledge with the conduction of experiments in the laboratory environment. Virtual or real experiments are reported to have positive effects on students' motivation [9], conceptual understanding [10] and attitudes towards the course [11]. Do it yourself (DIY) experiments which are simple and low cost are especially extensively recommended to perform since they are very beneficial in understanding the concepts and the theoretical structure [2].

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During the Covid-19 pandemic, students in various grade levels have started to investigate how they can perform physics experiments at home conditions without expensive laboratory equipment. For most of the students, it is not possible to reach equipment such as digital photogate, air tack, pulley, spring, launcher, inclined plane which are needed for basic experiments related to the subject of mechanics at any time. In addition, it is more difficult to reach relatively expensive equipment such as teslameter, multimeter, luxmeter and barometer which are utilized for other experiments related to physics subjects. There are several methods which reduce high-cost equipment need while performing the experiments. Among those methods, smartphone applications, video analysis programs and simulation development programs can be listed at first.

Smartphones have become an indispensable part of daily life. With the development of the sensors of the smartphones, there is an increase in their utilization in experimental setups. Quantities such as magnetic field, acceleration, illuminance and pressure can be determined in the experiments performed both in and out of the school environment with the help of free applications which are downloaded to smartphones. Recording a real experiment and using it during teaching which is called a video-based experimental activity (VBEA) is a very important application since it allows students to watch the experiment again when they want and they can discuss the results of the experiment with their peers online [12].

Except the experiments performed using smartphone applications and video analysis programs, students may be required to perform experiments in the conditions which cannot be created at home or in the laboratory. For example, elimination of air friction, creating an environment with a gravitational acceleration different than the World, avoiding the loss of energy during collisions, using frictionless pulleys are not possible to create in school laboratory environment. Besides, all students might not have smartphones or experiments' videos. In such cases, the importance of using simulation programs becomes clear.

In this study, it was aimed to compare the findings obtained from experiments which were conducted using a smartphone application, a video analysis program, and a simulation program to calculate the kinetic friction coefficient for a block moving on an inclined plane.

Detailed information is presented respectively about *Phyphox*, a smartphone application; *Tracker*, a video analysis and modelling program and *Algodoo*, a simulation program under the titles below.

1.1. Physical phone experiments (Phyphox)

Phyphox application which makes a smartphone act as a mobile laboratory allows us to perform various experiments with the help of the sensors in the smartphones. Considering the hardware of the smartphone, Phyphox supports accelerometer, magnetometer, gyroscope, light sensor, pressure, proximity sensor, microphone, GPS/location and Bluetooth as input. Also, it supports speaker and Bluetooth as output. The application can be downloaded on Google Play and App Store free of charge.

Phyphox can be controlled remotely from other devices that is on the same network as the phone and has a web browser [13]. Thus, data of the experiment can be monitored simultaneously in another computer or smartphone by the user [14]. Data obtained from the experiment can be downloaded to the computer in the form of comma-separated values (CSV), tab-separated values and MS Excel (xls). Also, Phyphox allows us to create experiments using a visual experiment editor, which will generate a simple file, that defines experiment including data analysis.

In the literature, different studies conducted by using Phyphox address subjects such as optics [15], mechanics [16] and magnetism [17].

1.2. Tracker

Tracker is a free of charge video/image analysis and modelling software designed to be used in physics teaching [18]. It is built on the Open Source Physics (OSP) Java framework by Douglas Brown. The program has versions which are compatible with Windows, Mac OS and Linux with 26 language options and more than 1 million users. Tracker is easy to use/learn and works on quite low specification computers [19].

To make analysis with the program, video recording should first be imported to the program.

The video can be analysed after adding the coordinate axis and calibrating the video with the help of 'calibration tool' in terms of the length. Data obtained from the analysis such as distance, velocity, acceleration, momentum, and energy can be presented to the user in the form of a graph. Also, data can be examined in detail using 'Data Tool' in the program. This tool allows the users to make detailed analysis of data (statistics, curve fits, Fourier spectrum). 'Protractor' and 'tape measure' are the other tools which are used to obtain data in the program. All data obtained from the program can be downloaded to the computer optionally.

The research conducted with Tracker mostly deal with the subject of mechanics [20]. In addition, there are also several research concerning optics [21], radioactivity [22] and thermodynamics [23].

1.3. Algodoo

Algodoo is a two-dimensional (2D) physics simulation software which can be downloaded and used free of charge [24]. This software allows the users to simulate experiments by changing the variables such as air friction, gravitational acceleration or coefficient of restitution which are very difficult or impossible to change in laboratory conditions. Algodoo can be used with computer (Windows and Mac OS) or iPad. Apart from these, it is possible to use Algodoo with interactive whiteboard (IWB) in the classroom to involve students actively in the learning process [25]. In addition to the school practice, Algodoo is also very practical to be used at home by the students for their physics learning [24].

Simulation scenes in Algodoo are created using simple drawing tools such as boxes, circles, polygons, gears, brushes, planes, ropes and chains. Also, various tools such as springs, hinges, motors, thrusters, light rays, tracers, and lenses can be added to the simulations. Thus, Algodoo can be utilized for several subjects including Newton's Laws of Motion at the first place. One of the most important features of Algodoo is the fact that it can present data obtained from the simulation related to distance, speed, velocity, acceleration, force, momentum, and energy in the form of a graph simultaneously. Besides, it also demonstrates velocity, momentum, and force vectors simultaneously.

The literature shows that a study utilizes Algodoo simulation software concerning Kepler's Laws which are difficult to demonstrate in the classroom environment experimentally [25]. Also, another study focuses on impulse-momentum activities [26].

2. Theoretical background

As can be seen in figure 1, let an object with a mass of m stay in a stationary position on an inclined plane which makes an angle of θ with the horizontal. The object is under the effect of a force, mg in the vertical due to the gravitational acceleration. Also, the object is under the effect of the normal force (F_N) which is perpendicular to the surface in addition to the static frictional force (f_s) which is parallel to the inclined plane. Here the frictional force called as static frictional force because the object is still. So, when the object is stationary in x-axis,

$$F_x - f_s = 0 \tag{1}$$

$$mg\sin\theta - f_s = 0 \tag{2}$$

and in y-axis,

$$F_N - F_y = 0 \tag{3}$$

$$F_N - mg\cos\theta = 0. \tag{4}$$

The abovementioned equations are obtained. When f_s is the static frictional force and μ_s is static friction coefficient,

$$f_s = \mu_s F_N. \tag{5}$$

If θ is increased gradually while the object is stationary, *sin* θ in equation (2) and *fs* increase. The block with a mass of m starts moving after a definite critical angle (θ_c) value. At the time the object starts moving, equations (2) and (4) are as follows:

$$mg\sin\theta_c = \mu_s F_N \tag{6}$$

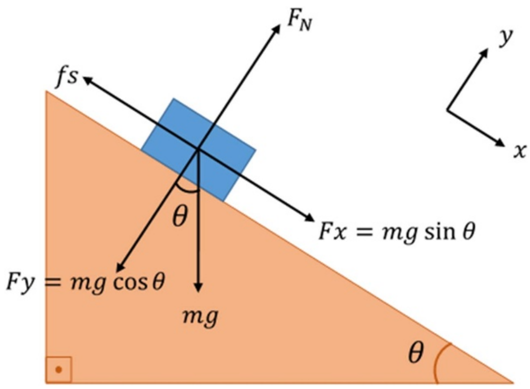


Figure 1. Mass on an inclined plane.

$$mg\cos\theta_c = F_N \tag{7}$$

Combining equations (6) and (7),

$$\mu_s = \tan\theta_c \tag{8}$$

When the object starts sliding on the inclined plane, the forces acting on the object will be in the same direction as the forces acting on it in the static position. In this case, the only difference will be the fact that the frictional force which is acting on the object will be the kinetic frictional force, not the static frictional force. As f_k is kinetic frictional force and μ_k is kinetic friction coefficient,

$$f_k = \mu_k F_N \tag{9}$$

When Newton's second law of motion is applied along the x-axis after the object starts sliding on the inclined plane,

$$F_x - f_k = ma_x \tag{10}$$

$$mg\sin\theta - \mu_k mg\cos\theta = ma_x \tag{11}$$

$$\mu_k = \frac{g\sin\theta - a_x}{g\cos\theta} \tag{12}$$

As a result, it is required to know the gravitational acceleration (g), acceleration of the object (a_x) and the angle of θ to determine the kinetic friction coefficient between the object moving on an inclined plane and the surface. Hereby, in a special case when the object moves with a constant velocity, the acceleration equals to zero and the term, acceleration is eliminated from the equation.

The change in the distance of an object which moves with a constant acceleration with respect to time can be defined as

$x(t) = At^2 + Bt + C$. The second derivative of this equation with respect to time also gives the acceleration of the object.

3. Experimental setup and data analysis

The experimental setups involved in the study were created in the laboratory for Phyphox and Tracker whereas computer environment was utilized for Algodoo. Detailed information about the experimental setups is presented below, respectively.

3.1. Experimental setup for Phyphox

Figure 2 demonstrates the experimental setup which aims to determine the kinetic friction coefficient with Phyphox application.

The experimental setup consists of a wooden inclined plane, a wooden block to locate smartphone on it, 6 neodymium magnets fixed on the inclined plane with a piece of tape and a stopper located at the end of the inclined plane to keep the smartphone safely in the end of the experiment. The smartphone (case) is fixed to the wooden block by using a double-sided tape so that the smartphone stays on the wooden block without slipping. In this way, it is ensured that the data received from Phyphox is correct.

Table 1 provides detailed information about the materials used in the experimental setting.

The distance between each of Neodymium magnets in the experimental setup is 10.0 cm. In this case, the total distance from which data is taken is 50.0 cm. Also, the height of the inclined plane is adjustable to repeat the experiment for several other inclination values. The angle value of the inclined plane was fixed before the experiment started. Then the wooden block and the smartphone were placed on the inclined plane. Meanwhile, the block was held until the experiment started.

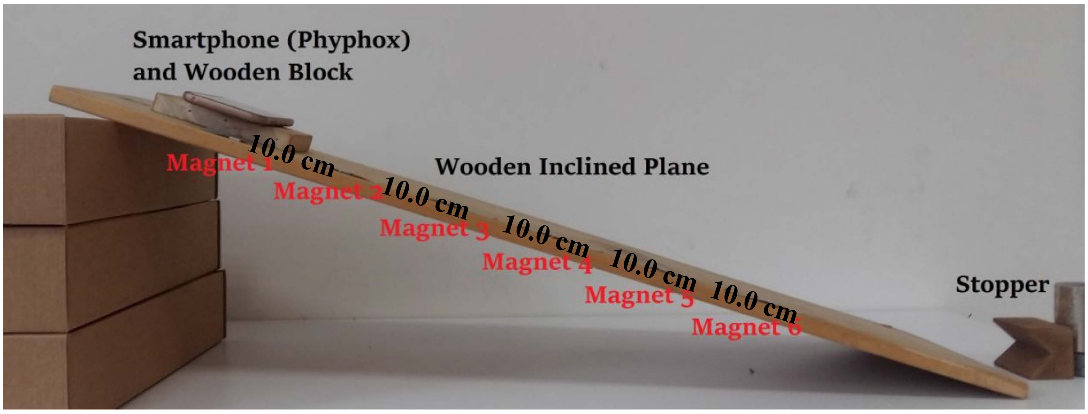


Figure 2. Experimental setup for Phyphox.

Table 1. Detailed information about experimental setup components.

Component	Material	Dimension (mm)	Mass (g)
Inclined plane	Wood	930.0 × 240.0 × 15.0	1491.5
Block	Wood	131.0 × 102.0 × 17.0	101.2
Smartphone (Samsung Galaxy A7-2017&Case)	—	159.8 × 80.6 × 8.9	206.8
Magnet	Neodymium N35	30.0 × 10.0 × 2.0	4.33

To determine the kinetic friction coefficient between the wooden block and wooden inclined plane, magnetometer feature of Phyphox application was used. Thus, a distance-time graph was obtained for the wooden block. Phyphox application shows the *x*, *y* and *z* components of the magnetic field on the screen while the magnetic sensor on the smartphone passes alongside the magnet. In the experiments conducted, only x components of data obtained from the magnetometer were considered. Besides, 'Inclination tool' of Phyphox application was utilized to determine the angle between the inclined plane and the horizontal. Also, those data were monitorized on the computer screen wirelessly and simultaneously.

Several pre-experiments were performed to keep the initial distance between the magnet and the phone in an optimum value before starting to conduct the experiments. In this way, destruction of the magnetic sensor of the smartphone was avoided. Also, correct data collection was achieved. Figure 3 presents the phone used in the study and the optimum initial distance values obtained for 'Magnet 1'.

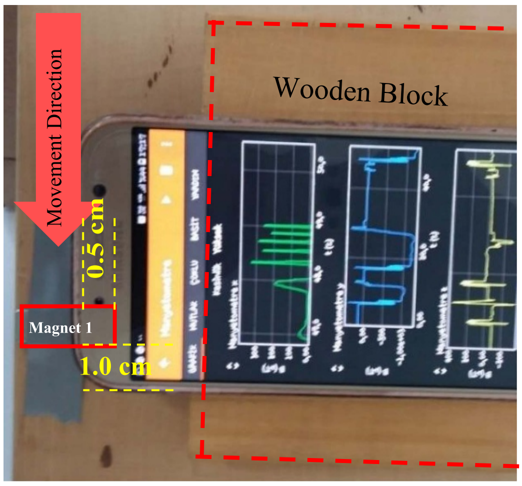
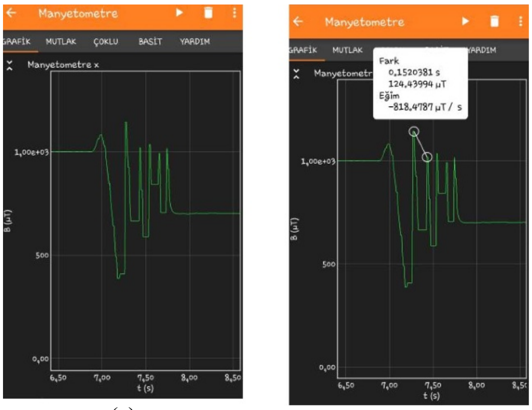


Figure 3. Initial position of smartphone and magnet 1.

3.1.1. Data analysis. Figure 4 shows example screen shots related to the wooden block which was released freely from its initial position in addition to the data obtained from the phone.

When figure 4(a) is analysed, six peaks are seen on the graph. Those peaks are data



(a) (b)

Figure 4. (a) Experimental data with Phyphox (b) data analysis.

which were obtained when the magnetic sensor of the smartphone passed alongside magnets. While analysing data, first of all, time differences between consecutive peak points were determined. Those time values with respect to distance (0.0–10.0–20.0–30.0–40.0–50.0 cm) were recorded in an Excel file. To minimize the experimental errors, the experiments were repeated for five times for each inclination value and the average of data concerning time was taken into consideration. Next, a distance-time graph was drawn using obtained average values. The graph was formulized in the form of a second-degree equation with respect to time. As mentioned earlier, the second derivative of this equation with respect to time gives the acceleration. By this way, the acceleration values for the motion of wooden block and phone were calculated. Afterwards, kinetic friction coefficient was determined with the help of the equation (12).

3.2. Experimental setup for Tracker

Another smartphone which was one meter away from the experimental setup was used to record the fifth video obtained for all angle values with Phyphox application (figure 2). Fps value of the smartphone which recorded video was 30.

3.2.1. Data analysis. Recorded videos were analysed with Tracker program (figure 5(a)). Video analysis was made for the entire inclined plane, not just for the first 50.0 cm part of the inclined plane, unlike the Phyphox program. The distance-time graph for the wooden block and smartphone was analysed using the 'Data Tool' which is the add-on to the program. The distance-time graph was fit into an equation in the form of $x(t) = At^2 + Bt + C$. The acceleration value was calculated by taking the second derivative of the equation with respect to time. The kinetic friction coefficient was calculated by placing the acceleration value in the equation (12).

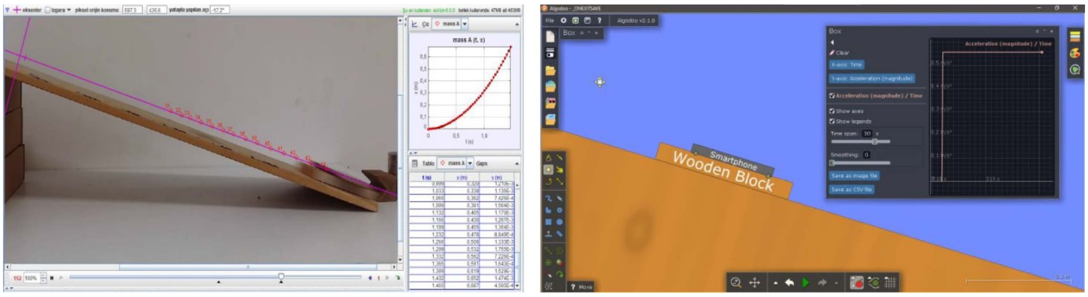
3.3. Experimental setup (scene) for Algodoo

Like the experiments conducted in the laboratory environment, 'wood' was preferred as the material to determine kinetic friction coefficient using the simulations developed with Algodoo. Several parameters of the materials such as density, friction, restitution, and attraction can be changed within certain limits in Algodoo program by the user. In the simulation created within the scope of the study, the density of wood was set as 0.60 kg m^{-2}, friction as 0.25, restitution as 0.50, and attraction as 0.00 Nm^2 kg^{-2}.

Friction, wind speed/angle and gravity strength/direction are the parameters which can be changed in Algodoo by the user. In the present study, gravity strength was taken as perpendicular to the Earth surface with a value of 9.81 m s^{-2} and wind speed was determined as 0 m s^{-1}. Also, air friction was turned 'off'.

The angle values which were considered for the inclined plane in the simulation designed were the same as in the experiments conducted with the Phyphox and Tracker in the laboratory environment.

3.3.1. Data analysis. Data obtained from the simulation are simultaneously displayed on the screen in the graphic form. To determine acceleration, the acceleration-time graph was drawn, and acceleration values were directly read on the graph. Next, kinetic friction coefficient was specified by placing the acceleration value in the equation (12).



(a) (b)

Figure 5. (a) Analysis of the experiment video with the tracker (b) Algodo simulation scene for kinetic friction calculation.

4. Experimental findings

In the scope of the study, experiments/simulations were made for three different angle values of the inclined plane (17.20°, 20.00°, 22.30°) using Phyphox, Tracker and Algodoo to determine kinetic friction coefficient. The distance-time graphs which were obtained as a result of the experiments were drawn with the help of Excel for Phyphox (figures 6(a), (c) and (e)) and Data Tool for Tracker (figures 6(b), (d) and (f)). The distance equation with respect to time was determined in an Excel file for the data obtained from Phyphox application and this equation was indicated on each of the graphs. Besides, a distance graph with respect to time was obtained for Tracker with the following steps, 'Data Tool- Analyze- Curve Fits- Fit Name: Parabola'.

Table 2 introduces the distance–time equations obtained from the graphs. Figure 7 displays acceleration–time graphs for the simulations created with Algodoo. Unlike Phyphox and Tracker, the acceleration values were directly determined from the simulation created with Algodoo.

The acceleration values obtained from the second derivatives of distance-time equations as displayed in table 2 with respect to time (Phyphox and Tracker) and the acceleration values reached with Algodoo (figure 7) are presented in table 3 considering the angle of inclined plane. Those acceleration values are placed in the equation (12) and kinetic friction coefficients were calculated for each of the angles.

According to the data obtained, the average kinetic friction coefficient was calculated to be $\mu_k = 0.248$ as a result of the experiments conducted with Phyphox. Besides, the average kinetic friction coefficient was calculated to be $\mu_k = 0.257$ as a result of the analyses conducted with Tracker. These kinetic friction coefficients were calculated by assuming the 'inclination tool' sensitivity of the Phyphox application is 0.01 degrees. When the data obtained with Algodoo were examined, the kinetic friction coefficient was observed to take almost the same value, $\mu_k = 0.250$ for three different angles. This is an expected situation since the friction coefficient was entered on to the Algodoo simulation program by the user.

Theoretically, kinetic friction coefficient for the wood on wood is $\mu_k = 0.200$ [27]. As well as the studies which report that they get similar values to this theoretical value [28, 29] ($\mu_k = 0.210$, $\mu_k = 0.20 \pm 0.03$), there is also research which concludes very close results to our study ($\mu_k = 0.25 \pm 0.01$) [30].

5. Results and discussion

In this study, the kinetic friction coefficient was determined with three different methods (Phyphox, Tracker and Algodoo). It was seen that consistent results were taken as a result of the experiments conducted with Phyphox and Tracker for three different angles of inclination. The difference between the theoretical and experimental values might be due to the structure or kind of the woods used in the experiments. As it is known, rubbing or polishing are the elements that make an influence on the friction coefficient of the wood.

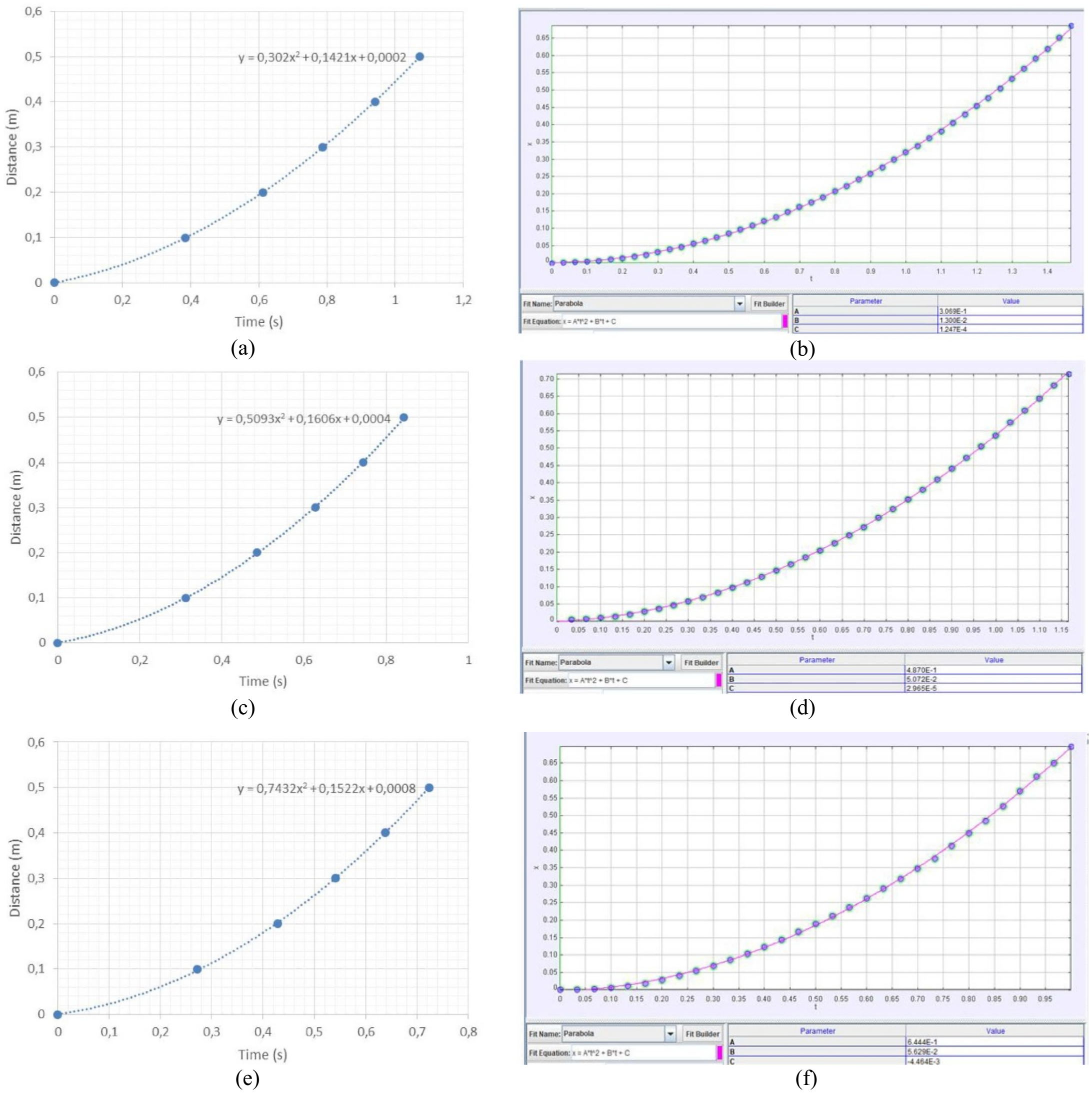
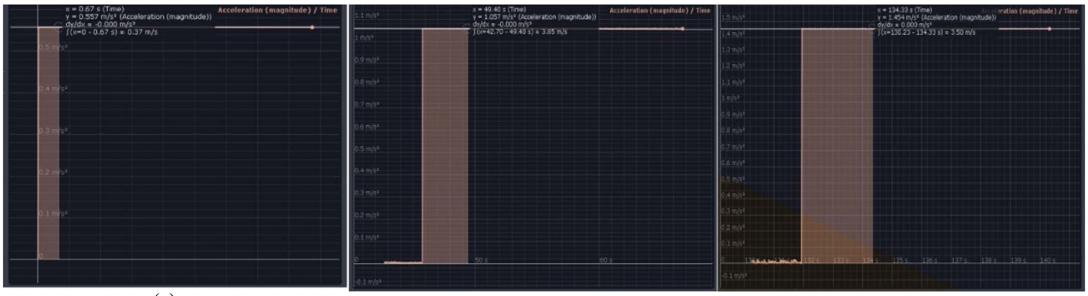


Figure 6. Distance-time graphs for Phyphox (a) 17.20° (c) 20.00° (e) 22.30° and Tracker (b) 17.20° (d) 20.00° (f) 22.30°.

Table 2. Distance—time equations for Phyphox and Tracker experiments.

Angle of inclined plane (°)	Method	Equation
17.20	Phyphox	$x = 0.3020t^2 + 0.1421t + 0.0002$
	Tracker	$x = 0.3069t^2 + 0.0130t + 0.0001$
20.00	Phyphox	$x = 0.5093t^2 + 0.1606t + 0.0004$
	Tracker	$x = 0.4870t^2 + 0.0507t + 0.0001$
22.30	Phyphox	$x = 0.7432t^2 + 0.1522t + 0.0008$
	Tracker	$x = 0.6444t^2 + 0.0563t - 0.0044$



(a) (b) (c)

Figure 7. Acceleration-time graphs for Algodoo (a) 17.20° (b) 20.00° (c) 22.30°.

Table 3. Kinetic friction coefficient according to the angle and method.

Angle of inclined plane (°)	Method	Acceleration (m s^{-2})	μ_k
17.20	Phyphox	0.604	0.245
	Tracker	0.614	0.244
	Algodoo	0.557	0.250
20.00	Phyphox	1.019	0.253
	Tracker	0.974	0.258
	Algodoo	1.057	0.249
22.30	Phyphox	1.486	0.246
	Tracker	1.288	0.268
	Algodoo	1.454	0.250

These three methods, which are carried out with the aim of determining the kinetic friction coefficient, can be preferred and used in teaching, considering the present conditions.

Especially in recent years when distance education has been used widely and gained popularity, it has become very important for students to conduct experiments with easily accessible materials outside of the school environment. Development of the sensors in smartphones with the increase in their numbers has made it possible to carry out several physics experiments using smartphones. When the accessibility is considered, it might be thought that students can carry out various mechanics experiments using smartphones and free applications. However, these smartphones and sensors are not sufficient for particular experiments. In this case, it is an alternative to analyse the experiments that were previously recorded as video. Also, the experiments which are not safe to be conducted by the students can also be used with video analysis methods in teaching. Apart from these, the experiments which require expensive setting can be analysed using video analysis programs. However, sometimes it is very important to use a camera with high resolution and high fps in order to obtain more accurate results in video analysis method. In our experiments, we determined that the difference in kinetic friction coefficient between Phyphox and Tracker increases with increasing speed of the block. In this case, we think that 30 fps may not be sufficient for high speed analyses.

Simulation programs seem like a strong alternative for the situations which are very difficult or impossible to create in the laboratory or classroom environment (for example removal of air friction, changing the gravitational acceleration). Also, simulation programs can be very efficient for the students who do not have possibility to reach the materials used in the experiments.

When the methods are compared with each other in terms of requiring pre-knowledge, smartphone applications can be stated to be one step ahead. The biggest advantage of this method is the fact that the user needs almost no learning procedure after downloading the application. In addition, the instrument which is frequently used in daily life acts as a sensor. On the other hand, a pre-learning procedure is required for using both video analysis methods and simulation programs.

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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