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TEACHING MOTION CONCEPTS THROUGH TRACKER - BASED VIDEO ANALYSIS

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Abstract

Difficulties in understanding kinematics concepts are widespread among students at various educational levels, as documented in physics educational research. Also, students find it challenging to connect the concepts of motion with the equations and graphs that describe them. Such difficulties often originate from intuitive understanding, shaped by their everyday experiences, which can conflict with scientific explanations. Without appropriate instructional intervention, students' misunderstandings regarding motion concepts are likely to persist and become reinforced over time, making it increasingly difficult for students to grasp more advanced topics in physics. This work presents a learning model that utilizes Tracker software to examine videos of the free fall and oscillatory motion experiments. By directly observing and tracking object motion, this approach helps students to develop a deeper understanding of the concepts of position, velocity, and acceleration. The method combines hands-on experiments with computer modeling, allowing students to analyze data and represent motion graphically and analytically. The accuracy of Tracker software is evaluated by measuring the magnitude of gravitational acceleration. In the first method, where free fall experiment video was analyzed by Tracker, an average value of $g = (9.984 \pm 0.611) m/s^2$ was the result. In the second method, analyzing the video of a simple pendulum experiment by using Tracker resulted in $g = (9.864 \pm 0.094) m/s^2$. Both results agree with the generally accepted gravitational acceleration and support the validity of using Tracker video analysis as an effective tool for school laboratory purposes.

Keywords: Tracker, experiment, video analysis, position, velocity, acceleration, free fall, oscillations.

1 Introduction

The basic concepts related to motion are time, position, displacement, velocity, and acceleration. These concepts become the core framework that students use to learn and understand physics. A significant challenge faced by students learning physics is associated with understanding these fundamental concepts [1]. Identifying misconceptions and their sources, as well as finding teaching strategies that help students overcome them, is the main goal of physics education research. Challenges with motion concepts have been extensively documented by numerous researchers, representing one of the most persistent difficulties in physics education [2-11]. Their findings revealed that students are unable to apply the concepts they have learned for solving problems, an ability widely accepted as a measure of student achievement in physics. Misconceptions occur when students understand the concept of motion primarily based on intuition or common sense, which often conflicts with scientific concepts [1-4]. Students' difficulties with motion concepts become evident when applying principles of motion in mechanics [5-9].

For students, different motion concepts, such as instant of time and time interval, position and displacement, as well as velocity and acceleration, are often mixed under the general notion of motion. Given that the concept of instantaneous velocity and acceleration remained a paradox for centuries and ultimately contributed to the development of calculus by Newton and Leibniz, it is reasonable to expect that students may struggle to understand these ideas easily or immediately [1-5]. As Arons [5] emphasized, it is necessary to help students clearly discriminate between instants and intervals of time, as well as between position and changes in position. Once these distinctions are understood, students can begin to analyze the properties and behavior of ratios of changes in position and velocity over time intervals. This technique can lead students to a deeper conceptual understanding of average values and, ultimately, the development of the concept of instantaneous quantities of velocity and acceleration.

Students also encounter difficulties in presenting and interpreting motion graphs, a challenge that reflects a limited conceptual understanding. This is frequently reinforced by the misconception that such graphs offer a pictorial rather than an abstract representation of motion. For instance, a straight line through the origin on a position versus time graph is often misinterpreted as presenting an object moving up an inclined plane. These challenges are present at nearly every educational level, and many are even carried further by new teachers who unintentionally transmit these misconceptions to their students. Accordingly, implementing carefully structured and research-based instructional strategies is crucial to effectively confronting these misconceptions and cultivating scientific thinking.

Observing and analyzing motion over time, such as through the video examination, supports students' ability to distinguish motion concepts and interpret motion graphs [10-17].

The selection and application of appropriate software for automatic motion tracking depends on factors such as cost, educational goals, user familiarity, and available analytical features. However, regardless of the software used, the method remains the same: a video camera records the position over time, and this data is subsequently processed frame by frame to analyze the motion [10-17].

In this study, Tracker software, developed by Douglas Brown and built on Java, is used as a tool for video-based motion analysis [16]. Tracker is a free and open-source tool widely used in physics education due to its easy accessibility and versatile functionality. To extract information, it tracks the motion of the object and marks the position at specific time intervals. Beyond basic tracking of the moving object, Tracker generates data and corresponding graphs for position, velocity, and acceleration versus time. It provides multiple reference frame systems and tools for calibrating the motion tracks, enhancing the accuracy of video analysis.

Growing interest in video-based learning has drawn attention to the use of Tracker software to help students better understand fundamental physics concepts. Wee et al. [18] examined the ease of installing and using Tracker for analyzing the projectile motion, concluding that the derived values of acceleration due to gravity from video analysis were consistent with real-world data. Providing a descriptive analysis of the impact of using Tracker on student learning, Wee et al. [19] suggested that students learned kinematics concepts more effectively than they would have with traditional lessons. Fianti et al. [20] found that using Tracker significantly improved students' communication skills by 56.3% and collaboration skills by 70.3%, with a strong positive correlation between the two (r = 0.876). They also highlight that learning to use Tracker video analysis can help students develop new knowledge and skills related to designing experiments. Prima et al. [21] investigated the acceleration, speed, and position of cylinders rolling down a ramp by using Tracker. They reported results consistent with theory and observed that the Tracker analyses are better at analyzing both speed and position than at analyzing acceleration. Amoroso and Rinaudo [22] used Tracker to study the oscillatory motion of simple and vertical pendulums, as well as the damped oscillatory motion of a body moving on a semi-circular track. Their study showed that the user-friendly design of the software enables students to visualize motion and engage with physical concepts, even outside of a traditional laboratory. Bhakat et al. [23] demonstrated that Tracker video analysis is highly effective for physics education. They applied it through the analysis of a simple pendulum motion, where experimental results, including period, phase-space trajectory, and first-order anharmonic coupling factor, were found to be reasonable with standard theoretical predictions. demonstrating improved comprehension of oscillatory phenomena. Claessens [24] introduced a novel instructional model that integrates the Tracker software with virtual computer simulations instead of analyzing videos to study the problem of a slipping/rolling cylinder on a rough surface. Sarkar [25] highlighted the effectiveness of using Tracker software to create a constructivist, inquiry-based classroom to make motion concepts more visible and meaningful, demonstrating how video-based analysis can be used to solve real-life problems in mechanics. Putri et al. [26] conducted a survey to evaluate the students' ability to operate the Tracker software effectively, with a particular focus on accelerated motion. They reported both ease of use and improved conceptual understanding, indicating that the software is technically user-friendly and effective in creating an active learning environment.

This study demonstrates the potential of Tracker software as a pedagogical tool for enhancing understanding of the concepts of position, velocity, and acceleration. It focuses on applying Tracker to examine videos of the free fall and oscillatory motion experiments. By measuring the acceleration due to gravity and comparing it with reference values, this work aims to evaluate the performance of Tracker software.

2 Materials and methods

2.1 Video analysis using Tracker

In this study, video analysis was performed using Tracker software built on the Open Source Physics (OSP) Java framework, designed to be used in Physics Education [16]. The open-source and freely available software was downloaded at https://opensourcephysics.github.io/tracker-website/. It provides frame-by-frame analysis of motion by segmenting imported videos. Manual tracking of the body in motion was conducted by marking its position at specific times. The software provides time-dependent data and graphical representations of position, velocity, and acceleration, which were used for further analysis. Calibration tools were used to define the spatial scale and reference frames were specified by defining origin and axis orientation relative to the object at its initial rest position. Although the software allows the user to define more than one coordinate system within the same video or across analyses, a single appropriate reference frame was used for each experiment.

2.2 Free fall

A well-known example of uniformly accelerated motion is that of free-falling objects near Earth's surface, in the absence of air resistance. Although air resistance affects the motion of falling objects, the simplified free fall model was used. Highly accurate and precise techniques have been used over the years to measure acceleration due to gravity g. It varies from $g_p = 9.80665\ m/s^2$ at the poles to $g_e = 9.7803\ m/s^2$at the equator [27], and it is influenced by factors such as latitude, altitude, and the Earth's rotation. The generally accepted standard value of acceleration due to gravity is $g_n = 9.806\ m/s^2$ [28], will be used as the reference in this work.

The first method in this experiment is based on video analysis by using Tracker software. A 30 frame per second video of free fall motion is recorded via a smartphone camera and Tracker is used to analyze the motion of a ball released from a known height. By tracking the position as a function of time, it is possible to determine quantities such as position, velocity, acceleration, and other variables. Materials used in this method include a tripod, a steel ball, a smartphone, Tracker software, a computer, a meter rule, and markers as shown in Fig. 1. A reference background (wall) is prepared by placing visual markers at specific intervals. The tripod is first set up and fixed in a position that allows the smartphone to capture the entire trajectory of the ball clearly within the frame.

Figure 1. Experimental setup to determine acceleration due to gravity, g.

The phone is then paired via Bluetooth with a remote control, which is used to start and stop video recording. After recording the motion, the video is imported into Tracker software using the "Import Video" option.

2.3 Simple pendulum

The experiment aims to use Tracker to investigate oscillatory motion. The most common example of oscillatory motion is a simple pendulum, which consists of a point mass suspended from a massless string with length L . The mass oscillates around its equilibrium position. The period of oscillations, T, represents the time taken for the ball to complete one full oscillation and for small angles (typically less than 15° [29]) is given by the approximation solution

$$T = 2\pi\sqrt{\frac{L}{g}}, \tag{1}$$

where g is the acceleration due to gravity.

The period of the pendulum's oscillations will be measured using Tracker, and this data will be used to calculate the acceleration due to gravity, g, by using equation (1).

A string with a length of 2 m was connected to a metal ball and attached to a fixed metal support previously mounted to the ceiling. To ensure the accuracy of the results, care is taken to eliminate any influence from air currents within the room, such as those caused by open windows or air conditioning systems. The tripod is positioned and fixed such that the smartphone provides a full field of view of the pendulum and clearly captures its motion throughout the oscillation, as shown in Fig. 2. The smartphone is linked with the remote control via Bluetooth, which is then used to start video recording. Once the camera is confirmed to be active, the ball is displaced at a maximal angle of 12º from the vertical to ensure that the pendulum motion remains in a vertical plane, minimizing any circular movement. The recorded video is imported into Tracker software to analyze the oscillatory motion.

Figure 2. Experimental setup to record videos of simple pendulum motion.

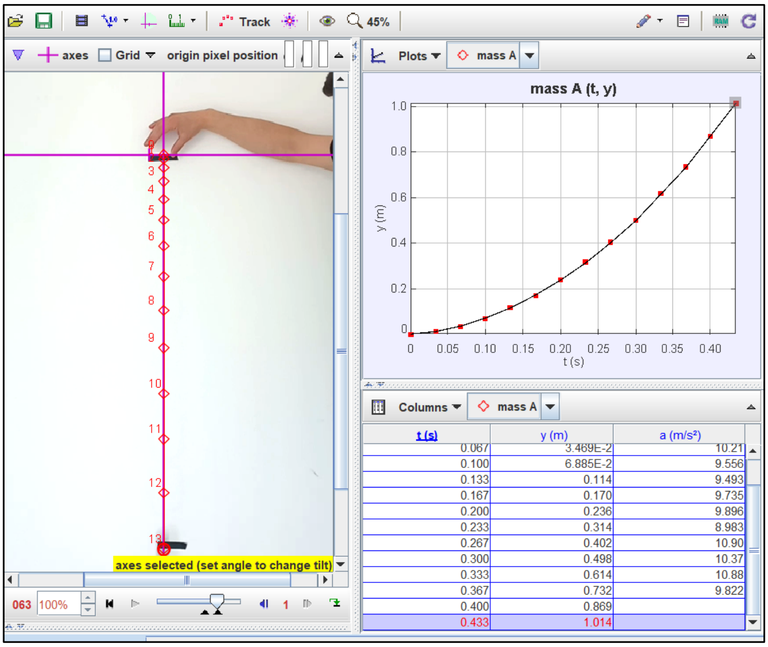
In reality, the oscillations of a pendulum do not continue indefinitely. Non-conservative forces of air resistance and friction at the pivot point gradually reduce the amplitude of the motion. Assuming the mass of the string is negligible, and friction is minimal, only air resistance is then considered, modeled as $f = -bv$, where b is the proportionality constant of the resistive force to the velocity. Under these assumptions, the solution of the differential equation derived from Newton's second law is

$$x = Ae^{-Bt} sin(\omega t + \varphi), \tag{2}$$

where $B = b/2m$ is the damping coefficient, A is the initial amplitude and φ is the phase constant determined by initial conditions. The term Ae^{-Bt} represents the exponentially decaying amplitude of the oscillation, while the angular frequency ω of the damped motion is given by $\omega^2 = \omega_0^2 - B^2$, where ω_0 is the natural angular frequency. For small damping, although amplitude slowly decreases, the effect of air resistance is minimal, and the period of oscillations remain nearly the same as that for a simple pendulum. Therefore, the calculated value of acceleration due to gravity based on the period of oscillations can be considered valid under the assumptions of the simple harmonic motion.

4 Results and discussions

After selecting the appropriate parameters and tracking position and times of the ball in free fall by using Tracker, a screen with three panels is generated, as displayed in Figure 1.

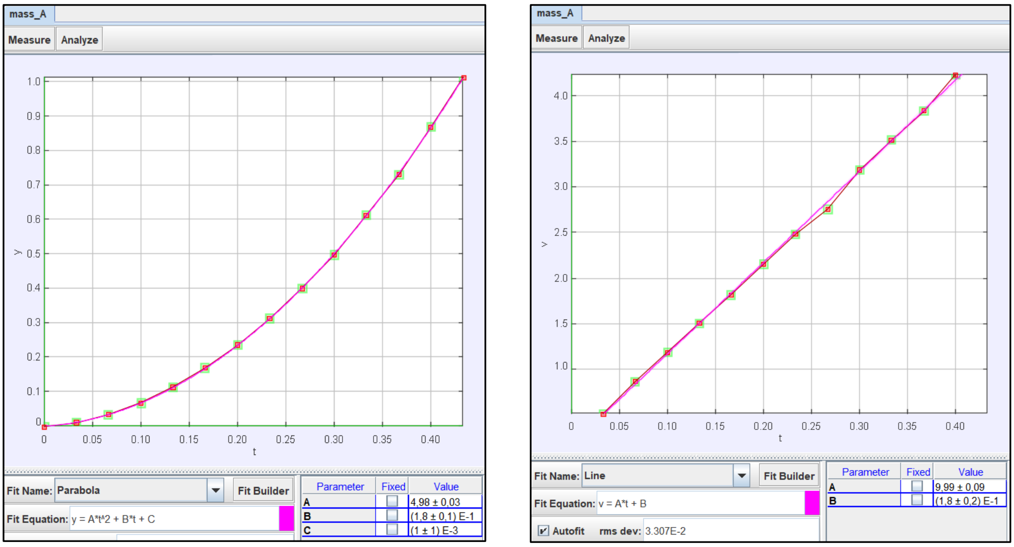


axes selected (set angle to change tilt)

t (s)	y (m)	a (m/s²)
0.067	3.469E-2	10.21
0.100	6.885E-2	9.556
0.133	0.114	9.493
0.167	0.170	9.735
0.200	0.236	9.896
0.233	0.314	8.983
0.267	0.402	10.90
0.300	0.498	10.37
0.333	0.614	10.88
0.367	0.732	9.822
0.400	0.869	
0.433	1.014	

Figure 3 Screenshot of Tracker software for free fall.

It consists of the view of motion (left panel), quantitative data of time, position, velocity, and acceleration (bottom right panel), and graphs (position versus time graph in upper right panel). A total of 14 position markers were recorded to represent the motion of the free-falling ball. The graph of position and velocity versus time, as provided by Tracker, is presented in Fig. 4a and Fig. 4b, respectively. The experience of tracking the motion of an object frame by frame is helpful for introducing the concepts of instant of time, time interval, position, and change in position, as well as analyzing their relationships.



Fit Name: Parabola
Fit Equation: y = A*t^2 + B*t + C

Parameter	Fixed	Value
A	☐	4,98 ± 0,03
B	☐	(1,8 ± 0,1) E-1
C	☐	(1 ± 1) E-3

Fit Name: Line
Fit Equation: v = A*t + B
☑ Autofit rms dev: 3.307E-2

Parameter	Fixed	Value
A	☐	9,99 ± 0,09
B	☐	(1,8 ± 0,2) E-1

(a) (b)

Figure 4 Screenshot of Tracker for a) position versus time and b) velocity versus time.

In the bottom of Fig. 4a the fitted second order equation developed for position (y) versus time (t), as $y = At^2 + Bt + C$ with parameters $A = 4.98$, $B = 0.18$ and $C = 0.001$ is presented. Hence, the equation for position as a function of time can be written as: $y = 0.001 + 0.18t + 4.98t^2$. By examining these data, students can observe and analyze how these data and graphical representations relate to one dimensional equation of motion under constant acceleration. The coefficient $A = 4.98$ in the equation of motion corresponds to half the acceleration due to gravity, from which the value $g = 9.96\ m/s^2$ can be deduced.

At the bottom of Fig. 4b, the fitted linear equation derived for velocity versus time with parameters $A = 9.99$ and $B = 0.18$ is presented. The slope of the velocity versus time graph, represented by the coefficient $A = 9.99$, indicates the acceleration due to gravity, determined from the linear function of velocity versus time: $g = (9.99\ \pm 0.09)\ m/s^2$. The value 0.18 of the interception of the line with the y-axis represents the initial velocity. This initial velocity, as shown in Figure 4b, has resulted from the first few frames of video and represents an average over the finite time interval between frames. In the analytical model, the velocity at t=0 is defined infinitesimally, but the experimental velocity is approximated from discrete measurements of position. The equation of the velocity versus time for the free-falling ball is then given by: $v = 9.99t + 0.18$.

To assess the accuracy of the measurement method, the standard deviation was calculated. The percentage error between the experimentally measured value and the theoretical value was used to evaluate the reliability of the method.

Using the data generated from Tracker, the mean value of gravitational acceleration, the standard deviation, and the percentage error (deviation from the standard value) were calculated, as presented in Table 1.

Table 1: Summary statistics of acceleration due to gravity.

Mean value **g** (m/s^2)	**Standard deviation** **σ** (m/s^2)	**Standard value** **g_n** (m/s^2)	**Percentage error** **ε** (%)
9.984	± 0.611	9.806	1.82

Based on the data collected using Tracker and calculations, the acceleration due to gravity was found to be $g = (9.984 \pm 0.611)\ m/s^2$. Compared to the reference value, this result differs by 1.82%.

Figure 5 shows a screenshot of the video displaying the motion of the simple pendulum during its oscillation.

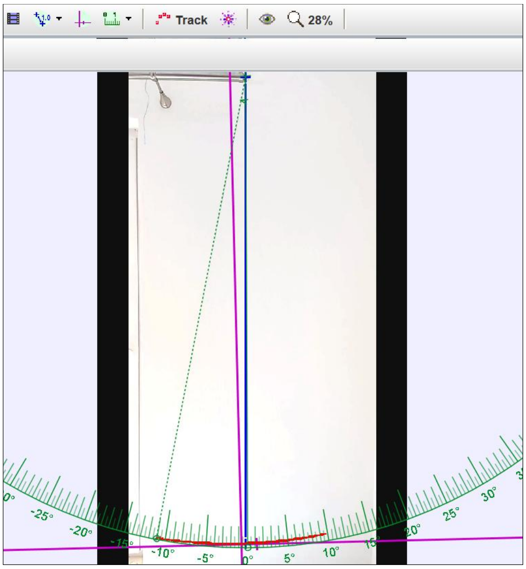
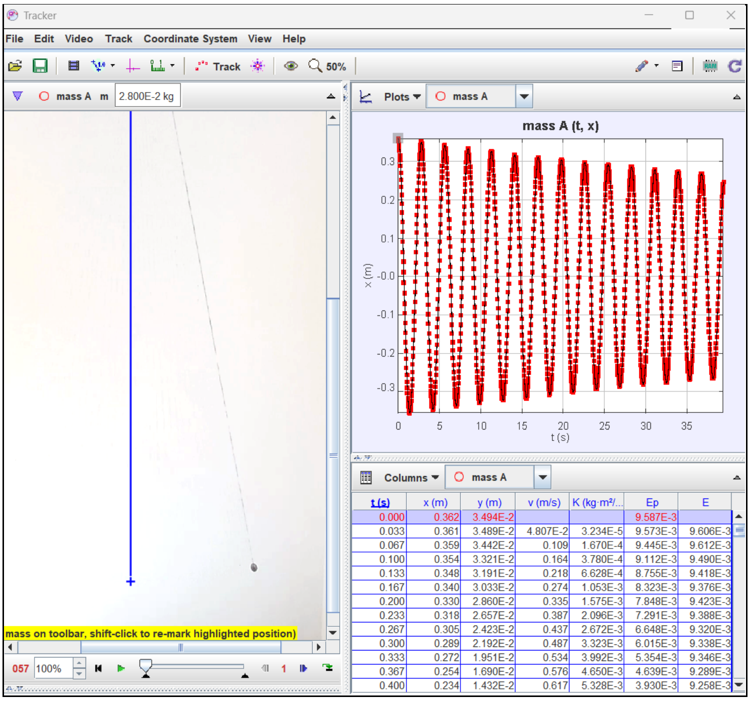


Figure 5. Screenshot of Tracker used to study the oscillations of a simple pendulum.

The origin of the coordinate system was chosen to be the equilibrium position, directly beneath the suspension point of the sphere, where it would remain at rest if undisturbed. At this point, gravitational potential energy is defined to be zero.

Once the appropriate parameters are configured in Tracker, the software produces data representing the tracked motion of the pendulum's bob. A screen with three panels is then displayed, as shown in Figure 6.



mass A m 2.800E-2 kg

mass on toolbar, shift-click to re-mark highlighted position)

t (s)	x (m)	y (m)	v (m/s)	K (kg·m²/...	Ep	E
0.000	0.362	3.494E-2			9.587E-3	
0.033	0.361	3.489E-2	4.807E-2	3.234E-5	9.573E-3	9.606E-3
0.067	0.359	3.442E-2	0.109	1.670E-4	9.445E-3	9.612E-3
0.100	0.354	3.321E-2	0.164	3.780E-4	9.112E-3	9.490E-3
0.133	0.348	3.191E-2	0.218	6.628E-4	8.755E-3	9.418E-3
0.167	0.340	3.033E-2	0.274	1.053E-3	8.323E-3	9.376E-3
0.200	0.330	2.860E-2	0.335	1.575E-3	7.848E-3	9.423E-3
0.233	0.318	2.657E-2	0.387	2.096E-3	7.291E-3	9.388E-3
0.267	0.305	2.423E-2	0.437	2.672E-3	6.648E-3	9.320E-3
0.300	0.289	2.192E-2	0.487	3.323E-3	6.015E-3	9.338E-3
0.333	0.272	1.951E-2	0.534	3.992E-3	5.354E-3	9.346E-3
0.367	0.254	1.690E-2	0.576	4.650E-3	4.639E-3	9.289E-3
0.400	0.234	1.432E-2	0.617	5.328E-3	3.930E-3	9.258E-3

Figure 6. Screenshot of Tracker software for simple pendulum.

It consists of the view of motion (left panel), quantitative data of time, position, velocity and kinetic, potential and total energy (bottom right panel), and graphs (position versus time graph in upper right panel).

Following the tracking process, the period of oscillation, T, was calculated using the time relation $T = t_2 - t_1$, where t_1 and t_2 are two successive instants of times at which the velocity of the object is zero (at turning points).

Using the calculated period, the acceleration due to gravity was determined by applying the equation (1) for the period of simple pendulum which is rearranged to solve for g:

$$g = \frac{4\pi^2}{T^2} L.$$

Table 2 presents the successive time instants, the calculated periods and the corresponding values of acceleration due to gravity.

Table 2: Recorded time instants, calculated periods, and acceleration due to gravity values.

Nr	**Pendulum length, L (m)**	**Instant of time, t_1 (s)**	**Instant of time, t_2 (s)**	**Period, T (s)**	**Acceleration, g (m/s^2)**
1	2	0.467	3.300	2.833	9.827
2	2	3.300	6.133	2.833	9.827
3	2	6.133	8.967	2.834	9.820
4	2	8.967	11.800	2.833	9.827
5	2	11.800	14.630	2.830	9.848
6	2	14.630	17.430	2.800	10.062
7	2	17.430	20.270	2.840	9.779
8	2	20.270	23.100	2.830	9.848
9	2	23.100	25.930	2.830	9.848
10	2	25.930	28.730	2.800	10.060
11	2	28.730	31.570	2.840	9.779
12	2	31.570	34.400	2.830	9.848
13	2	34.400	37.230	2.830	9.848
				Mean value	9.864

By using the data generated from Tracker and excel, the mean value of gravitational acceleration in this experiment, along with standard deviation and its deviation from the reference (percentage error), is presented in Table 3.

Based on the data collected using Tracker and calculations, the acceleration due to gravity was found to be $g = (9.864 \pm 0.094)\ m/s^2$. Compared to the reference value, this result differs by 0.59%. Such a small percentage error suggests that video analysis with Tracker can closely approximate the accuracy of traditional laboratory methods.

Table 3: Summary statistics of acceleration due to gravity.

Mean value **g** (m/s^2)	**Standard deviation** **σ** (m/s^2)	**Reference value** **g_n** (m/s^2)	**Percentage error** **ε** (%)
9.864	± 0.094	9.806	0.59

It is observed that this percentage error in determining the acceleration due to gravity g, is smaller compared to free-falling method. This suggests that the method of calculating g using a simple pendulum is the most accurate when compared to the free fall methods when Tracker software is used. In addition to the advantage of determining gravitational acceleration g, with pendulum experiment, the Tracker software also provides analysis of fundamental parameters in harmonic motion. Figures 7a, 7b and 7c show, respectively, the graphs of displacement from the equilibrium position x, velocity, and acceleration, as functions of time t.

From the data obtained through Tracker, the position of the bob's pendulum as a function of time is described by the periodic equation:

$$x = 0.308\, sin(2.22t + 1.56) + 0.0028.$$

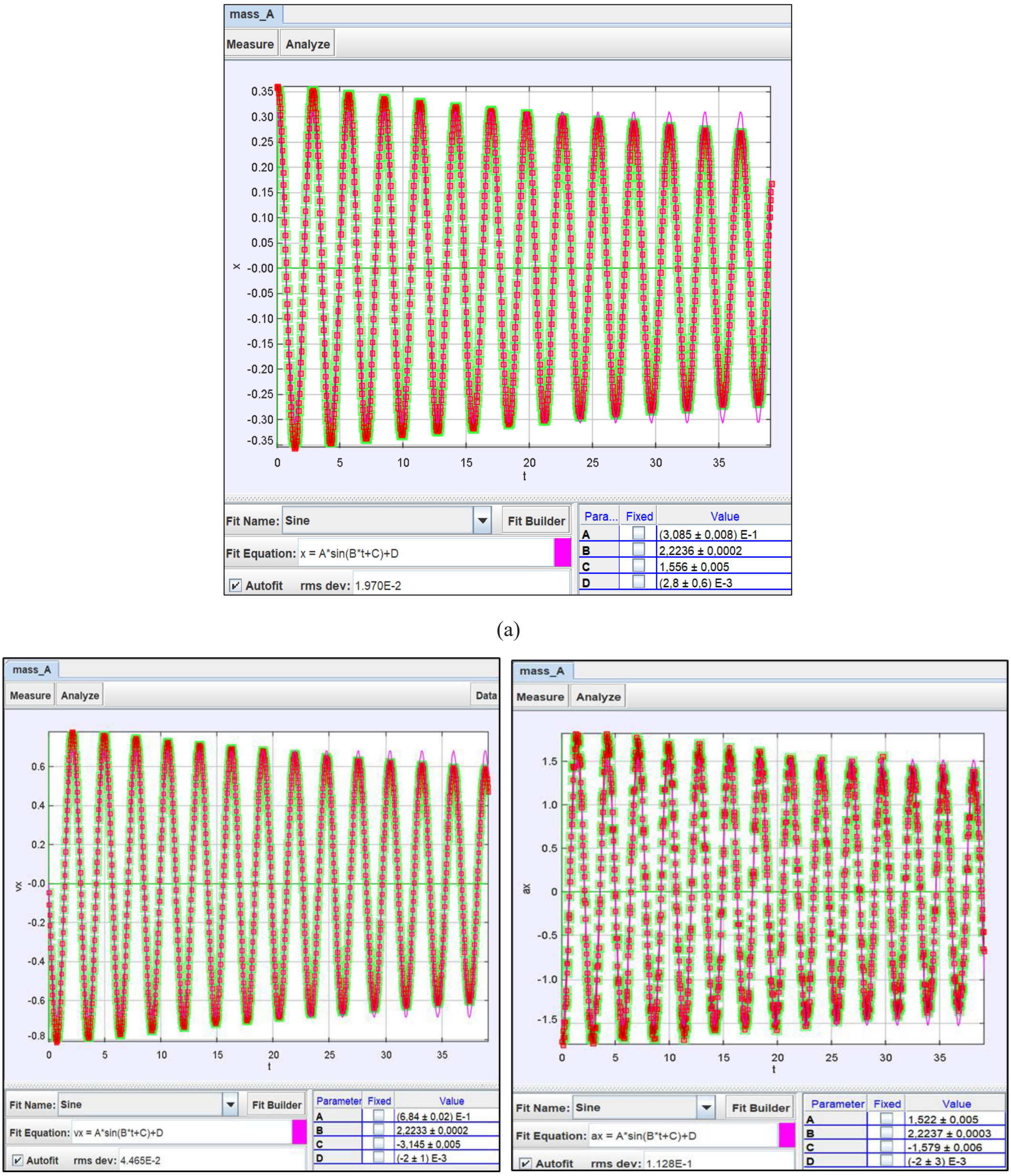
By analyzing the coefficients $A = 0.308$, $B = 2.22$, $C = 1.56$, and $D = 0.0028$ in the position - time graph, students can extract important parameters: the amplitude of oscillation ($A = 0.308m$), the angular frequency ($\omega = 2.22 rad/s$), and the phase constant ($\varphi = 1.56 rad$). The coefficient $D = 0.0028$ has no physical meaning, it represents the shift in the actual equilibrium position. Camera misalignment, calibration errors in Tracker, and asymmetries in the plane of oscillation may be the causes of this shift.

It is also observed that the amplitude of displacement $A = 0.308m$ significantly different from the value shown in the graph at $t = 0$, which is approximately $0.35m$. This difference is attributed to friction and air resistance, leading to energy loss of the system and damping effects.

To estimate the damping coefficient, the function

$$x(t) = Ae^{-Bt}\, sin(Ct + D) + E,$$

was used in Tracker, where Brepresents the damping coefficient, and Ae^{-Bt}describes the exponentially decreasing amplitude of the oscillations. The parameter $C = \omega$ is the angular frequency of the damped oscillations.



Fit Name: Sine
Fit Equation: x = A*sin(B*t+C)+D
☑ Autofit rms dev: 1.970E-2

Para...	Fixed	Value
A	☐	(3,085 ± 0,008) E-1
B	☐	2,2236 ± 0,0002
C	☐	1,556 ± 0,005
D	☐	(2,8 ± 0,6) E-3

(a)

Fit Name: Sine
Fit Equation: vx = A*sin(B*t+C)+D
☑ Autofit rms dev: 4.465E-2

Parameter	Fixed	Value
A	☐	(6,84 ± 0,02) E-1
B	☐	2,2233 ± 0,0002
C	☐	-3,145 ± 0,005
D	☐	(-2 ± 1) E-3

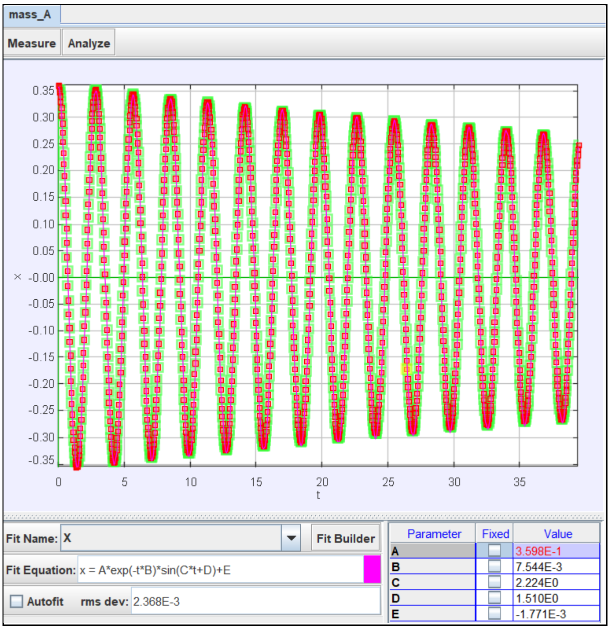
Fit Name: Sine
Fit Equation: ax = A*sin(B*t+C)+D
☑ Autofit rms dev: 1.128E-1

Parameter	Fixed	Value
A	☐	1,522 ± 0,005
B	☐	2,2237 ± 0,0003
C	☐	-1,579 ± 0,006
D	☐	(-2 ± 3) E-3

(b) (c)

Figure 7. Time graphs of the pendulum's a) displacement from the equilibrium position, b) velocity, and c) acceleration.

Figure 8 shows a screenshot of the graph of this function obtained from Tracker.



Fit Name: X

Fit Equation: x = A*exp(-t*B)*sin(C*t+D)+E

☐ **Autofit** **rms dev:** 2.368E-3

Parameter	Fixed	Value
A	☐	3.598E-1
B	☐	7.544E-3
C	☐	2.224E0
D	☐	1.510E0
E	☐	-1.771E-3

Figure 8. Screenshot of the graph illustrating position versus time for damped oscillations.

The damping coefficient is found to be $B = 0.0075$, indicating that the oscillations of the simple pendulum under real conditions closely approximate those of the ideal case.

Figure 9 represents the energy graph of the simple pendulum. The graph clearly illustrates that the kinetic energy (periodic blue curve) reaches its maximum value when the pendulum bob is at its lowest point in the oscillation. Conversely, the potential energy (periodic red curve) is maximum when the bob reaches the highest point of its oscillation. Also, the graph clearly shows that the total mechanical energy gradually decreases with each cycle, indicating the system is losing energy.

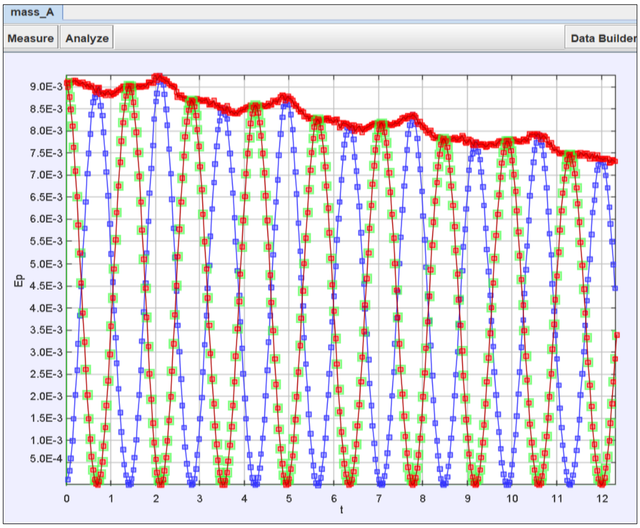


Figure 9. Graphs of a) kinetic energy (blue line), b) potential energy (red with green dashed line), and c) total energy (bold red line).

The total mechanical energy of the system is not conserved as the result of energy dissipation caused by air resistance. Figure 10 shows a screenshot of the energy graph over 40 s time interval. The total energy is observed to reduce by approximately 50% over a time interval corresponding to about 14 complete oscillation cycles. This result is consistent with a relatively small damping coefficient obtained from the fitted equation that describes damped oscillations.

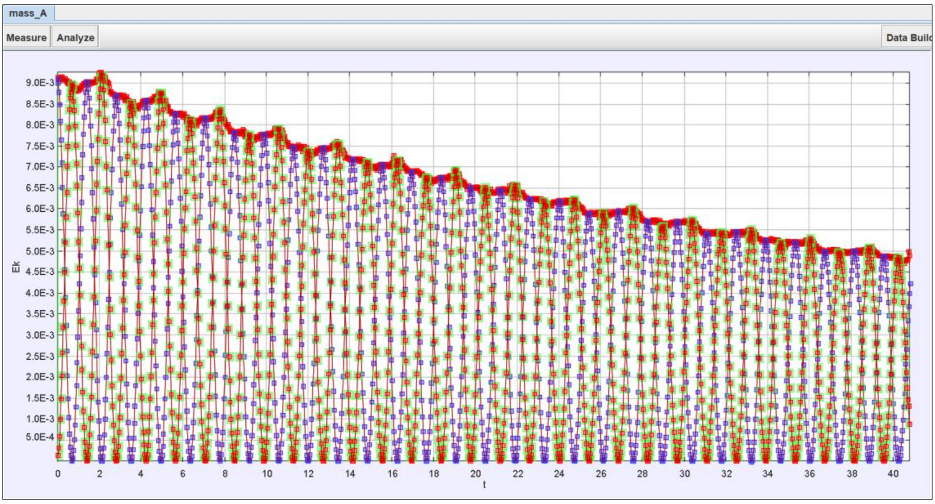


Figure 10. Screenshot of the total energy graph for time interval from t= 0 to t = 40 s.

Conclusions

The use of Tracker software in experiments with free fall and simple pendulum motion proved successful, as the results were consistent with theoretical predictions. In the free fall experiment, Tracker yielded an average acceleration of $g = (9.984 \pm 0.611)\ m/s^2$, with percentage errors of 1.82%. The most accurate result came from the pendulum experiment, with $g = (9.864 \pm 0.094)\ m/s^2$, showing a percentage error of 0.59 %, confirming Tracker's effectiveness in analyzing oscillatory motion.

The larger errors observed in the first method are primarily due to limitations in video capture quality, calibration inaccuracies, point selection, and the low frame rate of the recording. In contrast, the higher accuracy of the second method can be attributed to the slower motion of the tracked object, which produced more centralized trajectories and enabled more precise and efficient automatic tracking. The 30 fps (frames per second) recording in this experiment, using a smartphone, has limited temporal resolution, particularly in free fall experiments where motion occurs over very short time intervals. To improve measurement accuracy, particularly in cases involving rapid motion, the use of a professional high-speed camera is recommended. Additionally, if the camera is not positioned perpendicular to the plane of motion, parallax errors may occur, causing deviations between the marked and actual positions.

The energy transformation analysis, which shows that total energy halves after approximately 14 periods, demonstrates the analytical power of Tracker and its effectiveness in studying real-world problems.

These experiments demonstrate that Tracker creates an active learning environment, helping students visualize and understand key mechanics concepts such as time, position, velocity, acceleration, and energy through concrete experience and data-driven analysis. Furthermore, Tracker serves as an educational tool to bridge abstract theoretical concepts with experimental observation. Its integration into physics classrooms and labs can significantly enhance students' learning experience and deepen their understanding of fundamental principles.

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