PAPER

Phys. Educ. **60** (2025) 055024 (8pp) iopscience.org/ped

Pendulum Tracker—SimuFísica®: a web-based tool for real-time measurement of oscillatory motion

Marco P M de Souza[1,*], **Juciane G Maia**[1] **and Lilian N de Andrade**[2]

[1] Departamento de Física, Universidade Federal de Rondônia, 76900-726 Ji-Paraná, Rondônia, Brazil
[2] Secretaria de Estado da Educação de Rondônia, 78903-043 Porto Velho, Rondônia, Brazil

E-mail: marcopolo@unir.br

Abstract
We present Pendulum Tracker, a computer vision-based application that enables real-time measurement of the oscillatory motion of a physical pendulum. Integrated into the educational platform SimuFísica, the system uses the OpenCV.js library and runs directly in the browser, working on computers, tablets, and smartphones. The application automatically detects the pendulum's position via the device's camera, displaying in real time the angle-versus-time graph and estimates of the oscillation period. Experimental case studies demonstrate its effectiveness in measuring the period, determining gravitational acceleration, and analysing damped oscillations. The results show excellent agreement with theoretical predictions, confirming the system's accuracy and its applicability in educational contexts. Its web-based interface and support for data export make Pendulum Tracker suitable for a variety of experimental physics activities. A pilot classroom implementation suggests that the tool also helps students connect observed motion with its graphical representation.

Keywords: computer vision, pendulum motion, physics education, real-time measurement, web-based application

[*] Author to whom any correspondence should be addressed.

1. Introduction

The study of the pendulum plays a central role in physics education, offering an accessible and visually clear way to introduce fundamental concepts such as harmonic motion, energy conservation, damping, and the determination of gravitational acceleration. Due to its conceptual simplicity and ease of experimental setup, the pendulum has been widely used in classrooms and educational laboratories at different educational levels [1–3]. Its use also extends to more advanced investigations, including the Foucault pendulum [4], nonlinear oscillations, chaotic dynamics, and dissipative effects [5].

Despite the pedagogical value of pendulum experiments, research in physics education has shown that students often struggle to relate physical motion to its graphical representations, such as angle- or position-versus-time plots [6–8]. While expert physicists navigate seamlessly between real-world behaviour and abstract models, this cognitive transition is challenging for many learners. Notably, studies have demonstrated that integrating video motion analysis tools into instruction—especially in combination with hands-on activities—can significantly improve students' ability to interpret motion graphs. Beichner, for example, found that replacing traditional labs with video-based experiments produced measurable learning gains, whereas passive demonstrations alone had limited impact [7].

In recent decades, digital tools such as the Tracker software have been employed for experimental physics studies involving video analysis [9, 10]. Tracker enables data collection from camera-captured images, promoting greater interactivity and conceptual understanding. However, its use typically requires prior recording and often manual frame-by-frame analysis, which can limit its adoption in some educational settings—especially for real-time experiments.

These tools are part of a broader tradition of educational labware, which includes both commercial and open-source software developed over the past few decades. Notable examples include Logger Pro [11] and Video Physics [12] (Vernier), Coach [13] (CMA, University of Amsterdam), and Phyphox [14] (RWTH, Aachen University), among others. Although many of these systems offer powerful features, they may require paid licenses, external sensors, or software installation on specific operating systems. This highlights the need for more accessible, real-time alternatives that operate directly in the browser, without relying on additional hardware—a need that has motivated the development of the tool presented in this work.

In this work, we present Pendulum Tracker, a computer vision-based application integrated into the SimuFísica educational platform. Designed to run directly in the browser, the system allows automatic, real-time measurement of the angular motion of simple pendulums. Section 2 provides an overview of the Pendulum Tracker and its features. Section 3 presents three usage examples: oscillation period measurement, experimental determination of gravitational acceleration, and analysis of damped oscillations. Section 4 reports a pilot implementation in a real high school setting, illustrating the tool's practical effectiveness in classroom environments. The results demonstrate the tool's robustness and its usefulness as a complementary resource for experimental physics teaching at both high school and undergraduate levels.

2. The Pendulum Tracker—SimuFísica

2.1. Overview

Pendulum Tracker is a tool developed for the detailed experimental study of the oscillatory motion of pendulums, using computer vision to capture and analyse the angular position of the object in real time. Based on the OpenCV.js library [15], an implementation of OpenCV for JavaScript, Pendulum Tracker is integrated into the SimuFísica platform, which offers a wide range of applications and simulators aimed at teaching and learning physics in areas such as mechanics [16], electromagnetism [17], thermodynamics [18], and quantum mechanics [19].

Pendulum Tracker is a web-based application that runs in modern browsers and is compatible with a range of devices such as computers, tablets, and smartphones, provided an

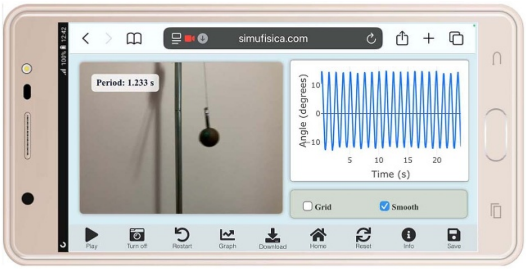

Figure 1. Pendulum Tracker application from the SimuFísica platform. Access link: https://simufisica.com/en/pendulum-tracker/.

integrated or external camera is available for video capture. The tool is already accessible through the online version of SimuFísica and has been included in the Android app distributed via the Play Store. Future updates will incorporate Pendulum Tracker into the offline packages for iOS (App Store), Windows (Microsoft Store), and Linux (Snapcraft), facilitating its use in educational environments with limited or no internet access.

2.2. Interface and functionality

Figure 1 shows the application interface in operation. After fixing the capture device on a stable support and properly aiming it at the pendulum, the camera can be activated using the `Turn on` button located on the toolbar. Then, the pendulum is set into motion. To ensure agreement with the theoretical model, it is advisable to maintain small oscillation amplitudes (typically less than 20°), for which the period T of a pendulum of length L is given by:

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

where g is the local acceleration due to gravity. However, this condition also presents an opportunity for pedagogical exploration: by varying the amplitude and comparing the measured periods to theoretical predictions, students can investigate the validity of the small-angle approximation and observe how deviations emerge as the angle increases.

It is also recommended to use a thin black string to minimise interference with automatic detection, and to centre the pendulum's motion in the frame, occupying a good portion of the screen. To assist with this positioning, the user can enable the `Grid` checkbox, which displays a reference mesh on the screen. A uniform background is not required, and the pendulum object does not need to be spherical—tests indicate that satisfactory results can be obtained in domestic environments using a pendulum composed of a cylindrical object or even a small padlock. One requirement is that no other motion occurs in the background besides the pendulum's oscillation.

After the initial setup, the user clicks the `Start` button. A short calibration interval (approximately 3 s) begins, during which the maximum and minimum positions of the pendulum are collected so that an angular estimate can be provided on the vertical axis of the graph. After this interval, the angle versus time curve is displayed on the screen. Shortly afterward, the user can observe the pendulum's period, obtained from the average of five oscillation cycles. Finally, for more precise measurements, as shown in section 3, the application allows data export via the `Download` button, enabling further analysis in software such as OriginLab, Microsoft Excel, or similar tools.

3. Application examples

In this section, we present three representative examples that illustrate the capabilities of the Pendulum Tracker application from the SimuFísica platform. These activities can be used in the classroom as practical tasks or integrated into home-based experimental work.

3.1. Period measurement

In the first example, we used a smartphone (iPhone SE, 2020 model) mounted on a generic holder (figure 2). As the pendulum mass, we used an aluminium cylinder with a hook. The pendulum length was measured with a tape measure and determined to be $L = 45.8 \pm 0.1$ cm, from the point of support to the cylinder's centre of mass. After a few oscillation cycles, the application

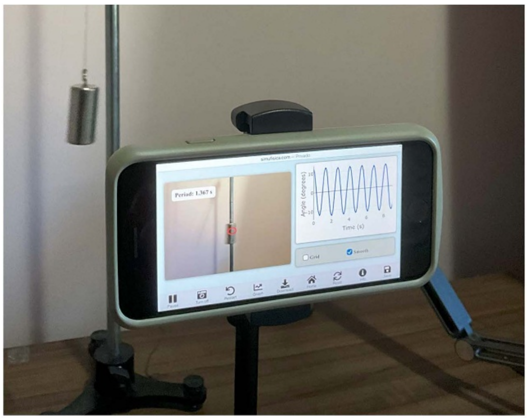

Figure 2. Measurements performed using the Pendulum Tracker—SimuFísica application with $L = 45.8 \pm 0.1$ cm.

began displaying the average period on the screen, with observed fluctuations between $T = 1.367$ s and $T = 1.374$ s. We compared these results with the theoretical value given by equation (1). The measurements were performed in the city of Ji-Paraná, in the state of Rondônia, Brazil, located at latitude $\phi \times 180/\pi = -10.88°$. Considering $g = 9.782\,1671$ m s^{-2} as the local gravitational acceleration, obtained from the equation [20]

$$g(\phi) = 9.780\,327\left[1 + 0.005\,3024\sin^2(\phi) - 0.000\,0058\sin^2(2\phi)\right] \text{ m s}^{-2}, \quad (2)$$

we found a maximum error of only 1.1%.

Figure 3 presents a more detailed analysis of the obtained data. In panel (a), we show the time evolution of the pendulum angle. Panel (b) shows a zoom of the first 4.7 s, revealing a sinusoidal curve with approximately 40 data points per cycle—this number depends on the device's frame rate and the pendulum length. The application's algorithm automatically smooths the data to reduce noise, but the user can disable this by unchecking the `Smooth` checkbox.

Figure 3(c) shows, in green, the spectrum obtained from the Fourier transform of the data in panel (a), using a 60 s time window. A Gaussian fit to the main peak yields a frequency of $f = 0.7337 \pm 0.0002$ Hz, corresponding to an experimental period of

$$T_{\text{exp}} = 1.3630 \pm 0.0004\,\text{s}, \quad (3)$$

which is very close to the theoretical value,

$$T_{\text{theo}} = 1.3595\,\text{s}, \quad (4)$$

although slightly outside the uncertainty margin.

3.2. Measurement of the acceleration due to gravity

In this second example, we used Pendulum Tracker to determine the local gravitational acceleration based on the dependence between the period T and the pendulum length L. To that end, we conducted measurements using different values of L. The procedure was similar to that in section 3.1: after each measurement, the data were exported, a Fourier transform was applied, and a Gaussian fit was performed to obtain the central frequency and calculate the period.

The results are presented in figure 4. Panel (a), in linear scale, shows good agreement between the experimental data (blue) and the theoretical curve (red). Panel (b), in log–log scale, reveals a power-law relationship $T = CL^n$, with a linear fit yielding

$$n_{\text{exp}} = 0.499 \pm 0.003, \quad (5)$$

which is consistent with the theoretical value $n_{\text{theo}} = 0.5$.

From the linear fit intercept $a = -0.695 \pm 0.005$ in figure 4(b), and the relation $T = CL^n$, we obtain

$$g = \left(\frac{2\pi}{10^{a+1}}\right)^2, \quad (6)$$

with uncertainty given by

$$\Delta g = \frac{8\pi^2 \ln(10)}{10^{2(a+1)}}\Delta a, \quad (7)$$

where Δa is the uncertainty in the value of a. Using the data from figure 4(b), we find

$$g_{\text{exp}} = 9.7 \pm 0.2\,\text{m s}^{-2}, \quad (8)$$

which is in excellent agreement with the expected local value ($g_{\text{theo}} = 9.78$ m s^{-2}).

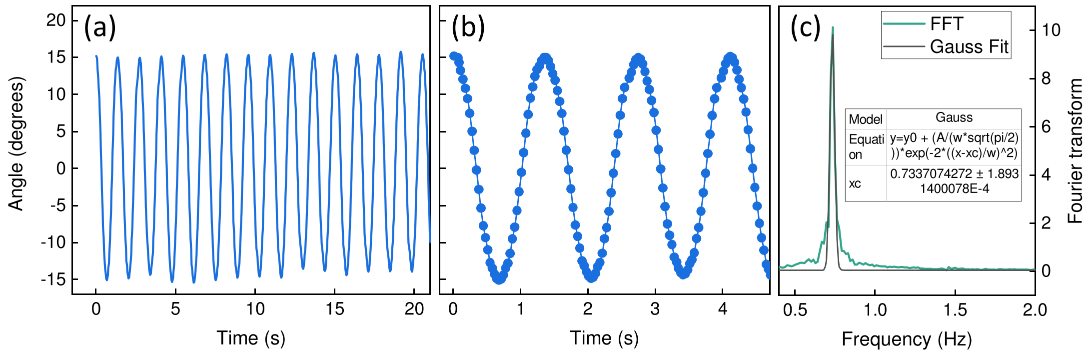

Figure 3. Results from the measurements shown in figure 2. (a) Angle as a function of time. (b) Zoom of (a) within a 4.7 s window. The line is a guide to the eye. (c) Green line shows the Fourier transform of (a), considering a 60 s interval. The black line is a Gaussian fit of the Fourier transform.

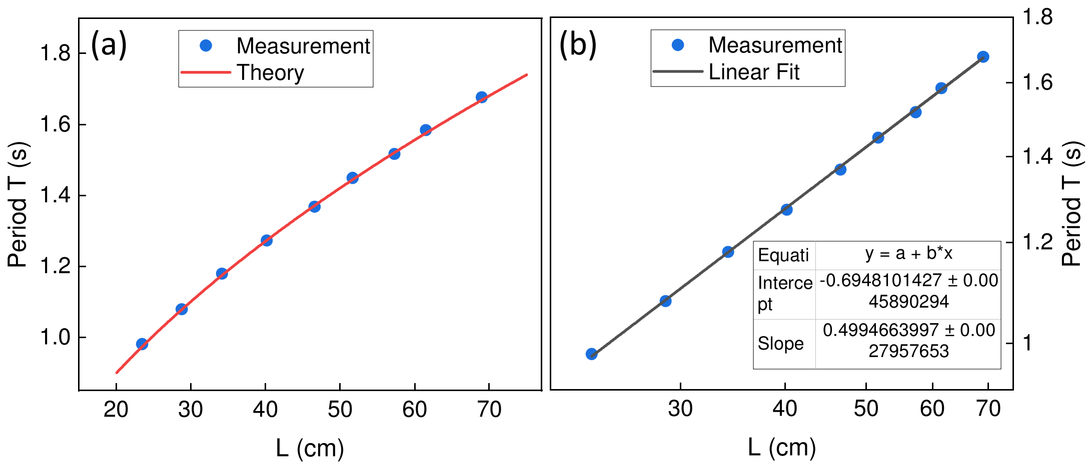

Figure 4. Pendulum oscillation period as a function of length. (a) Linear scale: experimental data in blue and theoretical curve in red. (b) Log–log plot of the experimental data (blue) with linear fit (black line).

3.3. *Damped oscillations—experiment vs theory*

In the final example, we explored Pendulum Tracker's ability to record damped oscillations over extended time intervals. We used a pendulum of length $L = 31.2 \pm 0.1$ cm, collecting data from $t = 0$ to $t = 150$ s, resulting in 4366 data points (figure 5). This data density demonstrates one of the main advantages of Pendulum Tracker over traditional tools like Tracker [21], which often require manual frame-by-frame analysis. Moreover, the SimuFísica platform's application provides the oscillation period and angle graph in real time on widely used devices such as smartphones.

The comparison with the theoretical model is based on the harmonic approximation for the motion of a damped pendulum [22]:

$$\theta(t) = \theta_0 e^{-\gamma t} \cos\left(t\sqrt{\frac{g}{L} - \gamma^2} - \delta\right), \qquad (9)$$

where $g = 9.782167\ \mathrm{m\,s^{-2}}$, $\theta_0 = 6.3°$, $\gamma = 0.005\ \mathrm{s^{-1}}$, and $\delta = 1.4\pi$. The values of θ_0, γ, and δ were chosen to maximise the agreement between the theoretical curve and the experimental data in the interval $t \in [0, 7]$ s (figure 5(b)). For longer times (figure 5(c)), we observe a slight phase shift between the model and the data, likely due to small variations in ambient conditions.

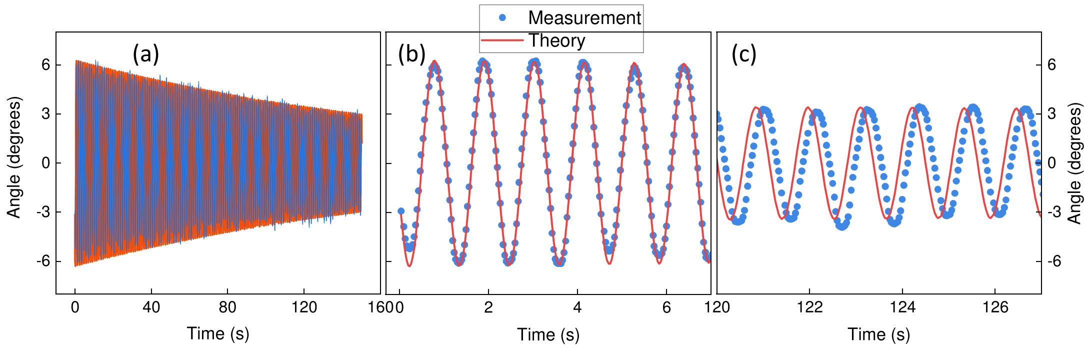

Figure 5. (a) Damped oscillations of a simple pendulum. Experimental data in blue and theoretical curve in red. (b) Zoom of (a) up to $t = 7$ s. (c) Zoom of (a) in the time window $t \in [120, 127]$ s.

In a classroom setting, this type of data can serve as the basis for investigative tasks. For example, rather than providing a predefined value for the damping coefficient γ, students can be encouraged to determine it experimentally by analysing the envelope of the oscillation amplitude over time. Such an activity reinforces the concept of damping while introducing students to real-world data analysis and curve fitting, using measurements obtained from their own experimental setup.

4. Classroom implementation

To evaluate the practical use of Pendulum Tracker in an educational setting, the tool was applied on 9 June, 2025, during two 50 min physics classes in each of three third-year high school groups, with an average student age of 17. After a brief introduction to the platform, students used their own smartphones to assemble and measure the oscillation period of simple pendulums. In accordance with Brazilian law, which restricts mobile phone use in classrooms except with explicit teacher authorisation, the activity was conducted in supervised groups of up to five students. Each group assembled a pendulum on a support, totalling seven experimental setups per class. To prevent interference between groups, all smartphones were oriented toward the classroom walls, ensuring that each device recorded only the motion of its respective pendulum. Students tested multiple values of the pendulum length L during the activity.

Although no formal assessment of learning outcomes was performed, informal observations suggest that the experiment contributed to students' understanding of the relationship between pendulum motion and its angular displacement graph displayed in real time. Many students initially struggled with this connection, a difficulty that may have been intensified by learning interruptions during the COVID-19 pandemic. During the activity, several groups initially measured the length L from the suspension point to the top of the cylindrical mass (the hook), which led to discrepancies between the observed and theoretical periods. After discussing the issue with the teacher, they adjusted their measurement to account for the centre of mass of the pendulum. Even after this correction, some students expressed surprise that their results did not exactly match the theoretical value predicted by equation (1), using $g = 9.8\,\mathrm{m\,s^{-2}}$. For instance, group 03 measured a length that led to a theoretical period of $T_{\mathrm{theo}} = 0.973$ s, while the value reported by the application was $T_{\mathrm{exp}} = 1.020$ s, corresponding to a 4.8% deviation. This reaction reflects a common misconception among students that theoretical models should yield results identical to experimental measurements, overlooking the effects of experimental uncertainty, idealisations, and approximations in the formula.

5. Conclusions

In this work, we presented Pendulum Tracker, a computer vision-based application that allows precise real-time measurements of a pendulum's oscillatory motion using an ordinary device camera. The tool proved effective both for verifying well-known experimental relations, such as the period equation and its dependence on gravitational acceleration, and for more advanced investigations, such as the study of damped oscillations. The good agreement with the theory taught at high school and undergraduate levels confirms the application's reliability. Its use in high school classrooms also demonstrated the tool's practicality in engaging students with experimental data and enhancing their understanding of motion graphs.

As future work, we plan to expand the application's functionalities, including support for different experimental configurations, such as double[3] or coupled pendulums[4]. In addition, we are updating the SimuFísica app store versions to include the Pendulum Tracker tool, thereby enabling offline use in educational environments with limited internet access.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.15569631.

Acknowledgment

This research was funded by Fundação de Amparo ao Desenvolvimento das Ações Científicas e Tecnológicas e à Pesquisa do Estado de Rondônia (FAPERO, Grant 36214.577.20546.20102023) and Universidade Federal de Rondônia (UNIR, Grant 23118.006316/2024-79). M P M de Souza acknowledges financial support from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq, Grant 304017/2022-1).

[3] https://simufisica.com/en/double-pendulum/.

[4] https://simufisica.com/en/coupled-pendulums/.

Author contributions

Marco P M de Souza 0000-0003-4199-2862
Conceptualization (lead), Data curation (lead), Funding acquisition (lead), Investigation (lead), Methodology (lead), Project administration (lead), Software (lead), Supervision (lead), Validation (lead), Writing – original draft (lead)

Juciane G Maia
Validation (supporting), Writing – review & editing (supporting)

Lilian N de Andrade
Validation (supporting), Writing – review & editing (supporting), Data curation (supporting)

Received 10 June 2025, in final form 2 July 2025
Accepted for publication 24 July 2025
https://doi.org/10.1088/1361-6552/adf406

References

[1] Oliveira V 2016 *Phys. Educ.* **51** 063007
[2] Dandare K 2018 *Phys. Educ.* **53** 055002
[3] Lacsny B, Štubna I and Teleki A 2014 *Eur. J. Phys.* **35** 065023
[4] Salva N N and Salva H R 2025 *Am. J. Phys.* **93** 297–307
[5] Hinrichsen P F 2020 *Eur. J. Phys.* **41** 055002
[6] McDermott L C, Rosenquist M L and van Zee E H 1987 *Am. J. Phys.* **55** 503–13
[7] Beichner R J 1996 *Am. J. Phys.* **64** 1272–7
[8] Becker S, Knippertz L, Ruzika S and Kuhn J 2023 *Phys. Rev. Phys. Educ. Res.* **19** 020142
[9] Pedersen H B, Andersen J E V, Nielsen T G, Iversen J J, Lyckegaard F and Mikkelsen F K 2020 *Eur. J. Phys.* **41** 015701
[10] Cross R 2025 *Phys. Educ.* **60** 033005
[11] Vernier Software & Technology 2023 Logger pro (available at: www.vernier.com/product/logger-pro/)
[12] Vernier Software & Technology 2023 Video physics app (available at: www.vernier.com/physics/vernier-video-analysis/)
[13] CMA—Centre for Microcomputer Applications 2023 Coach 7 software (available at: https://cma-science.nl/coach7_desktop_downloads_en)
[14] Staacks S, Hütz S, Heinke H and Stampfer C 2018 *Phys. Educ.* **53** 045009
[15] Intel, Willow Garage 2000 OpenCV: open source computer vision library (available at: https://opencv.org/)

[16] Souza M P M, Oliveira C M and Araújo R P P 2024 arXiv:2410.17951 [physics.ed-ph]
This is the English version of a peer-reviewed paper published in Portuguese: Souza M P M, Oliveira C M and Araújo R P P 2024 *Fís. Escola* **22** 240173

[17] Souza M P M, Oliveira S P and Luiz V 2024 arXiv:2410.17951 [physics.ed-ph]
This is the English version of a peer-reviewed paper published in Portuguese: Souza M P M, Oliveira S P and Luiz V 2024 *Rev. Bras. Ensino Fís.* **46** e20230219

[18] Souza M P M and Siqueira A B 2025 arXiv:2506.03289 [physics.ed-ph]

[19] Souza M P M, Pavão G H H, de Almeida A A C and Vianna S S 2025 arXiv:2506.01108

[20] Hinze W J, von Frese R R B and Saad A H 2013 *Gravity and Magnetic Exploration: Principles, Practices and Applications* (Cambridge University Press)

[21] Brown D, Christian W and Hanson R M 2025 Tracker: video analysis and modeling tool (available at: https://opensourcephysics.github.io/tracker-website/)

[22] Quiroga G D and Ospina-Henao P A 2017 *Eur. J. Phys.* **38** 065005