Physics Education

PAPER • OPEN ACCESS

Implementation of smartphone-based experimental exercises for physics courses at universities

To cite this article: A Kaps *et al* 2021 *Phys. Educ.* **56** 035004

OPEN ACCESS

PAPER

Phys. Educ. **56** (2021) 035004 (8pp)

iopscience.org/ped

Implementation of smartphone-based experimental exercises for physics courses at universities

A Kaps, T Splith and F Stallmach

Didactics of Physics, University of Leipzig, Prager Straße 36, 04317 Leipzig, Germany

E-mail: stallmac@physik.uni-leipzig.de

CrossMark

Abstract

A concept for undergraduate mechanics courses at universities is introduced where traditional pencil-paper based exercises are partially replaced by experimental exercises, in which smartphones are used as measurement devices. A detailed guidance for practical realization and implementation of these tasks formats into the course is presented. Three smartphone-based experimental exercises 'The tilting smartphone', 'The oscillation balance' and 'Using the Smartphone in a Torsion Pendulum' are presented. First empirical results with respect to the learning achievement indicate a mid size effect on the understanding of the physical concepts. Compared to the traditional pencil-paper based exercises, the students performance in the experimental exercises is slightly lower, although the motivation to solve these tasks is higher.

Keywords: theory-experiment interplay, mechanics, smartphone-based exercises, tilting motion, oscillation balance, torsional pendulum

1. Introduction

In recent years smartphones and their internal sensors have been used as valuable tools for physical experiments in introductory experimental lectures [1–3]. These mobile devices can be used to measure physical quantities like acceleration [4–9], angular velocity [10–14], air pressure [15–17] or the magnetic flux density [18]. Therefore they are applied in various experimental setups [19]. In addition smartphones as experimental tools for physics education offer many advantages like user-friendly interfaces and the plurality of applications.

The benefits of using smartphones in education for the conceptual understanding are still discussed in the literature. In [20, 21] it is argued that the use of smartphones and tablets and the implementation of laboratory work do not have an advantage for the learning achievement of the students. In contrast, other authors showed that smartphones and tablets as experimental tool are an attractive and effective way to foster the motivation, the interest and the learning achievement [22–25]. Especially the topic of the harmonic oscillations is suitable to increase curiosity and motivation as well as conceptual understanding of the learners when students learn how to work with smartphones or tablets as experimental tools [22, 24, 26].

The use of smartphones offers the possibility to implement laboratory-like activities during the self-study time and to focus the problem solving process. We denote such experimental exercises, in which students work on interesting and authentic physical problems with their smartphones as experimental tools as the *smart physics lab*.

In this paper we present the integration of smartphone-based experimental exercises in the weekly worksheets, where pencil-paper based exercises where partially replaced for the students of an undergraduate course for physics teachers trainees at our university. At first the implementation and the content of three smartphone-based exercises are presented and discussed. Afterwards we compare the students performances in the new experimental exercises with the traditional paper-pencil based exercises. We also include a quantitative measurement of the learning achievement for one of the presented tasks. In our view, the presented approach is also a new possibility for exercises for other undergraduate physics courses, because the basic organization of such courses is nearly the same in many national and international universities.

2. The smart physics lab

2.1. Implementation and content

The introductory physics courses for physics teacher trainees at our university consist of two separate lectures (2×1.5 h, per week), one recitation (1×1.5 h, per week) and a lab-course at the end of the term. Traditionally the students get weekly worksheets with four or five pencil-paper-based problems, of which they have to solve at least 50% in order to get the permission for the exam at the end of the semester. Biweekly one of the pencil-paper-based exercises was replaced by a smartphone-based experimental exercise to establish the theory-experiment interplay and to foster the students' construction of knowledge and their understanding of physics.

Students are required to write a short report for each experimental exercise, consisting of a description of the experiment with the relevant equations, the experimental setup and the procedure, the representation of the measured data including their analysis and the estimation of the of measurement uncertainties. The short reports have an unitary standard of evaluation. For a complete and exact solution the students receive ten points for the experimental homework. In comparison, for the correct solution of the pencil-paper exercises the students get between four and eight points per exercise depending on its complexity. Throughout the whole course all collected points of the homework are summed up. One third of the total points may be collected by the new experimental smartphone-based exercise and two thirds by the traditional pencil-paper exercises.

In order to support the students to solve the smartphone-based experimental exercise a general introduction into the experimental exercises with the *smart physics lab* and into data analysis of the digital recorded physical quantities are an integral part of the first two physics lectures and the first recitation. In particular, we present a detailed demonstration experiment using the smartphone for simultaneous measurements of linear acceleration and angular velocity to prove the relationship between both quantities for a rotational motion.

The topics for these biweekly smartphone-based exercise are coordinated with the content of the lecture. During the lecture similar demonstration experiments are shown, visualizing the physical content of the topic (see figure 1). Once the students received the experimental homework, they may attend an additional tutorial, during which the topic of the experiment is explained and discussed with the students.

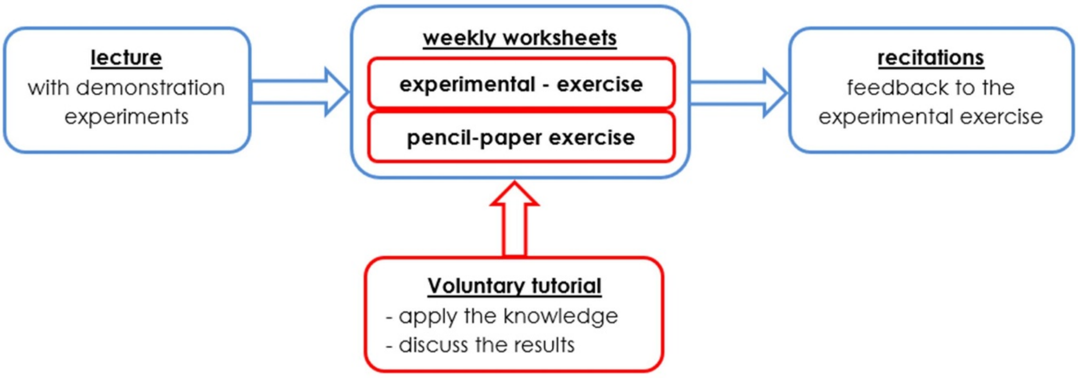

Figure 1. Integration of the educational concept of the *smart physics lab* in the introductory mechanics course.

During the tutorial and the recitations, the students obtain the possibility to discuss their experimental problems. It is important that students understand the relevant physical assumptions of the experiment and possible limitations of their set-up and their measuring devices, i.e. their smartphones. E.g., the maximum recordable angular frequency of the MEMS-gyroscope of the smartphone might be to small for the chosen experimental set-up or it supplies data with an insufficient resolution or signal-to-noise ratio for a reliable data interpretation. These restrictions are discussed in the tutorial to find workarounds.

2.2. *Practical realization*

In order to make sure that students have the material for the experimental setup they receive a package with the required material. These packages include paper clips, reclosable bags, rubber bands, *Velcro fasteners*, a thin wire and a spring [27]. For data acquisition we recommended the application *phyphox* (RWTH Aachen, Germany) which is available for android and iOS smartphones. This app can access nearly all available sensor and allows a remote control data acquisition via Wi-Fi. Therefore, the students are able to record the data with one smartphone and to start and stop the measurement with another device without interfering with the experiment [1, 16]. In cases where the smartphone of the students might not be equipped with the necessary sensors to solve a specific experimental task we lend suitable smartphones and tablets to the students upon request.

3. Example exercises of the smart physics lab

In the following section we present three examples of smartphone-based experimental exercises for the *smart physics lab*. In the first task the tilting motion of a smartphone is investigated [10] to determine its moment of inertia. The concept of rigid bodies, rotational motion and conservation of energy needed to be applied. In the second exercise the smartphone is used to construct an oscillation balance to determine unknown masses [9], in which Hooke's Law and the concept of the oscillation motions are required. In the third exercise the smartphone is used to construct a torsional pendulum [11] to determine the shear modulus of a thin wire. To solve the task the concepts of the deformable solid bodies and of the free damped oscillator need to be applied. For a complete description of the experiment and the solution of these three exercise tasks we refer the reader to the [9–11]. In the following, we present the texts of these exercises including hints which we provide to the students in our course.

3.1. *The tilting smartphone*

The text of this experimental exercise is: 'Analyse the tilting motion of your smartphone with the assistance of the MEMS-gyroscope and produce the angular velocity $\omega(t)$ graph of the motion. Calculate the moment of inertia of the smartphone with the measured data. Compare this result with the moment of inertia calculated via the mass and the dimension of your smartphone'. In order to guide our students to the solution of this task, we provide support with the following detailed hints:

- A tilting motion of the smartphone is a rotational movement from an instable equilibrium state (e.g. standing perpendicular on one edge) to a stable equilibrium state (e.g. lying face up) under the influence of the gravitational force.
- Let your smartphone tilt freely around the x- or the y-axis of the internal MEMS—gyroscope. Please perform the experiment on a soft mat in order to protect your smartphone.
- The smartphone may be considered as a homogeneous cuboid.
- Before you start the experiment prepare the energy conservation law for the tilting motion and a concept how to analyse the recorded $\omega(t)$ data.
- Consider the parallel axis theorem.

3.2. The oscillation balance

The text of the second experimental exercise is: 'Construct an oscillation balance with your smartphone and the supplied spring. Measure the oscillation period T of the balance and determine the mass m of an unknown item. Compare this result with the mass measured with a digital balance and discuss your result'. In order to guide our students to the solution of this task, we provide the following detailed hints:

- Use the sensor 'acceleration without g' of your smartphone in the *phyphox*-app.
- Consider Hooke's law and use small oscillation amplitudes.
- Make sure that the damping is not to strong. If possible record ten complete oscillations.
- Before you start the experiment prepare an equation, which describes the measurement principle without the use of the spring constant D.
- Attach your smartphone carefully with the fastening materials.
- Calibrate your oscillation balance with a known mass, e.g. of your smartphone itself.

3.3. Using the smartphone in a torsion pendulum

The text of the third experimental exercise is: 'Construct a torsional pendulum with your smartphone and a thin wire. Measure the oscillation period for each principal axis of your smartphone. Calculate the directional moment and the shear modulus G of the torsion wire'. We provide support with the following detailed hints:

- Use the MEMS—gyroscope of your smartphone in the *phyphox*-app to determine the angular frequency and oscillation period.
- The smartphone as pendulum bob can be approximated as a homogeneous cuboid.
- Make sure that the smartphone is attached to the thin wire in a way that the axis of rotation corresponds to one of the axes of symmetry of the smartphone.
- Start the rotational oscillation carefully by twisting the smartphone out of the equilibrium position.
- To obey Hooke's law for shear stress use an initial amplitude of the angle of rotation not larger than 270°.
- Consider that friction causes a decaying amplitude and a slight increase of the period of the damped oscillation.
- For an optimal data acquisition adjust the oscillation period by modifying the wire length to obtain oscillation periods between two and 20 s.

4. Results and discussion

The *smart physics lab* is an integral part of our introductory mechanics course for physics teachers trainees since winter term 2018/2019. At the end of the courses 2018/2019 and 2019/2020 we performed a survey under the participating students to get feedback for our educational draft. The predominant evaluation of the students was positive. The students confirmed that the new smartphone-based experimental exercises motivated them to learn and read more about the concepts from the lecture. Additionally, they said that the smartphone-based experimental exercises foster their interest for experimental mechanics. Especially the detailed hints in each exercises

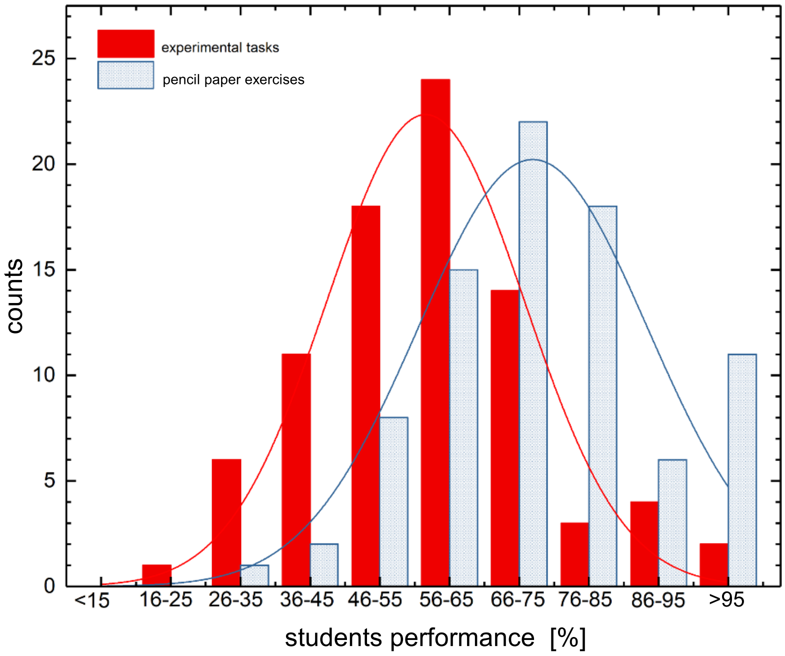

Figure 2. The distribution of the students performance in the pencil paper exercises and the experimental task in the winter term 2019/2020.

helped the students to solve the smartphone-based exercises. Only the time consuming report preparing was criticized by the students. This first results from the evaluation are in agreement with recent reports [22, 23, 28], where the fostering effect of multimedia-based learning setups to the motivation and the interest of the students was investigated.

Figure 2 shows a comparison of the students averaged performance in the two different types of exercises for the winter term 2019/2020. The average performance in the pencil-paper exercises is nearly 66%–75% of the assigned points. In comparison, the average performance in the experimental task is 56%–65%. It is obvious that the averaged performance of the students is better in the pencil-paper exercises. One reason for this might be the increased complexity of the experimental tasks. As pointed out in [26], performing the experiment requires more skills and knowledge as a simple pencil-paper exercise, since student have to analyse data and compare the experiment with the theoretical model by themselves during the problem-solving process. Further reasons for different performances in both exercise types are the students motivation, their curiosity and the cognitive load. In order to investigate the influence of these learning factors we currently perform an empirical study how the smartphone-based experiments increase the learning achievement, the motivation and the curiosity of the students in comparison to the pencil-paper exercises. The design of the study is a quasi-experimental control-treatment group intervention in which physics teacher trainees and physics students participate.

In a small study, in which 71 students participated, the effectiveness for the learning achievement in conceptual knowledge of the rotational motion of rigid bodies was tested. The study was conducted before and after the students performed 'The tilting smartphone' experimental exercise in a pre-post test design. The students answered five multiple-choice questions as pre-test and five multiple-choice questions as a post-test. These were partially adapted from a validated conceptual test [29] and supplemented with items inspired by questions from physics textbooks [30–32]. The questions dealt with the rotational energy, the angular velocity and the moment of inertia. To measure the learning achievement the Hake index g was calculated (see in [33, 34]). For analysing the learning achievement the pre- and the post-test data were evaluated. This results in an averaged learning achievement $g = 0.31$ showing that our approach with the smartphone-based exercises has a mid size effect on the understanding and the application of the underlying physical concepts [35].

Overall the analysis of these data shows that the approach with the smartphone-based experimental exercises was successful. It suggests that the *smart physics lab* encourage the motivation, the interest and the conceptual knowledge of our students [22, 23, 26] since the interaction link between the theory-experiment is intensified. The experimental activities and the analytical skills which are integrated to the problem solving process promote the conceptual understanding and can help the students to full-fill higher expectations during successive lab courses [24–26]. Our approach may be adapted by others lecturers at universities because the classical course-structure is not altered.

5. Conclusion

In this paper we presented the implementation of smartphone-based experimental exercises which we integrated into the weekly worksheets in the introductory mechanics course for physics teacher trainees. With the broadly available internal sensor-based measurement technology of the smartphones our students develop their own experimental setups. The task format offers a theory–experiment interplay which we consider beneficial for experimental physics education. This theory-experiment interplay represents an important difference compared to typical pencil-paper based tasks. The experimental tasks offer a significantly different approach to physics by letting the students take part in the experimentation actively by applying their knowledge in a practical way. Thereby we assume that the understanding of the principles of physics is supported.

Acknowledgments

The authors are grateful for financial support received via the STIL project of the University of Leipzig which is supported by the Federal Ministry of Research and Education (BMBF) of Germany, Grant No. 01PL16088. We also thank the *phyphox* development team at RWTH Aachen (Germany) for discussions.

Compliance with ethical standards

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. We are in accordance with the principles outlines in the ethical policy of the journal *Physics Education*.

The study was approved by the study committee of the faculty for physics and earth sciences of Leipzig University on the 30 January 2018.

ORCID iD

A Kaps https://orcid.org/0000-0003-0601-2099

Received 7 December 2020, in final form 6 January 2021
Accepted for publication 22 January 2021
https://doi.org/10.1088/1361-6552/abdee2

References

[1] Staacks S, Hütz S, Heinke H and Stampfer C 2018 Advanced tools for smartphone-based experiments: phyphox *Phys. Educ.* **53** 045009

[2] Stampfer C, Heinke H and Staaks S 2020 A lab in the pocket *Nat. Rev. Mater.* **5** 169–70

[3] Vieyra R *et al* 2018 Turn your smartphone into a science laboratory *Sci. Teach.* **82** 32–40

[4] Monsoriu J A, Salinas I, Gimenez M H and Sans J A 2019 Demonstration of the parallel axis theorem through a smartphone *Phys. Teach.* **57** 340–1

[5] Barrera-Garrido A 2014 A smartphone inertial balance *Phys. Teach.* **55** 249

[6] Vogt P and Kuhn J 2012 Analyzing simple pendulum phenomena with a smartphone acceleration sensor *Phys. Teach.* **50** 439–40

[7] Kuhn J and Vogt P 2012 Analyzing spring pendulum with a smartphone acceleration sensor *Phys. Teach.* **50** 504–5

[8] Lopez D, Caprile I, Corvacho F and Reyes O 2018 Study of a variable mass Atwood's

machine using a smartphone *Phys. Teach.* **56** 183–4

[9] Kaps A and Stallmach F 2020 Using the smartphone as oscillation balance *Phys. Teach.* **58** 678–9

[10] Kaps A and Stallmach F 2020 Tilting motion and the moment of inertia of the smartphone *Phys. Teach.* **58** 214–15

[11] Kaps A, Splith T and Stallmach F 2020 Shear modulus determination using the smartphone in a torsion pendulum *Phys. Teach.* accepted

[12] Monteiro M, Cabeza C and Marti A 2014 Rotational energy in a physical pendulum *Phys. Teach.* **52** 312–13

[13] Shakur A and Sinatra T 2013 Angular moment *Phys. Teach.* **51** 564–5

[14] Patrinopoulos M and Kefalis C 2015 Angular velocity direct measurement and moment of inertia calculation of a rigid body using a smartphone *Phys. Teach.* **53** 564–5

[15] Macchia S 2016 Analyzing Stevin's law with the smartphone barometer *Phys. Teach.* **54** 373–4

[16] The phyphox homepage by the RTWH Aachen 2020 (available at: https://phyphox.org/de/home-de/) (Accessed 20 October 2020)

[17] Kuhn J, Vogt P and Mueller A 2014 Analyzing elevator oscillation with the smartphone acceleration sensors *Phys. Teach.* **52** 55–6

[18] Pili U 2018 Measurement of g using a magnetic pendulum and a smartphone magnetometer *Phys. Teach.* **56** 258–9

[19] Kuhn J and Vogt P (ed) 2019 *Physik Ganz Smart—Die Gesetze der Welt mit dem Smartphone Entdecken* (Berlin: Springer)

[20] Wiemann C and Holmes N G 2015 Measuring the impact of an instructional laboratory on the learning of introductory physics *Am. J. Phys.* **83** 972–8

[21] Holmes N G, Olsen J, Thomas J L and Wiemann C E 2017 Value added or misattributed? A multi-institution study on the educational benefit of labs for reinforcing physics content *Phys. Rev. Phys. Educ. Res.* **13** 010129

[22] Hochberg K, Becker S, Malte L, Klein P and Kuhn J 2020 Using smartphones as experimental tools—a follow-up: cognitive effects by video analysis and reduction of cognitive load by multiple representations *J. Sci. Educ. Technol.* **29** 303–17

[23] Hillmayr D, Reinhold F, Ziernwald L and Reiss K 2017 Einsatz digitaler Medien im mathematisch-naturwissenschaftlichen Unterricht der Sekundarstufe: Eine Metastudie zur Lernwirksamkeit (https://doi.org/10.13140/RG.2.2.13319.70561)

[24] Mazzella A and Testa I 2016 An investigation into the effectiveness of smartphone experiments on students conceptual knowledge about acceleration *Phys. Educ.* **51** 055010

[25] Gröber S, Klein P and Kuhn J 2014 Video-based problems in introductory mechanics physics courses *Eur. J. Phys.* **35** 055019

[26] Sokoloff D R, Laws P W and Thornton R K 2007 RealTimePhysics: active learning labs transforming the introductory laboratory *Eur. J. Phys.* **28** 83–94

[27] Hütz S, Kuhlen S, Stampfer C and Heinke H 2019 Kleiner Aufwand, großer Nutzen?—Experimentiersets zur Unterstützung Experimenteller Übungsaufgaben mit Smartphones *PhyDid B—Didaktik der Physik—Beiträge zur DPG-Frühjahrstagung* (*Aachen, Germany March 25–30, 2019*) (http://www.phydid.de/index.php/phydid-b/article/view/947)

[28] Hochberg K, Kuhn J and Müller A 2018 Using smartphones as experimental tools—effects on interest, curiosity and learning in physics education *J. Sci. Educ. Technol.* **27** 385–403

[29] Rimoldini L G and Singh C 2005 Student understanding of rotational and rolling motion concepts *Phys. Rev. ST Phys. Educ. Res.* (https://doi.org/10.1103/PhysRevSTPER.1.010102)

[30] Tipler P A and Mosca G P 2015 *Physics for Scientists and Engineers* (Basingstoke: Palgrave Macmillan)

[31] Halliday D, Resnick R and Walker J 2010 *Fundamentals of Physics* 9th edn (New York: Wiley)

[32] Demtröder W 2017 *Mechanics and Thermodynamics* (*Mechanics and Thermodynamics*) (Cham: Springer International Publishing)

[33] Bao L 2006 Theoretical comparisons of average normalized gain calculations *Am. J. Phys.* **74** 917–22

[34] Klein P, Kuhn J and Müller A 2018 Förderung von Repräsentationskompetenz und Experimentbezug in den vorlesungsbegleitenden Übungen zur Experimentalphysik *Z. Didaktik Naturwissenschaften* **24** 17–34

[35] Hake R 1998 Interactive-engagement versus traditional methods: a six-thousand-student survey of mechanics test data for introductory physics courses *Am. J. Phys.* **66** 64–74

Andreas Kaps PhD student, is a search associate in the Didactics of Physics Group at the University of Leipzig. He has a fellowship from the University Leipzig for his doctorate. His research focuses on smartphone-based experimental exercises to foster the conceptual understanding of the students.

Tobias Splith PhD, is a research associate in the Didactics of Physics Group at the University of Leipzig. His research interests focus on the development of smartphone-based experimental exercises to increase students conceputal understanding of data analysis.

Frank Stallmach PhD with postdoctoral lecturing qualification, is a lecturer for Experimental Physics in the Didactics of Physics Group at the University of Leipzig. He leads projects for the development of digital teaching and learning environments for physics education at university level. His current research interests focus on using smartphones as experimental tools in physics education.