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Development and Evaluation of an Arduino-Based Free-Fall Experiment Kit and Changes in Pre-Service Physics Teachers' Conceptual Understanding

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Abstract

Free-fall motion and gravitational acceleration are fundamental topics in mechanics; however, conventional laboratory activities are often affected by manual-timing uncertainty and may provide limited opportunities for learners to connect theoretical relationships with experimental evidence. This study aimed to develop an Arduino-based free-fall experiment kit, evaluate its scientific, technical, and instructional quality, and examine changes in pre-service physics teachers (PSPTs)' conceptual understanding after participating in the learning activities. The study employed a research-and-development process guided by the ADDIE framework, together with a pre-experimental one-group pretest–posttest implementation. There were 30 first- to third-year PSPTs selected through purposive sampling. The developed apparatus integrated an Arduino Uno R3, an HC-SR04 ultrasonic distance sensor, a servo-controlled release mechanism, and a liquid-crystal display. Three experts evaluated the quality and instructional suitability of the kit. Technical performance was examined through 10 repeated trials, and conceptual understanding was assessed using a 30-item multiple-choice test. The apparatus produced a mean gravitational acceleration of 9.26 ± 0.19 m/s², with an average error of approximately 5.62% relative to the adopted reference value of 9.81 m/s². The expert evaluation yielded an overall rating at the highest level ($M = 4.70$, $SD = 0.40$). Based on the item-level results, the mean percentage of correct responses increased from 28.3% before learning to 78.0% after learning, representing an increase of 49.7 percentage points. The corresponding normalized gain was 0.69, indicating a moderate gain approaching the high-gain threshold. The findings suggest that the kit provided relatively consistent measurements and supported hands-on data collection and interpretation. Further calibration and controlled comparative studies are required before stronger conclusions regarding measurement accuracy and instructional effectiveness can be made.

Keywords: Arduino, free-fall experiment, gravitational acceleration, ultrasonic distance sensor, conceptual understanding, pre-service physics teachers

1. Introduction

The study of fundamental physics concepts, particularly free fall and the measurement of gravitational acceleration (g), constitutes a core component of classical mechanics curricula at all educational levels (Çoban & Erol, 2022). A thorough comprehension of this principle is not only essential for explaining everyday physical phenomena but also serves as a critical foundation for understanding Newton's laws of motion and other advanced concepts. Nevertheless, designing laboratory instruction that enables students to accurately measure g and develop deep conceptual understanding remains a significant challenge (Sarapak, Luengsiriwan, et al., 2025; Sreejivungsa et al., 2025). Traditional experimental methods, such as the simple pendulum or the ticker timer, while historically and conceptually valuable, suffer from several limitations. These include setup complexity, high inaccuracies due to environmental factors, and, most notably, human error in time measurement, which can lead to misconceptions and diminish student interest in scientific experimentation (Saehana et al., 2024).

Technology-enhanced learning has increasingly incorporated open-source microcontroller platforms, such as Arduino, into physics laboratory instruction (Sarapak, Jumpatam, et al., 2025; Siqueira et al., 2023). Arduino-based systems offer relatively low-cost and flexible approaches to integrating sensors, automated data acquisition, and real-time experimental measurements. Previous studies have demonstrated the feasibility of using microcontroller-based apparatus to measure gravitational acceleration, although measurement accuracy depends on sensor characteristics, experimental configuration, and calibration procedures (Kingkunya et al., 2023; Shoaib et al., 2021). From an educational perspective, microcontroller-assisted physics experiments and ICT-supported learning activities have also shown potential for supporting students' conceptual understanding and engagement through hands-on experimentation and data interpretation (Boimau & Mellu, 2019; Liang et al., 2021).

Previous studies have generally emphasized either the technical development of Arduino-based apparatus or student learning outcomes separately (Boimau & Mellu, 2019; Kause & Boimau, 2019; Suprapto et al., 2018). However, fewer studies have explicitly integrated the evaluation of measurement accuracy, precision, repeatability, instructional suitability, and learners' conceptual understanding within a single Arduino-based free-fall experiment, particularly in the context of pre-service physics teacher education. Since pre-service teachers are expected not only to understand physical concepts but also to design, conduct, and interpret experiments for their future classroom practice, an experimental kit developed for this group should be evaluated from both technical and pedagogical perspectives (Sarapak, Kong-In, et al., 2025).

Accordingly, this study aimed to: (1) design and develop an Arduino-based free-fall experiment kit and accompanying instructional materials for measuring gravitational acceleration; (2) evaluate the scientific, technical, and instructional quality of the developed kit and examine its measurement consistency and accuracy; and (3) examine changes in PSPTs' conceptual understanding of free-fall motion before and after participating in the learning activities.

2. Methodology

2.1 Research Design

This study employed a Research and Development design integrated with a pre-experimental one-group pretest–posttest design. The research and development process was guided by the ADDIE framework and organized into three phases corresponding to the research objectives. Phase 1: Analysis, Design, and Development. This phase involved analyzing the physics curriculum, identifying limitations of existing free-fall experiments, determining the specifications of the apparatus, designing the hardware and physical

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structure, modifying the Arduino control program, constructing the prototype, and developing the instructional materials. Phase 2: Expert and Technical Validation. The developed experiment kit, user manual, learning activities, and conceptual understanding test were evaluated by three experts. The technical performance of the apparatus was also examined in terms of measurement accuracy, precision, and repeatability through repeated measurements under controlled conditions. Phase 3: Implementation and Evaluation. The validated experiment kit was implemented with 30 PSPTs using a pre-experimental one-group pretest–posttest design. The participants' conceptual understanding of free-fall motion was assessed before and after the learning intervention.

2.2 Participants

The participants consisted of 30 pre-service physics teachers (PSPTs) enrolled in the Bachelor of Education Program in Physics at the Faculty of Science and Technology, Surindra Rajabhat University (SRRU), during the second semester of the 2025 academic year. The participants included seven first-year, ten second-year, and thirteen third-year PSPTs. The learning activities were conducted in three instructional groups according to their academic year levels, while the assessment data were analyzed collectively. The participants were selected using purposive sampling based on their enrollment in the physics teacher education program and their availability to participate in all stages of the experimental activity. All participants had received or were receiving introductory instruction in mechanics and physics laboratory work relevant to free-fall motion and gravitational acceleration. The inclusion criteria were as follows: (1) being enrolled as a first-, second-, or third-year pre-service physics teacher; (2) possessing fundamental knowledge of mechanics or participating in a mechanics-related course; (3) being available to participate in the complete experimental activity; and (4) voluntarily agreeing to participate in the study.

Although the learning activities were conducted separately for each academic year-level group, all participants received the same instructional intervention. The three groups were not treated as separate experimental conditions, as the primary purpose of the study was to examine changes in conceptual understanding following participation in the developed Arduino-based free-fall learning activities.

2.3 The Arduino-Based Free-Fall Experiment Kit

The developed free-fall experiment kit consisted of an Arduino Uno R3 microcontroller, an HC-SR04 ultrasonic distance sensor, a single SG90 servo motor serving as the object-release mechanism, a 16 × 2 liquid-crystal display, a vertical PVC support structure, a falling object, and a landing pad. The physical structure and arrangement of the components were designed and assembled by the researchers to support the measurement of gravitational acceleration and to ensure that the falling object moved vertically along the predetermined measurement path. The overall design and arrangement of the experimental apparatus are presented in Figure 1.

As illustrated in Figure 1, the servo motor was installed at the upper part of the vertical support structure and functioned as the object-release mechanism. The servo motor was programmed to release the object in a consistent manner, thereby reducing variation associated with manual release. The ultrasonic distance sensor was positioned to detect changes in the position of the falling object and obtain the motion-related data required for determining displacement and fall time. The Arduino Uno R3 served as the central controller, receiving sensor signals, controlling the servo motor, processing the measurement data, and transmitting the results to the LCD display. The Arduino control code used in this study was adapted from the Arduino-based approach reported by Çoban and Salar (2023) and subsequently modified to suit the hardware configuration and experimental objectives of the present study. The modifications included the servo motor

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control sequence, sensor initialization, distance-data acquisition, timing procedures, calculation of gravitational acceleration, and real-time presentation of the measured values on the LCD display. Additional adjustments were made to improve the synchronization between the object-release command and the beginning of data collection. The Arduino program was configured to determine the falling time based on changes in distance detected by the HC-SR04 ultrasonic sensor. The timing process was initiated when the measured distance began to change and terminated when no further change in distance was detected. The servo motor was used to release the object, whereas the ultrasonic sensor provided the signals used to determine the beginning and end of the timing interval. The developed system was designed to provide users with access to the measured distance and time data rather than displaying only the final gravitational acceleration value. This feature allowed the participants to examine the relationship between displacement and time, calculate gravitational acceleration from the experimental data, and discuss possible sources of measurement error. The design therefore supported both technical measurement and inquiry-oriented physics learning. Before implementation, the assembled apparatus and the modified program were examined through preliminary functional testing. The researchers inspected the operation of the servo motor, the stability of the sensor readings, the communication between the Arduino board and the display unit, and the consistency of the data-recording process. Necessary adjustments were subsequently made to the sensor position, release angle, timing sequence, and program parameters before the kit was evaluated by the experts and implemented with the participants.

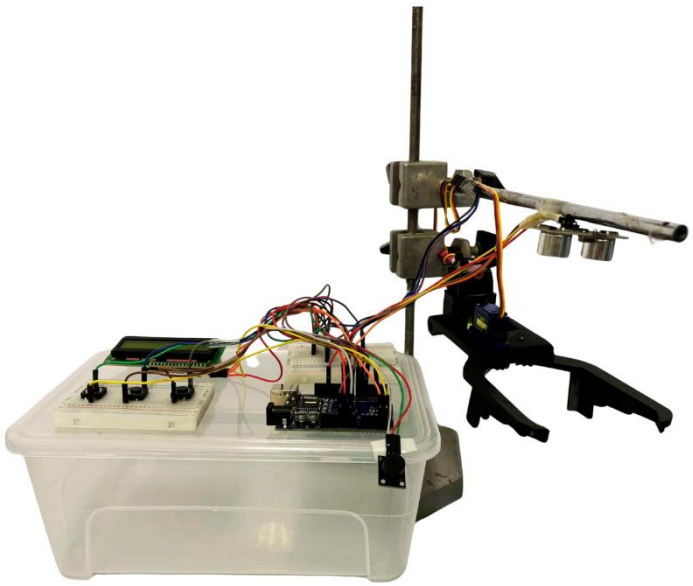


Figure 1. Configuration of the developed Arduino-based free-fall experiment kit, showing the HC-SR04 ultrasonic sensor, SG90 servo motor, Arduino Uno R3, LCD display, and landing pad.

2.4 Learning Intervention and Experimental Procedure

The learning intervention was conducted in a single three-hour session. Participants first completed the conceptual-understanding pretest for 20 minutes. The learning activities were conducted in three instructional groups based on the participants' academic year levels, comprising seven first-year, ten second-year, and thirteen third-year PSPTs (N = 30). All three groups participated in the learning activities using the same developed Arduino-based free-fall experiment kit and instructional procedures. Each group predicted the motion of the falling object, operated the experiment kit, collected distance–time data

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from 10 repeated trials, calculated gravitational acceleration, compared the measured value with the adopted reference value, and discussed possible sources of measurement error. The instructor provided procedural guidance but did not provide the answers to the conceptual questions. After completing the activities, the participants completed the posttest under the same administration conditions as the pretest.

2.5 Physical Model and Calculation

Under the assumptions that the object was released from rest, air resistance was negligible, and the motion occurred vertically, the falling distance was described by

$$h = \frac{1}{2} g t^2 \quad (1)$$

Therefore, gravitational acceleration was calculated as

$$g = \frac{2h}{t^2} \quad (2)$$

The developed apparatus allows the falling distance to be adjusted according to the experimental setup. By positioning the apparatus near the edge of a laboratory table and adjusting the relative vertical distance between the release position and the detection position, different falling heights can be established for instructional activities. For the technical evaluation reported in Table 1, a nominal falling height of 0.500 m was selected and maintained throughout the ten repeated trials to ensure consistent experimental conditions. The falling distance was defined as the vertical separation between the release position and the position at which the detection event was registered. This adjustable configuration enables students to investigate the relationship between falling distance, falling time, and gravitational acceleration under different experimental conditions. The falling time was automatically determined using the HC-SR04 ultrasonic sensor. The Arduino program monitored changes in the measured distance, initiating the timing process when a change in distance was detected and stopping it when the measured distance no longer changed. The recorded time interval was subsequently used to calculate gravitational acceleration according to Eq. (2), independently of the servo-release command.

2.6 Expert Evaluation and Content Validation

The developed Arduino-based free-fall experiment kit and its instructional materials were evaluated by three experts using a five-point rating scale. The evaluation instrument comprised 20 items organized into five dimensions, with four items in each dimension: (1) scientific accuracy of the content, (2) technical suitability of the measurement system, (3) safety and durability of the equipment, (4) alignment with inquiry-based learning and constructivism, and (5) appropriateness for use in higher-education physics classes. The expert evaluation results were summarized using the mean and standard deviation. Written recommendations were also considered for improving the experiment kit and instructional materials before classroom implementation.

2.7 Conceptual Understanding Test

The conceptual understanding test consisted of 30 four-option multiple-choice items covering the meaning of free fall, gravitational acceleration, the relationships among displacement, time, velocity, and acceleration, graphical interpretation, the effects of mass and air resistance, experimental error, and the interpretation of measured gravitational acceleration. Each correct response was awarded one point, whereas an incorrect response was awarded zero points, resulting in a maximum possible score of 30 points. The content validity of the test was evaluated by three experts using the Index of Item–Objective

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Congruence. The item-level IOC values ranged from 0.67 to 1.00, indicating that all items met the predetermined acceptance criterion. Each expert rated the congruence between each test item and its intended learning objective using a three-point scale (+1 = congruent, 0 = uncertain, and −1 = incongruent). An IOC value of 0.67 or higher was considered acceptable.

2.8 Data Analysis

Data analysis was conducted according to the research objectives. The development of the experiment kit was described in terms of its components, operational procedures, program functions, prototype revisions, and final product characteristics. The expert ratings of the experiment kit, user guide, and learning activity worksheet were analyzed using the mean and standard deviation. The content validity of the conceptual understanding test was analyzed using the Index of Item–Objective Congruence. The experts' written recommendations were also considered when revising the experiment kit and instructional materials. Technical performance was analyzed using the mean, standard deviation, minimum and maximum values, coefficient of variation, and percentage error relative to the reference gravitational acceleration. A low coefficient of variation was interpreted as evidence of relatively low dispersion and repeatability under the same experimental conditions. The percentages of correct responses on the conceptual understanding test before and after the intervention were analyzed descriptively. The normalized gain was also calculated as supplementary evidence of conceptual development.

For the item-level analysis, the pretest and posttest responses were analyzed individually for all 30 participants. Although the learning activities were conducted in three instructional groups based on academic year levels, all conceptual understanding assessments were administered and analyzed individually for the 30 participants. The frequency of correct responses for each item was obtained directly from the individual assessment records, and the corresponding percentage was calculated based on the total number of participants (N = 30), without aggregating group responses or converting rounded percentages into frequencies. The percentage-point increase was calculated by subtracting the pretest correct-response percentage from the corresponding posttest percentage.

3. Results and Discussion

The results are presented in accordance with the three research objectives: (1) the development of the Arduino-based free-fall experiment kit, (2) the evaluation of its quality and technical performance, and (3) the comparison of PSPTs' conceptual understanding before and after learning with the developed experiment kit.

3.1 Development of the Arduino-Based Free-Fall Experiment Kit

The first research objective was to design and develop an Arduino-based free-fall experiment kit for measuring gravitational acceleration. The completed apparatus consisted of an Arduino Uno R3 microcontroller, an ultrasonic distance sensor, a single SG90 servo motor used as the object-release mechanism, a 16 × 2 liquid-crystal display, a vertical supporting structure, and a falling object. The arrangement of the components was designed to maintain a consistent release position and falling path during repeated trials. The Arduino Uno served as the central control and data-processing unit. It controlled the movement of the servo motor, received measurement signals from the ultrasonic sensor, processed the experimental data, calculated the gravitational acceleration, and displayed the measured results on the LCD screen. The servo motor was used to release the object from a predefined position, thereby reducing variation caused by manual release and minimizing the possibility of an unintended initial velocity. The operation of the apparatus

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was based on the relationship for an object released from rest under constant gravitational acceleration, as described by Eq. (1). The experimental value of gravitational acceleration was calculated using Eq. (2). The Arduino control program was adapted from the work of Çoban and Salar (2023) and modified to correspond with the hardware configuration and learning objectives of the present study. The modifications included controlling the servo-based release mechanism, initializing the ultrasonic sensor, acquiring distance and timing data, calculating gravitational acceleration, displaying the results, and resetting the system for repeated trials. The final instructional package consisted of the experiment kit, a user manual, learning activities, data-recording worksheets, a conceptual understanding test, and assessment instruments. The learning activities required participants to predict the motion of the falling object, identify relevant variables, conduct repeated measurements, calculate gravitational acceleration, compare the experimental result with the reference value, and discuss possible sources of measurement error. The development results therefore addressed the first research objective by producing a functional Arduino-based apparatus and accompanying instructional materials that could be used for both gravitational-acceleration measurement and university-level physics laboratory learning.

3.2 Quality and Technical Performance of the Developed Experiment Kit

The second research objective was to evaluate the quality of the developed experiment kit in terms of scientific and instructional suitability, measurement accuracy, precision, and repeatability. The evaluation consisted of two complementary components: repeated technical measurements and expert evaluation.

3.2.1 Measurement Accuracy, Precision, and Repeatability

The technical evaluation was conducted separately from the student learning activities. Ten repeated measurements were performed under controlled experimental conditions to assess the measurement performance of the developed apparatus. The same falling object, release position, apparatus, sensor position, and falling distance were maintained throughout the measurements. The results are presented in Table 1.

Table 1 Results of gravitational acceleration measurements using the Arduino-based free-fall experiment kit (10 trials).

Trial	Fall Time (s)	Calculated Acceleration g (m/s²)	Error (%)
1	0.324	9.53	2.9
2	0.331	9.13	6.9
3	0.327	9.35	4.7
4	0.335	8.91	9.2
5	0.329	9.24	5.8
6	0.325	9.47	3.5
7	0.332	9.07	7.5
8	0.328	9.30	5.2
9	0.326	9.41	4.1
10	0.330	9.18	6.4
Average ±SD	0.329 ± 0.003	9.26 ± 0.19	5.62%

As shown in Table 1, the measured falling time ranged from 0.324 to 0.335 s, with a mean of 0.3287 ± 0.0034 s. The coefficient of variation was approximately 1.03%. The measured gravitational acceleration ranged from 8.91 to 9.53 m/s², with a mean of 9.26 ± 0.19 m/s² and a coefficient of variation of approximately 2.07%, indicating that the repeated measurements exhibited a relatively limited degree of dispersion. The percentage error for individual trials ranged from 2.9% to 9.2%, while the average percentage error was 5.62% when compared with the reference value of 9.81 m/s² adopted in this study. To

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further examine the observed systematic deviation, the mean measured falling time of 0.3287 s was compared with the theoretical falling time of approximately 0.3193 s for the nominal falling height of 0.500 m. The difference of approximately 9.4 ms suggests that the underestimation of gravitational acceleration may be partly associated with the timing and distance-detection procedures. In the developed system, timing was controlled by changes in distance detected by the ultrasonic sensor rather than directly by the servo-release command. Therefore, possible sources of systematic error include the sensor response, the criteria used to initiate and terminate timing, and uncertainty in the effective falling distance. However, the present data do not allow these contributions to be determined independently. Although the apparatus allows different falling heights to be established for instructional activities, the technical evaluation reported in Table 1 was conducted at a fixed nominal height. Further measurements at multiple heights and graphical analysis of the relationship between falling distance and squared time would be useful for improving calibration and supporting students' interpretation of experimental data. The repeated measurements demonstrate that the apparatus was able to generate reasonably consistent results under the same experimental conditions. Nevertheless, all measured values were lower than the adopted reference value. This pattern suggests that the difference may not have resulted solely from random variation but may also have involved systematic measurement effects. Potential sources include uncertainty in the effective falling distance, sensor-response delay, the definition of the beginning or ending point of the measurement, structural alignment, and a small non-zero initial velocity produced by the release mechanism. Therefore, the results support the precision and repeatability of the apparatus within the investigated conditions, but they also indicate that further calibration is required to improve its measurement accuracy. In particular, the sensor position, effective falling distance, release timing, and calculation procedure should be carefully verified before concluding that the apparatus provides highly accurate gravitational-acceleration measurements.

3.2.2 Expert Evaluation of the Experimental Kit's Quality

The quality and instructional suitability of the developed experiment kit were evaluated by three experts. The evaluation covered five dimensions: scientific accuracy, technical suitability, safety and durability, alignment with inquiry-based and constructivist learning, and appropriateness for higher-education physics instruction. The results are presented in Table 2.

Table 2 Expert evaluation of the quality and instructional suitability of the Arduino-based free-fall experiment kit and accompanying materials (three experts).

Evaluation Aspect	Mean	SD	Quality Level
1. Scientific accuracy of the content	4.83	0.29	Highest
2. Technical suitability of the measurement system	4.67	0.47	Highest
3. Safety and durability of the equipment	4.67	0.47	Highest
4. Alignment with Inquiry-based Learning and Constructivism	4.50	0.50	High
5. Appropriateness for use in higher education physics classes	4.83	0.29	Highest
Overall	**4.70**	**0.40**	**Highest**

The three experts rated the overall quality and instructional suitability of the developed experiment kit at the highest level (M = 4.70, SD = 0.40). Scientific accuracy and appropriateness for higher-education physics instruction received the highest mean ratings (M = 4.83 for both dimensions). Technical suitability and safety and durability

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were also rated at the highest level (M = 4.67 for both dimensions), whereas alignment with inquiry-based learning and constructivism was rated at a high level (M = 4.50). The experts recommended adding more explicit graph-interpretation activities to strengthen the connection between experimental data and theoretical models. These ratings indicate that the experts considered the kit and its instructional materials appropriate for further classroom implementation. However, the ratings represent expert judgments of suitability and should be interpreted separately from the technical measurement results.

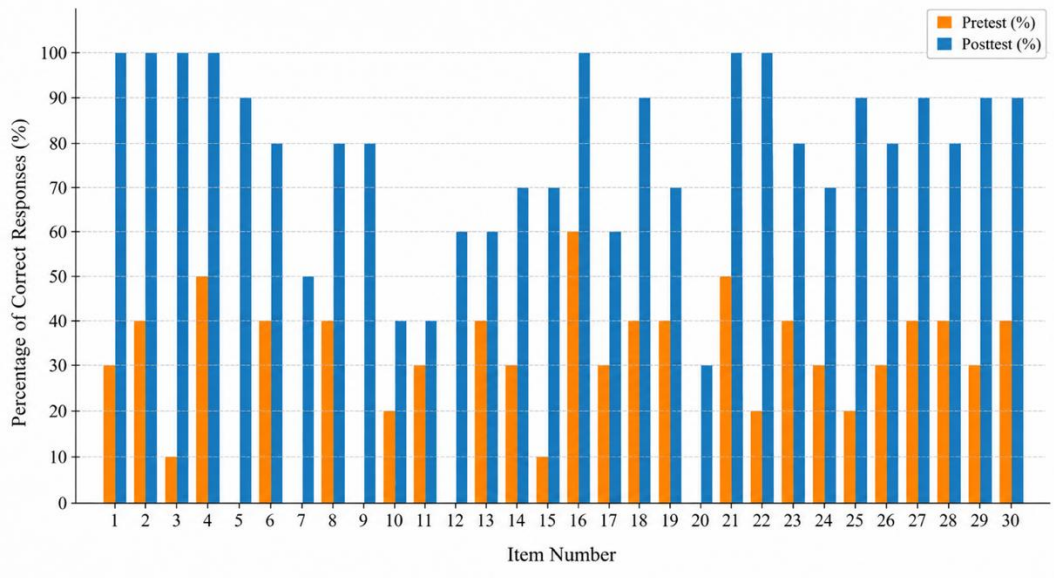


Figure 2. Percentage of participants answering each conceptual-understanding test item correctly before and after the learning intervention. The posttest percentage was higher than the pretest percentage for all 30 items, although the magnitude of improvement varied across the items.

3.3 Comparison of Conceptual Understanding Before and After Learning

The third research objective was to compare PSPTs' conceptual understanding of free-fall motion before and after learning with the developed Arduino-based experiment kit. The percentage of participants who answered each test item correctly before and after the intervention is presented in Table 3 and Figure 2.

Table 3. Number and percentage of participants answering each item correctly before and after the learning intervention (N = 30)

Item	Pretest, n (%)	Posttest, n (%)	Percentage-point increase
1	9 (30.0)	30 (100.0)	70
2	12 (40.0)	30 (100.0)	60
3	3 (10.0)	30 (100.0)	90
4	15 (50.0)	30 (100.0)	50
5	0 (0.0)	27 (90.0)	90
6	12 (40.0)	24 (80.0)	40
7	0 (0.0)	15 (50.0)	50
8	12 (40.0)	24 (80.0)	40
9	0 (0.0)	24 (80.0)	80
10	6 (20.0)	12 (40.0)	20
11	9 (30.0)	12 (40.0)	10
12	0 (0.0)	18 (60.0)	60
13	12 (40.0)	18 (60.0)	20

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Item	Pretest, n (%)	Posttest, n (%)	Percentage-point increase
14	9 (30.0)	21 (70.0)	40
15	3 (10.0)	21 (70.0)	60
16	18 (60.0)	30 (100.0)	40
17	9 (30.0)	18 (60.0)	30
18	12 (40.0)	27 (90.0)	50
19	12 (40.0)	21 (70.0)	30
20	0 (0.0)	9 (30.0)	30
21	15 (50.0)	30 (100.0)	50
22	6 (20.0)	30 (100.0)	80
23	12 (40.0)	24 (80.0)	40
24	9 (30.0)	21 (70.0)	40
25	6 (20.0)	27 (90.0)	70
26	9 (30.0)	24 (80.0)	50
27	12 (40.0)	27 (90.0)	50
28	12 (40.0)	24 (80.0)	40
29	9 (30.0)	27 (90.0)	60
30	12 (40.0)	27 (90.0)	50

As shown in Table 3 and Figure 2, the percentage of correct responses increased for all 30 test items after the learning intervention. This overall pattern indicates that participants demonstrated improved conceptual understanding across the content areas assessed by the test following their engagement with the Arduino-based free-fall experiment. The reported overall mean percentage increased from 28.3% before learning to 78.0% after learning, representing an increase of 49.7 percentage points. Based on these overall values, the normalized gain was 0.69. According to Hake's (1998) normalized-gain classification, the obtained value of 0.69 indicates a moderate gain approaching the high-gain threshold. The result suggests that the learning activity enabled participants to improve their understanding of free-fall motion beyond their initial level of knowledge. The greatest improvements were observed for Items 3 and 5, each of which increased by 90 percentage points. Item 3 increased from 10% correct responses on the pretest to 100% on the posttest, while Item 5 increased from 0% to 90%. These results indicate substantial improvement in the concepts assessed by these items. Items 9 and 22 also showed large improvements of 80 percentage points. The percentage of correct responses for Item 9 increased from 0% to 80%, while Item 22 increased from 20% to 100%. In addition, Items 1 and 25 increased by 70 percentage points, and Items 2, 12, 15, and 29 increased by 60 percentage points. The large improvements in these items suggest that direct experimentation, automated data acquisition, and guided data interpretation may have helped participants connect the theoretical relationships among falling distance, time, velocity, and gravitational acceleration with observable experimental evidence. The activities also provided opportunities to examine experimental procedures, measurement error, sensor operation, and the interpretation of numerical results. Despite the overall improvement, several items remained comparatively difficult after the intervention. Item 20 had the lowest posttest correct-response percentage at 30%, followed by Items 10 and 11 at 40%, Item 7 at 50%, and Items 12, 13, and 17 at 60%. The relatively low posttest performance on these items indicates that some concepts were not fully understood by all participants. The smallest improvement occurred for Item 11, which increased by only 10 percentage points, from 30% to 40%. Items 10 and 13 increased by 20 percentage points, while Items 17, 19, and 20 increased by 30 percentage points. These results suggest that the concepts represented by these items may require additional explanation, alternative representations, more explicit discussion, or revised learning activities. Therefore, although the overall findings demonstrate substantial descriptive improvement, the item-

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level results also reveal areas in which conceptual difficulties remained. These findings can be used to revise the worksheets and instructional procedures by increasing emphasis on the concepts measured by Items 7, 10, 11, 13, 17, and 20.

The findings demonstrate that the Arduino-based free-fall experiment kit achieved the first research objective by providing an integrated system for controlling the release of a falling object, collecting measurement data, and calculating gravitational acceleration. The combination of an Arduino Uno, an ultrasonic sensor, and a servo-controlled release mechanism reduced learners' dependence on manual timing and provided immediate experimental results. This design is consistent with previous studies indicating that Arduino is a flexible platform for integrating sensors and automated timing into free-fall experiments (Kause & Boimau, 2019). However, the mean gravitational acceleration obtained in the present study was 9.26 ± 0.19 m/s², with an average percentage error of approximately 5.62% relative to the adopted reference value of 9.81 m/s². Although the relatively low dispersion of the repeated measurements indicates reasonable precision and repeatability under the investigated conditions, all measured values underestimated the reference value. This pattern suggests the possible presence of systematic measurement effects associated with the effective falling distance, ultrasonic sensor response, timing criteria, or experimental configuration. These findings highlight the need for further calibration and verification of the measurement procedures. Differences in sensor characteristics and apparatus configurations may also contribute to variations in measurement performance across Arduino-based experimental systems (Kause & Boimau, 2019; Suprapto et al., 2018).

Regarding the second research objective, the experts rated the overall quality and instructional suitability of the developed experiment kit at the highest level ($M = 4.70$, $SD = 0.40$). The particularly high ratings for scientific accuracy and appropriateness for higher-education physics classes indicate that the apparatus, instructional content, and learning procedures were considered suitable for PSPTs. The ratings for technical suitability, safety, and durability also support its feasibility for laboratory implementation. Moreover, the alignment with inquiry-based and constructivist learning was rated at a high level, reflecting the opportunities provided for learners to predict outcomes, conduct measurements, analyze data, and construct explanations from experimental evidence. These characteristics are consistent with technology-enhanced active-learning approaches in which students develop understanding by collecting and interpreting their own data (Çoban & Erol, 2022; Dat et al., 2024). Nevertheless, expert evaluation represents judgments concerning the quality and suitability of the design and should not be treated as direct evidence of measurement accuracy; therefore, it should be interpreted together with the technical results.

For the third research objective, the mean percentage of correct responses increased from 28.3% before learning to 78.0% after learning, representing an increase of 49.7 percentage points. The normalized gain of 0.69 indicates a moderate gain close to the high-gain threshold according to Hake's (1998) criterion. The percentage of correct responses increased across all 30 test items, particularly for concepts concerning the meaning of free fall, the application of kinematic equations, the distinction between constant velocity and constant acceleration, and the interpretation of experimental measurements. These findings suggest that hands-on experimentation and real-time data presentation helped participants connect abstract mathematical relationships with observable evidence. Similar improvements in conceptual understanding have been reported in microcontroller-assisted mechanics learning (Boimau & Mellu, 2019). Nevertheless, several items remained relatively difficult after the intervention, indicating that future revisions should place greater emphasis on graphical interpretation, sensor operation, and measurement uncertainty. Because the study employed a pre-experimental one-group pretest–posttest design without a comparison group, the observed improvement cannot be attributed

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exclusively to the developed Arduino-based free-fall experiment kit. Other factors, including familiarity with the test items, instructor guidance, group discussion, and repeated practice, may also have contributed to the participants' posttest performance. Therefore, the findings should be interpreted as descriptive evidence of improvement following the learning intervention rather than definitive evidence of a causal effect.

4. Conclusion

This study developed and evaluated an Arduino-based free-fall experiment kit for measuring gravitational acceleration and supporting laboratory learning among PSPTs. The system integrated an Arduino Uno R3, an ultrasonic distance sensor, a servo-controlled release mechanism, an LCD unit, and accompanying instructional materials. Across 10 repeated trials, the apparatus produced a mean gravitational acceleration of 9.26 ± 0.19 m/s². The relatively low dispersion of the measurements indicated reasonable consistency under the investigated conditions. However, the average error of approximately 5.62% and the consistent underestimation of the adopted reference value indicate the presence of possible systematic measurement effects. Further calibration of the effective falling distance, sensor position, release timing, and data-processing procedure is therefore required. The experts rated the overall quality and instructional suitability of the kit at the highest level (M = 4.70, SD = 0.40), although the technical measurement results should be interpreted separately from these expert judgments. Based on the item-level percentages presented in Table 3, the mean correct-response percentage increased from 28.3% before learning to 78.0% after learning, with a normalized gain of 0.69. These results provide descriptive evidence of improved immediate posttest performance following participation in the learning activities. Nevertheless, difficulties remained in several assessed concepts, indicating the need for more explicit activities concerning graph interpretation, sensor operation, and measurement uncertainty. Overall, the developed kit shows potential as a laboratory resource for integrating microcontroller technology, automated data acquisition, and evidence-based interpretation into physics teacher education. The findings are limited by purposive sampling, the single-institution setting, the absence of a comparison group, and the lack of a delayed posttest. Future studies should improve the calibration of the system, use controlled research designs, and examine the retention and transfer of conceptual understanding.

Ethics Approval

Ethical approval for this study was obtained from the relevant research ethics committee of Surindra Rajabhat University, with administrative coordination through the Research and Development Institute (Approval No. HE692014). Participation was voluntary, and all participants were informed of the research objectives and procedures. The collected data were treated confidentially and used solely for research purposes.

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Declaration

The authors declare that Generative AI (ChatGPT/Gemini) was only used to help improve the English language and for minor translation tasks. The AI was not used to create any scientific content, conduct data analysis, or interpret results. All ideas, experimental design, data collection, analysis, and conclusions were solely carried out by the authors. Following ethical research standards and academic integrity policies, the

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authors confirm that AI tools were used openly, ethically, and under the full supervision of the authors to ensure the manuscript's accuracy and appropriateness.

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