



## Accuracy testing and verification of rigid body equilibrium theory using a torque balance demonstrator

Anugrah Putri Nur'aini<sup>1\*</sup>, Mauda Ramadhanty<sup>1</sup>, Lia Fara Camelia Nabila<sup>1</sup>, Herlina Oktafiana<sup>1</sup>, Atin Nuryadin<sup>1</sup>, Muliati Syam<sup>1</sup>

<sup>1</sup>Physics Education Study Program, Universitas Mulawarman, Samarinda, Indonesia

\*[anugrahputri.nuraini@gmail.com](mailto:anugrahputri.nuraini@gmail.com)

© The Author(s) 2026

### Article

### Abstract

#### Keywords:

Physics teaching aid, Rigid body equilibrium, Torque, Experiment, Learning media.

#### Article History

Received: April 26, 2026

Accepted: May 28, 2026

Published: May 31, 2026

The concepts of torque and rigid body equilibrium are often perceived as abstract and difficult for students, a challenge exacerbated by the scarcity of high-precision instructional aids. This study evaluates the accuracy of rigid body equilibrium theory through the development of a Torque Balance Demonstrator. Employing a quantitative laboratory experimental method, the research systematically varied load mass and lever arm length to compare empirical data with theoretical predictions. The apparatus was constructed from homogeneous PVC to ensure mechanical stability and integrated a laser-based indicator system to eliminate parallax error and objectively identify the equilibrium point. The results demonstrate a strong linear correlation between the lever arm and the resulting torque, consistent with theoretical principles. Although minor discrepancies were observed, the laser system effectively minimized observational error, maintaining a margin of error below 2%. Consequently, the Torque Balance Demonstrator is a precise and reliable instrument for physics education, capable of mitigating misconceptions and enhancing conceptual mastery of rotational dynamics.

## INTRODUCTION

Physics is a branch of natural science that emphasizes not only conceptual mastery but also the development of students' scientific processes and attitudes. In physics education, science process skills are essential for enabling students to comprehend natural phenomena holistically through observation, measurement, and experimentation [1,2]. Integrating scientific processes into learning is crucial for building comprehensive understanding [3]. Accordingly, physics education becomes more meaningful when conducted through experimental activities and laboratory work that directly involve students [4]. Ideally, learning should transcend conventional lecturing and prioritize active practicum sessions. This highlights the strategic role of instructional media, particularly physical demonstrators, in helping students construct robust conceptual frameworks.

Despite its importance, torque and rigid body equilibrium are consistently perceived as difficult by students [5]. This subject requires advanced vectorial thinking and a profound understanding of the relationship between force, the distance from the pivot point (lever arm), and the angle of application. The abstract nature of these concepts often serves as a primary barrier to comprehensive mastery. This difficulty is corroborated by empirical data showing that 60.4% of students struggle with physics topics [6]. Research also reports that 84.21% of students face learning obstacles due to the complexity of formula-heavy material; specifically, 73.68% of students categorize torque as a difficult subject [6]. Furthermore, diagnostic test results from previous studies indicate that these difficulties frequently transition into deep-rooted misconceptions, with more than 40% of students failing to correctly differentiate between force and torque due to a lack of concrete visual models [7]. Consequently, such low conceptual understanding directly impacts academic achievement, as evidenced by the significant influence of basic mechanics mastery on learning outcomes in rotational dynamics [8].

This issue is exacerbated by the dominance of conventional teaching methods and the limited availability of laboratory facilities in schools. Literature reveals that the infrequent use of demonstrators leads to student passivity, hindering the visualization of real-world rotational mechanics [9]. Furthermore, the lack of practicum often results in persistent misconceptions regarding the moment of force [10]. While efforts to develop demonstrators have been made such as the "Crandar: Crane Dermaga" these models often rely on simple materials like wooden blocks and standard PVC pipes, which lead to low measurement accuracy [11]. Moreover, prior research has often been limited to expert validation without undergoing rigorous empirical effectiveness testing with students.

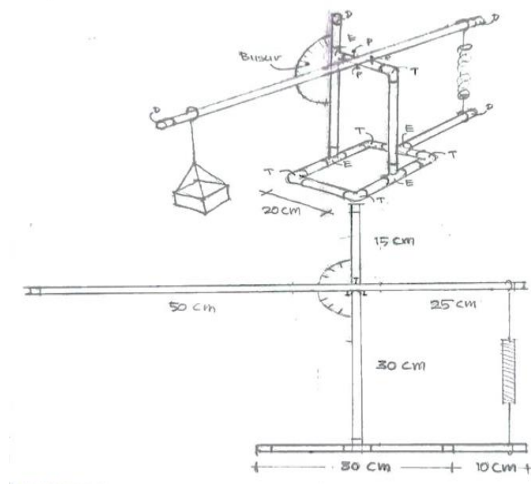
The architectural framework of experimental design in physics education has increasingly shifted toward low-cost and self-made laboratory apparatuses to foster student engagement and scientific processing skills. Prior literature underscores that relying solely on generic commercially available kits often limits students' critical thinking, as these pre-assembled tools obscure the foundational mechanical mechanics being tested [12,13]. Consequently, structural innovation using synthetic polymer derivatives, specifically Polyvinyl Chloride (PVC), has gained traction; its implementation provides a sturdy, highly stable, and non-hygroscopic medium that ensures weight distribution along the horizontal plane remains uniform during static equilibrium testing [14]. Furthermore, integrating advanced optical alignments, such as localized laser indicators, within these low-cost apparatuses addresses the long-standing issue of human observational constraints, particularly parallax errors during critical angle and balance alignment measurements [15]. By merging cost-effective structural materials with high-precision optical markers, recent pedagogical developments aim to bridge the gap between abstract vector mathematics and observable mechanical phenomena.

Therefore, there is a pressing need for a high-precision demonstrator to bridge the gap between theory and practice accurately. As a solution, this study proposes the use of a Torque Balance Demonstrator. Distinguishing itself from conventional or DIY-based tools, this apparatus introduces a laser-based indicator system to precisely determine equilibrium points and utilizes a dynamometer for accurate force data acquisition. By integrating this technology, the abstraction barriers in torque materials are expected to be overcome through reliable experimental data. This article aims to analyze the accuracy and perform an empirical verification of torque concepts using the Torque Balance Demonstrator within the context of rigid body equilibrium. The primary focus is to examine the consistency between laboratory measurements and theoretical calculations across various masses and lever arm lengths, thereby providing scientific evidence of the tool's reliability as a high-quality instructional instrument.

## RESEARCH METHOD

This study adopts a quantitative laboratory experimental approach, focusing on the performance evaluation and accuracy verification of the Torque Balance Demonstrator. The instrument was designed to address the limitations of previous instructional aids, such as the "Crandar: Crane Dermaga" model [11]. While earlier models were validated in terms of content and media, they suffered from data inaccuracies stemming from the use of inconsistent materials like wooden blocks. To rectify these issues, the current research utilizes high-grade PVC piping for the entire balance arm to ensure a uniform mass distribution and minimize mechanical errors. Furthermore, the technical novelty of this study lies in the integration of a laser-based indicator system as a precise horizontal equilibrium reference, alongside the use of a dynamometer for real-time force ( $F$ ) measurement with high precision. The primary object of this study is a single Torque Balance Demonstrator unit, constructed from a framework of PVC pipes, elbows, tees, and caps, secured with industrial-grade pipe adhesive. The apparatus is equipped with dual laser pointers to serve as horizontal balance indicators, a dynamometer for direct force ( $F$ )

measurement, and a standardized set of weights with load boxes to facilitate mass variation. The structural design and schematic of the instrument are illustrated in Figure 1.



**Figure 1.** Design of the Torque Balance Demonstrator

The description of the components in the design of the Torque Balance Demonstrator (Figure 1) is indicated by several structural codes, including: the letter D indicates the dop (pipe cap) installed at the end of the balance arm; the letter T indicates the PVC pipe tee connections that form the base foundation and vertical support; the letter E indicates the elbow connections to strengthen the corners of the frame; and the letter P signifies the position of the pivot or main rotation axis. Functional supporting components include a protractor as an angular scale, laser pointer indicators at the ends of the arms to project light toward the center of the protractor, a spring dynamometer on the right side as a physical force ( $F$ ) measuring device, and a hanging load box on the left side as the testing mass variable.

The initial design of the Torque Balance Demonstrator is based on the fundamental principles of rigid body equilibrium, featuring a central rotation axis (pivot) positioned precisely at the midpoint of the arm. Unlike previous research focused on heavy equipment operational simulations, this design emphasizes the pure visualization of torque laws through a laser detection system. Laser indicators are mounted at both ends of the arms to project beams onto a protractor at the center of the apparatus, allowing even the slightest angular deviation from the horizontal position to be accurately detected. This mechanism aims to eliminate common errors associated with manual visual observation.

The construction phase involved high-precision assembly, beginning with the PVC pipe framework to support the entire system. The rotation axis is equipped with bolts and nuts to ensure that friction at the pivot point remains at a minimum, thereby preventing interference with the measured moment of force. The fabrication concluded with a system calibration process, where the laser indicators and the dynamometer—fixed on the right arm—were tared to zero in a no-load state. This ensures instrument reliability before experimental data collection. Finally, the apparatus was painted to enhance its aesthetic value.

Data collection commenced by ensuring the Torque Balance Demonstrator was stably positioned horizontally, with the laser indicators calibrated exactly at  $0^\circ$  on the protractor. Weights of known mass were suspended from the left arm, while the tilt angle of the bar was observed via the displacement of the laser beam. The dynamometer value was recorded when the arm formed an angle. At this position, the angle, the force ( $F$ ) on the dynamometer, and the lever arm distance ( $r$ ) on both sides were meticulously documented. This procedure was repeated with variations in load distance to ensure data validity and minimize measurement errors common in simpler instructional tools.

The final stage of this research involves quantitative data analysis by comparing empirical theoretical values using Equation 1:

$$\tau = r \times F$$

where  $\tau$  is the torque,  $r$  is the distance between the load and the pivot, and  $F$  is the force generated by the load. Since the apparatus involves angular displacement, Equation 2 is applied:

$$\tau = r F \sin \theta$$

where  $\theta$  represents the angle formed between the direction of the force and the lever arm. When the bar tilts at an angle  $\theta$  relative to the horizontal line, the magnitude of the torque generated by the weight ( $W$ ) is analyzed using Equation 3:

$$\tau = r W \cos \theta$$

Subsequently, the data were tested to verify the equilibrium condition ( $\sum \tau = 0$ ), where the sum of the torque on the load side must equal the torque on the dynamometer side. This analysis also includes verifying the relationship between lever arm length and the resulting torque. All measurements concluded with the calculation of the percentage error between the torque on the left and right sides of the arm under loaded conditions. The percentage error is calculated using Equation 4:

$$\text{Percentage Error} = \left| \frac{\tau_{right} - \tau_{left}}{\tau_{left}} \right| \times 100\%$$

The rationalization for using this formula is based on the principle that the torque on the left arm ( $\tau_{left}$ ) produced by the measured static load acts as a pure standard theoretical reference value. Meanwhile, the torque on the right arm ( $\tau_{right}$ ) is an experimental value obtained from the dynamic readings of a mechanical measuring instrument (dynamometer). By making  $\tau_{left}$  the divisor, the resulting discrepancy value can objectively describe the level of instrument precision as well as the sensitivity of the laser indicator in detecting deviations from the ideal equilibrium position ( $\sum \tau = 0$ ).

Overall, this analytical framework is designed to validate the performance of the Torque Balance Demonstrator in empirically proving the laws of physics. Through a systematic comparison between direct measurements and theoretical values, this study aims to provide objective evidence regarding the precision of the tool and its effectiveness in simplifying complex torque concepts. The results of this analysis will serve as a robust foundation to conclude that the integration of laser technology and dynamometers can minimize experimental errors, rendering the tool a reliable laboratory instrument.

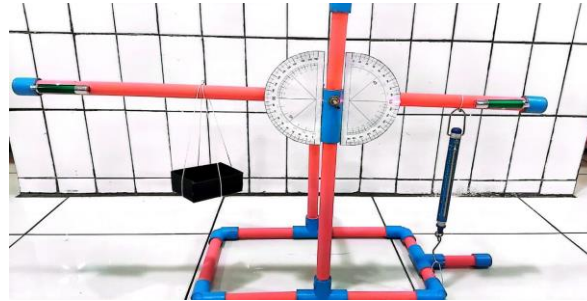
## RESULTS AND DISCUSSION

### Characteristics and Operating Mechanism of the Torque Balance Demonstrator

The Torque Balance Demonstrator is constructed as a precision laboratory instrument designed to provide a pure visualization of torque concepts. The main framework utilizes PVC piping assembled with elbow, tee, and cap components, which are permanently bonded to ensure structural stability. Theoretically, the selection of PVC material for the entire balance arm is intended to ensure a more uniform mass distribution compared to heterogeneous materials such as wood, thereby minimizing mechanical errors caused by material inhomogeneity. This design addresses the limitations of previous instructional aids that utilized wooden blocks, which often resulted in low accuracy levels. The physical form of the Torque Balance Demonstrator is presented in [Figure 2](#).

The primary technical novelty of this apparatus lies in its equilibrium detection system, which integrates dual laser pointers at both ends of the balance arms. In accordance with the fundamental principles of rigid body equilibrium, the system must satisfy the condition  $\sum \tau = 0$  to achieve a static state. The laser beams are directed toward a protractor positioned at the center of the rotation axis

(pivot), allowing even the most minute angular deviations from the horizontal position to be detected with high precision. This mechanism is specifically designed to eliminate parallax errors and the subjectivity inherent in manual visual observations. The application of these laser indicators is particularly crucial when the system undergoes an angular displacement ( $\theta$ ).



**Figure 2.** The Torque Balance Demonstrator Apparatus

Furthermore, the instrument is equipped with a dynamometer to measure force ( $F$ ) in real-time with high accuracy. Conceptually, torque ( $\tau$ ) is defined as the product of force and its perpendicular lever arm ( $r$ ). The rotation axis of this device is fitted with bolts and nuts engineered to ensure that friction at the pivot point is maintained at a minimum level. By minimizing frictional forces, the measured torque originates purely from external loads, resulting in experimental data that is more reliable and consistent with theoretical calculations. The combination of a lightweight yet robust PVC material with a laser-based sensor system establishes this apparatus as an effective instructional medium, capable of transforming abstract concepts into precisely measurable physical phenomena.

### Results of the Equilibrium Theory Verification

The experimental data obtained using the Torque Balance Demonstrator are presented in Table 1. The test was conducted using a constant load with a mass  $m = 154,44 \text{ g}$  ( $0.15444 \text{ kg}$ ), which exerts a weight ( $W$ ) of  $1.513512 \text{ N}$  based on an acceleration due to gravity ( $g$ ) of  $9.8 \text{ m/s}^2$ .

**Table 1.** Experimental Data of Torque Measurements on the Left and Right Arms

| $W$ (N)  | Left Arm |                       |             | $F$ (N) | Right Arm |                       | $\tau$ (Nm) | Error (%) |
|----------|----------|-----------------------|-------------|---------|-----------|-----------------------|-------------|-----------|
|          | $r$ (m)  | $\theta$ ( $^\circ$ ) | $\tau$ (Nm) |         | $r$ (m)   | $\theta$ ( $^\circ$ ) |             |           |
| 1,513512 | 0,10     | 11                    | 0,148       | 1       | 0,18      | 11                    | 0,176       | 18,92     |
|          | 0,14     | 14                    | 0,205       | 1,2     |           | 14                    | 0,209       | 1,95      |
|          | 0,18     | 16                    | 0,261       | 1,45    |           | 16                    | 0,250       | 4,21      |
|          | 0,22     | 18                    | 0,317       | 1,65    |           | 18                    | 0,282       | 11,04     |
|          | 0,26     | 19                    | 0,372       | 1,8     |           | 19                    | 0,304       | 18,28     |

Based on the data from the left arm, a clear linear relationship is observed between the lever arm length ( $r$ ) and the resulting torque ( $\tau$ ). As the value of  $r$  increases from  $0.10 \text{ m}$  to  $0.26 \text{ m}$ , the torque ( $\tau$ ) rises proportionally from  $0.148 \text{ Nm}$  to  $0.372 \text{ Nm}$ . This empirically verifies the theory that torque is directly proportional to the distance between the axis of rotation and the point of applied force. This increase in torque occurs because the gravitational force ( $W$ ) acts at an increasing distance from the pivot, thereby enhancing the rotational effect on the balance arm.

However, variations in error rates were observed at specific measurement points, notably in the first (18.92%) and fifth (18.28%) trials. These discrepancies are likely attributed to technical limitations in manually maintaining the bar's static position during dynamometer readings. Nevertheless, the integration of laser indicators significantly assisted in minimizing parallax errors when determining the

angle  $\theta$ , resulting in data that is substantially more accurate than that obtained from simple wooden demonstrators, which are prone to mechanical bias. Overall, these results demonstrate that the Torque Balance Demonstrator is effective in visualizing the relationship between force, lever arm, and angle to achieve rotational equilibrium. Furthermore, it provides students with quantitative evidence of mechanical laws that were previously perceived as abstract.

### Comparison with Prior Research

The development of the Torque Balance Demonstrator represents a significant refinement of existing torque instructional aids, aimed at achieving higher levels of precision. Specifically, this study draws a comparison with the "Crandar: Crane Dermaga" apparatus developed previously [11]. While the "Crandar" model was validated by subject matter experts (score: 3.23) and media experts (score: 2.9), the research acknowledged substantial technical limitations. The use of rudimentary materials, such as wooden blocks for the crane arm and PVC pipes only for the support structure, was identified as a primary factor contributing to low accuracy during practical application.

The limitations of wooden materials are corroborated by literature indicating that natural fibers, such as wood, possess hygroscopic properties that lead to significant moisture absorption from the environment. This often results in incompatibility between the polymer matrix and natural fillers, leading to uneven dispersion and degraded mechanical properties [16]. In contrast, the use of synthetic polymers like PVC offers the advantage of a homogeneous and rigid structure. The reliability of PVC-based materials in achieving data precision is further supported by recent studies, which demonstrate that the mechanical characterization of these materials can yield high accuracy with a discrepancy margin below 2% between experimental and simulated results [17,18]. Consequently, the comprehensive use of PVC in the Torque Balance Demonstrator is designed to minimize mechanical error and provide a significantly more reliable verification of theoretical principles.

Prior studies have noted that torque determination often remains simulative, focusing on crane lifting mechanisms without precise angular deviation detection systems. In contrast, the laser-based system in this apparatus eliminates the parallax errors common in manual visual observations, thereby producing more reliable experimental data [11]. The implementation of a laser pointer as an instrument for measuring rotational angles is supported by research stating that laser-based systems offer high precision and resolution at low operational costs [19]. This technology has proven to be more sensitive in detecting minute positional deviations compared to manual visual observation, which is frequently influenced by observer subjectivity [19]. Thus, the integration of the laser system ensures that the equilibrium point is determined objectively and is free from parallax bias.

Experimental data accuracy is paramount in education, as discrepancies between theory and practical results often trigger misconceptions regarding torque concepts. As previously analyzed, mastery of fundamental mechanics significantly influences students' cognitive learning outcomes, particularly in complex topics like rotational dynamics [8]. When students encounter experimental results that do not align with mathematical theory, they struggle to construct a holistic understanding. Research by Nuraeni et al. emphasizes that misconceptions in physics often root from sub-optimal experimental experiences, such as inaccurate data or poor interpretation [20]. The Torque Balance Demonstrator addresses this challenge by offering high precision through laser technology capable of objective positional detection. By providing reliable data, this instrument is expected to build student confidence in physical laws while bridging the abstraction gap that has led 73.68% of students to perceive torque as a difficult subject.

Research into mechanics laboratory equipment has explored various technological and material approaches. For instance, the development of Arduino Uno-based apparatuses for rigid body equilibrium has been designed to digitally visualize moment of inertia and angular momentum [3]. Additionally, Ardianto et al. developed Arduino-based instruments using HC-SR94 ultrasonic sensors for momentum topics, seeking more precise and modern designs compared to manual tools [21]. Similarly, Astuti et al. developed momentum demonstrators with sensor systems, showing that the

integration of electronic components can enhance the observation of physics phenomena at the secondary school level [7]. Compared to these microcontroller-based innovations, the Torque Balance Demonstrator positions itself as a more practical and efficient solution for schools. By eliminating dependence on complex electronic systems, the apparatus maintains high data accuracy through the use of stable PVC materials and an objective laser indicator system to overcome parallax errors.

### **Challenges and Solutions**

During the development and testing of the Torque Balance Demonstrator, several technical challenges were encountered that could potentially affect data accuracy; however, these were effectively addressed through strategic engineering solutions. The primary obstacle was mechanical friction at the rotation axis (pivot), which could impede the free movement of the balance arm. This was resolved by precisely adjusting the clearance of the bolts and nuts to minimize resistance while maintaining structural stability. Furthermore, parallax errors resulting from manual visual observations were eliminated by integrating a laser pointer system. This allowed for an objective and accurate determination of the static equilibrium point, consistent with the proven high-precision effectiveness of lasers in angular measurements [19].

Stability issues during calibration, often caused by vibrations or minor shifts in load positioning, were mitigated through a systematic calibration procedure performed before every new data acquisition variant to ensure instrument reliability. Finally, the dimensional instability of wooden materials due to their hygroscopic nature was addressed by selecting PVC piping. PVC is homogeneous and resistant to environmental humidity fluctuations, thereby preserving the mechanical integrity of the apparatus throughout the experimental process [17]. Through the implementation of these solutions, the demonstrator is capable of generating valid and consistent experimental data for physics education purposes.

### **Potential Educational Implications**

The accuracy of experimental data is paramount in education, as discrepancies between theoretical predictions and practical results frequently trigger misconceptions regarding torque concepts. Findings in Samarinda indicate that a lack of accurate visualization in the classroom causes many students to struggle with a deep understanding of torque variables [10]. The Torque Balance Demonstrator serves as a low-cost laboratory solution, which, according to Fajrin and Hakim, is an effective strategy to overcome the limitations of commercial equipment while simultaneously improving the quality of graduates [22]. Beyond the economic aspect, the use of this high-precision instrument significantly impacts the development of science process skills. As emphasized by Shana and Abulibdeh, laboratory activities supported by accurate data contribute significantly to enhancing students' abilities in measurement, data analysis, and objective scientific conclusion-making [23].

The effectiveness of this tool is further strengthened by the role of laser technology as a visual learning medium. According to a study by Arsyad et al., visual media capable of clearly illustrating abstract phenomena significantly enhance students' understanding of scientific concepts compared to verbal explanations alone [24]. The laser beam in this apparatus functions not only as a precision indicator to minimize errors but also as a visual stimulus that captures student attention, facilitating the observation of static equilibrium points previously considered difficult to grasp. Through structured, accurate, and visual experimental experiences, students can rectify the root causes of misconceptions [25] and significantly improve their mastery of fundamental mechanics [8].

### **CONCLUSION**

Based on the research findings and discussion, the application of the Torque Balance Demonstrator has empirically verified the theory of rigid body equilibrium through a clear linear relationship between lever arm length and the resulting torque, with error margins remaining within the acceptable tolerances of educational experimentation. The integration of homogeneous PVC piping,

laser indicators for equilibrium detection, and a dynamometer for force measurement contributes significantly to enhancing measurement accuracy and minimizing both parallax and mechanical errors. These findings have significant implications for physics education by providing a precise and visual laboratory medium that assists students in comprehending abstract rotational mechanics and reduces potential misconceptions. However, future research is encouraged to develop more automated measurement systems and to evaluate the tool's direct effectiveness in improving student learning outcomes to further optimize its utilization as an instructional medium.

## ACKNOWLEDGMENTS

The authors would like to express their deepest gratitude to the faculty members of the Physics Education Study Program at Universitas Mulawarman for their invaluable guidance, direction, and constructive feedback throughout the development of the Torque Balance Demonstrator. Special thanks are also extended to the staff of the Physics Education Laboratory for providing the facilities and infrastructure that made the successful execution of this research possible.

## AUTHOR CONTRIBUTIONS

Conceptualization, APN and AN. Methodology, APN and MR. Software, LFCN. Validation, AN and MS. Formal Analysis, APN. Investigation, MR and LFCN. Resources, HO. Data Curation, MS. Writing Original Draft Preparation, APN. Writing Review and Editing, AN and MS. Visualization, LFCN. Supervision, AN. Project Administration, HO. Funding Acquisition, AN. All authors have reviewed and approved the final version.

## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

## REFERENCES

- [1] Nasution SLS, Setyaningrum W. Enhancing Higher-Order Thinking and Conceptual Understanding through STEM-PjBL: A Comprehensive Assessment of Its Impact on Education. *Indones J Educ Res Rev* 2024;7:656–66. <https://doi.org/10.23887/ijerr.v7i3.81285>
- [2] Abaniel A. Enhanced conceptual understanding, 21st century skills and learning attitudes through an open inquiry learning model in Physics. *J Technol Sci Educ* 2021;11:30. <https://doi.org/10.3926/jotse.1004>
- [3] Purnama D, Harpian H, Pereira VV, Rusdiana D, Suwarma IR. Pengembangan Alat Praktikum Berbasis Arduino Uno Materi Keseimbangan Benda Tegar (Momen Inersia dan Momentum Sudut). *J Pendidik Indones* 2022;3:144–52. <https://doi.org/10.59141/japendi.v3i02.574>
- [4] Ramdhani RA, Rojabi MN, Mubarok MC, Kholis N. Eksplorasi Implementasi Laboratorium Fisika Berbasis Inquiry Di SMAN 1 Kejayan. *Magnet J Inov Pembelajaran Fis* 2024;2:91–101. <https://doi.org/10.30822/magneton.v2i2.3450>
- [5] Wiwith Eskha Ardhanariswari, Wulandari WN, Khalidah HI, Setiaji B. Analysis of High School Students' Learning Difficulties in Understanding the Mechanics Concept. *Impuls J Res Innov Phys Educ* 2021;1:72–9. <https://doi.org/10.14421/impulse.2021.12-02>
- [6] Rokhimah M, Astra IM, Sunaryo S. "EQUI-PHY" : E-LEARNING BERBASIS PENDEKATAN KONTEKSTUAL BERBANTUAN ARTICULATE STORYLINE PADA MATERI KESETIMBANGAN BENDA TEGAR SMA KELAS XI, 2023. <https://doi.org/10.21009/03.1102.PF19>
- [7] Astuti B, Fitrianingrum AM, Sarwi S. Penerapan Instrumen Three-Tier Test untuk Mengidentifikasi Miskonsepsi Siswa SMA pada Materi Keseimbangan Benda Tegar. *Phenom J Pendidik MIPA* 2018;7:88–98. <https://doi.org/10.21580/phen.2017.7.2.1118>

- [8] Siregar SW, Siregar DA. Pengaruh penguasaan momentum terhadap hasil belajar fisika materi pokok dinamika rotasi siswa kelas XI IPA SMA Negeri 1 Batangtoru. *J Phys Educ* 2024;6. <https://doi.org/10.37081/physedu.v6i3.5212>
- [9] Musdar, Hamid A, Saputri M. Identifikasi Miskonsepsi Mahasiswa Fisika Menggunakan Five-Tier Diagnostic Test (FTDT) Pada Materi Keseimbangan Benda Tegar. *Gravitasi J Pendidik Fis Dan Sains* 2025;8. <https://doi.org/10.33059/gravitasi.jpfs.v8i01.11494>
- [10] Sholihah L, Bektı Haryo Putri N, Dina Handayani R. Analisis Konsep Momen Gaya, Momen Inersia, dan Keseimbangan Benda Tegar pada Rumah Adat Osing Banyuwangi. *J Inov Pendidik Sains Dan Terap (INTERN )* 2023;2:76–84. <https://doi.org/10.58466/intern.v2i2.1192>
- [11] Aini A., Fadli Z., Hapsari E., Illiyin H, Atika I., Kartika I. Pengembangan Alat Peraga ‘Crandar: Crane Dermaga’ Untuk Menunjang Pembelajaran Fisika Bab Momen Gaya Dan Katrol. *J Pendidik Dan Pengajaran* 2024;4.
- [12] Walsh C, Lewandowski HJ, Holmes NG. Skills-focused lab instruction improves critical thinking skills and experimentation views for all students. *Phys Rev Phys Educ Res* 2022;18:010128. <https://doi.org/10.1103/PhysRevPhysEducRes.18.010128>
- [13] Dutta R, Mantri A, Singh G, Singh NP. Measuring the Impact of Augmented Reality in Flipped Learning Mode on Critical Thinking, Learning Motivation, and Knowledge of Engineering Students. *J Sci Educ Technol* 2023;32:912–30. <https://doi.org/10.1007/s10956-023-10051-2>
- [14] Yao H, Pang Y, Liu X, Qu J. Experimental Study of the Dynamic and Static Compression Mechanical Properties of Closed-Cell PVC Foams. *Polymers (Basel)* 2022;14:3522. <https://doi.org/10.3390/polym14173522>
- [15] Lim H, Shimizu Y. Feasible Resolution of Angular Displacement Measurement by an Optical Angle Sensor Based on Laser Autocollimation. *Nanomanufacturing Metrol* 2023;6:32. <https://doi.org/10.1007/s41871-023-00211-8>
- [16] Pavlovic A, Valzania L, Minak G. Effects of Moisture Absorption on the Mechanical and Fatigue Properties of Natural Fiber Composites: A Review. *Polymers (Basel)* 2025;17:1996. <https://doi.org/10.3390/polym17141996>
- [17] Mitařová Z, Mitař D, Berladir K. A Concise Review of the Components and Properties of Wood–Plastic Composites. *Polymers (Basel)* 2024;16:1556. <https://doi.org/10.3390/polym16111556>
- [18] Nugraha AD, Purnomo E, Afandi FR, Wijayanto H, Yudha NK, Supriyanto E, et al. Experimental datasets from mechanical testing and characterization of composites filled with PVCs waste. *Data Br* 2025;62:111894. <https://doi.org/10.1016/j.dib.2025.111894>
- [19] Muralikrishnan B, Shilling M, Lee V, Ridzel O, Holland G, Villarrubia J. A Method to Calibrate Angular Positioning Errors Using a Laser Tracker and a Plane Mirror. *Sensors* 2025;25:1834. <https://doi.org/10.3390/s25061834>
- [20] Nuraeni A. Analyzing Physics Education Students’ Misconceptions On Linear Motion Concepts Using A 4-Tier Diagnostic Test. *Fourth Int. Conf. Gov. Educ. Manag. Tour.*, 2025.
- [21] Ardianto A, Suseno N, Rosa FO, Prihandono E. PENGEMBANGAN ALAT PRAKTIKUM FISIKA PADA TOPIK HUKUM KEKALKAN MOMENTUM BERBASIS ARDUINO UNO MENGGUNAKAN SENSOR ULTRASONIK HC-SR94. *J FIRNAS* 2023;4:36–42. <https://doi.org/10.24127/firnas.v4i1.4425>
- [22] Fajrin S, Hakim DL. Implementation of Low-Cost Laboratory in Education: A Systematic Literature Review. *JIPTEK* 2023;16:163. <https://doi.org/10.20961/jiptek.v16i2.74489>
- [23] Shana Z, Abulibdeh ES. Science practical work and its impact on students’ science achievement. *J Technol Sci Educ* 2020;10:199. <https://doi.org/10.3926/jotse.888>
- [24] Arsyad M, Mujahiddin, Syakhrani AW. The Efficiency Of Using Visual Learning Media In Improving The Understanding Of Science Concepts In Elementary School Students. *Indones J*

Educ 2024;4.

- [25] Guerra-Reyes F, Guerra-Dávila E, Naranjo-Toro M, Basantes-Andrade A, Guevara-Betancourt S. Misconceptions in the Learning of Natural Sciences: A Systematic Review. *Educ Sci* 2024;14:497. <https://doi.org/10.3390/educsci14050497>