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PhyFizball: a game-based tool to enhance student's understanding of force and motion

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ABSTRACT

Difficulties in understanding the concepts of force and motion continue to challenge secondary school students due to the abstract nature of physics and the limited use of interactive teaching methods. This study introduces PhyFizball, a pinball-inspired, low-cost game-based learning (GBL) tool designed to make physics learning more engaging and concrete. The tool aims to help students visualize fundamental concepts such as Newton's laws, friction, and the relationship between force and motion through hands-on and collaborative gameplay. A quasi-experimental pretest–posttest control group design was employed with 30 form two students from a Malaysian secondary school, divided equally into experimental (n =15) and control (n =15) groups. Over four weeks, the experimental group learned using PhyFizball, while the control group received conventional lecture-based instruction. A validated conceptual understanding test was administered before and after the intervention. Results from paired and independent t-tests revealed that the experimental group achieved significantly higher post-test scores than the control group ($t(28) = 3.282$, $p = 0.003$). The findings confirm that PhyFizball effectively enhances students' conceptual understanding and engagement in learning physics. Its accessible design demonstrates potential as a cost-effective and scalable teaching tool for improving science learning outcomes in secondary education.

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1. INTRODUCTION

Physics plays a pivotal role in education by driving technological advancement, fostering essential cognitive skills, and preparing students to address real-world challenges. As a core scientific discipline, physics underpins innovation and sustainable development, making a strong grasp of its foundational principles essential for navigating global issues and supporting technological progress [1]. Moreover, physics education cultivates critical thinking and problem-solving abilities that extend beyond the classroom and are highly valued across professional fields [2], [3]. A solid understanding of physics also empowers students to participate meaningfully in discussions involving scientific and technological issues, enabling them to make informed, responsible decisions [1].

Despite it is importance, abstract concepts such as force and motion often pose significant learning challenges and contribute to persistent misconceptions. Because forces are invisible, students struggle to visualize their effects on motion, leading to inaccurate assumptions about everyday phenomena. For example, many believe that objects require continuous force to maintain motion or that heavier objects fall faster than lighter ones [4], [5]. Students also frequently confuse the horizontal and vertical components of projectile motion, assuming they behave similarly when in fact they function independently [6].

National assessment data reinforce these learning challenges. According to the Malaysian Examinations Board [7], the average grade point for physics in the Malaysian Certificate of Education or *Sijil Pelajaran Malaysia* (SPM) examination declined slightly from 4.40 in 2021 to 4.37 in 2022. This trend suggests that difficulties with fundamental concepts, particularly those related to force and motion, remain widespread. These challenges may stem from traditional teaching methods, limited access to interactive learning tools, and insufficient opportunities for hands-on exploration. Supporting this, Taqwa *et al.* [8] reported that students face substantial difficulty in understanding these topics. Similarly, the research in [4], [9], [10] highlight that learning outcomes are influenced by factors such as textbook quality, teacher instruction, peer dynamics, and community attitudes. Over the past decade, various tools have been introduced to enhance physics instruction, including online simulations (e.g., PhET), digital games, and laboratory kits. While effective, these technologies often require computers, stable internet access, or specialized facilities that are not consistently available in rural or underfunded schools [11], [12]. Innovations such as Majumder *et al.* [13] Android-based 3D virtual laboratories and Gunturu *et al.* [14] augmented physics, an artificial intelligence (AI)-assisted system that transforms textbook diagrams into interactive simulations that aim to create immersive learning environments. Other approaches, such as Excel-based modeling for visualizing optical phenomena [15] and haptic simulations using audio–visual–tactile feedback [16] further support physics learning. However, their reliance on technological infrastructure limits their accessibility.

Given these constraints, educators have increasingly explored game-based learning (GBL) as a means of enhancing motivation, engagement, and conceptual understanding. GBL integrates gameplay elements into instruction, making abstract concepts more relatable and enjoyable. For example, Zafeiropoulou *et al.* [17] developed an augmented reality physics game that significantly improved students' motivation, while Khouna *et al.* [18] found that interest-based educational video games sustain attention and deepen learning. Games such as a slower speed of light and Kirchhoff's revenge have been used to teach advanced topics like special relativity and circuit laws, yielding positive outcomes across educational levels [19]. Similarly, the authors in [20]–[22] demonstrated that immersive virtual reality physics games combining narrative, challenge, and collaboration improve motivation and learning. Empirical evidence further supports the effectiveness of GBL. Zeng *et al.* [23] reported that interactive engagement and immediate feedback enhance learning outcomes. Augmented reality physics games have shown higher engagement, achievement, and satisfaction compared to traditional methods [24]. Kuo *et al.* [25] demonstrated that the Space adventure physics game, especially when paired with structured scaffolding that improves progressive learning and sustained motivation. Nevertheless, the use of GBL adoption remains limited by infrastructural challenges, insufficient teacher training, and time constraints [26].

In response to these challenges, the present study introduces PhyFizball, a kinesthetic, collaborative, and interactive GBL tool designed to enhance the teaching of force and motion among form two students. Unlike digital games, PhyFizball uses tangible materials that allow students to observe and experience cause-and-effect relationships directly. The tool supports exploratory learning, promotes peer interaction, and aligns with the Malaysian Form Two Science Curriculum (DSKP), which emphasizes inquiry-driven and competency-based learning. This study, therefore, evaluates the effectiveness of PhyFizball in improving students' conceptual understanding of force and motion compared to traditional instructional approaches.

2. METHOD

2.1. Research design

This study employed a quasi-experimental pretest–posttest control group design to evaluate the effectiveness of PhyFizball in enhancing secondary school students' conceptual understanding of force and motion. The design enabled meaningful comparison between an experimental group, which received instruction using PhyFizball, and a control group, which was taught through conventional lecture-based methods commonly used in Malaysian secondary schools. Both groups received instruction aligned with the Form Two science curriculum during two 40-minute sessions per week over four weeks. Using the same teacher for both groups minimized variability in instructional delivery.

2.2. Participants

Participants consisted of 30 Form Two students from the Sekolah Menengah Kebangsaan Indera Mahkota 2, Pekan, Pahang, Malaysia. The sample was drawn from two intact classrooms selected based on availability and willingness to participate. Fifteen students from class A formed the experimental group and engaged with PhyFizball as part of a GBL approach, while fifteen students from class B comprised the control group and received conventional instruction. Prior to data collection, informed consent was obtained from all participants.

2.3. Tool construction

PhyFizball was designed as a pinball-inspired instructional tool to promote kinesthetic, collaborative, and student-centered learning in physics. Figure 1 illustrates the overall structure of the tool, including the board layout, labelled checkpoints representing physics concepts, and the motion pathway of the ball. Students launch and guide the ball through the board, observing changes in speed and direction caused by obstacles, textured surfaces, and frictional elements, while guiding question cards accompany each checkpoint to prompt students to articulate the underlying physics principles and reflect on how each interaction demonstrates specific concepts such as momentum, energy transfer, and frictional forces.

The tool was constructed using low-cost, easily accessible materials such as recycled cardboard, colored rubber balls, manila cards, rubber bands, marker pens, and ice cream sticks assembled with a hot glue gun; the total material cost was approximately RM30 (USD7). The design, inspired by classic arcade pinball, was adapted to reflect physics checkpoints rather than score-based targets, ensuring the tool is both visually engaging and portable for classroom use, and simple enough for teachers and students to replicate or modify for different lesson objectives.

Each component of PhyFizball was intentionally designed to represent a specific physics concept. The launching mechanism models applied force and Newton's second law, while the rolling motion demonstrates inertia consistent with Newton's first law. Collisions with barriers illustrate action–reaction pairs in Newton's third law, and textured surfaces represent the effects of friction. Labelled checkpoints and guiding questions encourage students to connect observations with theoretical explanations, ensuring that gameplay remains conceptually meaningful.

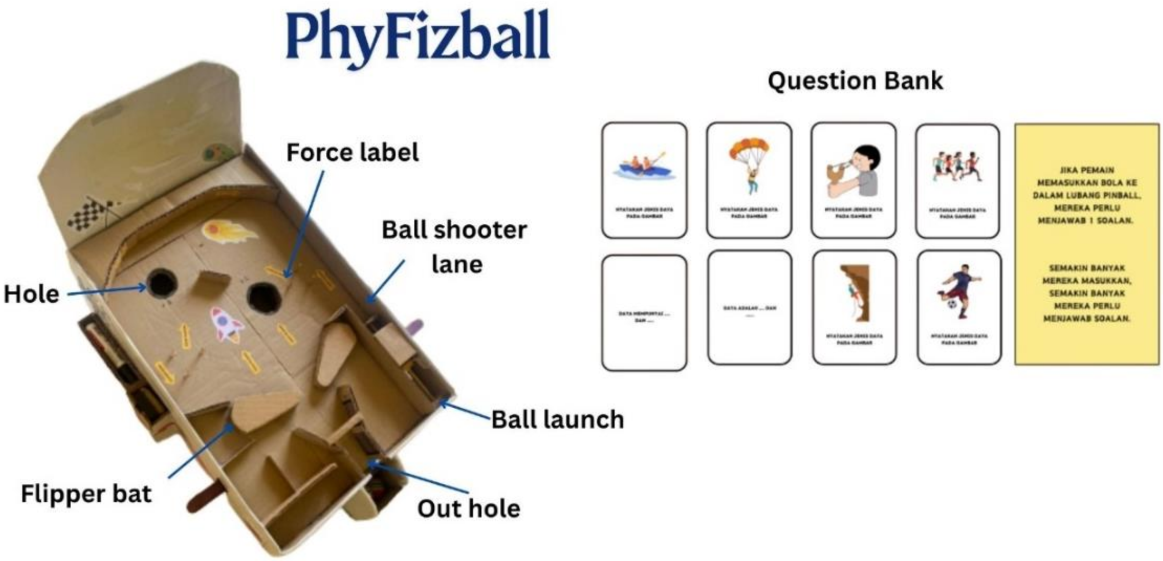

Figure 1. Structural design of the PhyFizball GBL tool for force and motion

2.4. Instructional design

The instructional design of PhyFizball reflects core principles of constructivist learning, emphasizing exploration, collaboration, reflection, and student-centered engagement. The tool supports the goals of competency-based education by enabling students to demonstrate understanding through discussion, justification, and observable performance during gameplay. Each checkpoint corresponds to a learning objective in the DSKP curriculum, allowing students to apply, explain, and refine their understanding of force and motion. Teachers facilitate the learning process by guiding discussions, posing probing questions, and supporting conceptual reasoning. The conceptual mapping of the PhyFizball GBL tool is summarized in Table 1, while Table 2 illustrates how its instructional design reflects the core components of constructivist learning.

Table 1. Structural design and conceptual mapping of the PhyFizball GBL tool for force and motion

Structural component	Physical description	Mapped physics concept	Learning objective	Sample question/activity from question bank
Ball shooter lane	A narrow ramp where the player launches the ball using a spring or rubber band mechanism.	Applied force and Newton's Second Law ($F = ma$)	Explain how applied force affects acceleration and motion.	"What happens to the ball's motion when you increase the launching force?"
Flipper bat	Movable levers used to hit or redirect the ball during gameplay.	Action–reaction pair (Newton's Third Law)	Identify equal and opposite forces acting during motion.	"When the flipper strikes the ball, what forces act on the ball and the bat?"
Force-label checkpoints	Marked areas labeled with key physics terms (e.g., friction, gravity, normal force).	Types of forces	Recognize different types of forces acting on a moving object.	"Describe the forces acting on the ball when it moves through a rough surface."
Hole (target zone)	Openings where the ball can fall through at specific points.	Gravitational force and potential energy	Relate gravitational pull and energy conversion during free fall.	"Why does the ball accelerate as it falls into the hole?"
Ball launch area	Starting position where the ball is initially placed before being shot into motion.	Inertia and initial force application	Understand the concept of inertia and initiation of motion.	"What happens to the ball if no force is applied at the launcher?"
Ball-shooter mechanism (rubber band/spring)	Mechanism that propels the ball forward through elastic potential energy.	Elastic force and energy conversion	Explain how stored potential energy converts into kinetic energy.	"How does stretching the rubber band affect the ball's motion?"
Out hole (end zone)	Area where the ball exits the playfield.	Energy dissipation and frictional force	Describe how friction and resistance gradually reduce motion.	"Why does the ball stop moving after reaching the out hole?"
Question bank cards	Illustrated cards depicting real-life examples of motion and forces.	Application of force in daily life	Apply physics concepts to everyday phenomena.	"Relate the parachute landing image to the concept of air resistance."

Table 2. Instructional design of the PhyFizball GBL tool based on constructivist learning principles

Component	Corresponding features in PhyFizball
Student-centered engagement	Students manipulate the game components, such as the ball launcher, flippers, and checkpoints, to explore the concepts of force and motion through direct experience. The activity promotes active involvement rather than passive observation and encourages collaboration and discussion within small groups.
Exploration and discovery	The game environment allows students to observe the effects of different forces, including gravity, friction, and contact forces. By adjusting the ball's movement and interpreting the outcomes, students test their predictions and discover the relationships between force, motion, and energy. Each labeled checkpoint serves as a learning station for hands-on exploration.
Collaboration and social interaction	Students work in teams to discuss the guiding questions, justify their observations, and reach a shared understanding of physics concepts. This cooperative learning experience encourages social interaction and collective problem solving consistent with constructivist learning principles.
Reflection and concept reinforcement	After the game session, students participate in reflection activities led by the teacher. They discuss the causes of specific phenomena, relate their observations to Newton's laws, and answer follow-up questions that strengthen conceptual understanding and correct misconceptions.
Teacher as facilitator	The teacher serves as a facilitator who guides inquiry by posing questions, providing feedback, and scaffolding students' reasoning during and after gameplay. This approach supports learner autonomy while ensuring an accurate understanding of scientific concepts.

2.5. Classroom implementation

The intervention was carried out over four weeks. Each session began with a brief conceptual review to activate prior knowledge. Students in the experimental group then engaged in approximately 20 minutes of gameplay using PhyFizball, discussing concepts collaboratively and responding to guiding questions. The session concluded with a structured reflection facilitated by the teacher to consolidate learning and address misconceptions. The control group followed an equivalent schedule but received traditional lecture-based instruction. Figure 2 shows students interacting with PhyFizball while exploring the concept of force and motion.

2.6. Evaluation metrics

Students' conceptual understanding was measured using a validated conceptual understanding test consisting of 20 items: 15 multiple-choice questions and 5 structured open-ended questions. The items were adapted from established physics concept inventories and aligned with the national curriculum. Content validity was confirmed through expert review by three physics educators, and a pilot test produced a high reliability index (Cronbach's alpha =0.87). Data collection consisted of three phases: pre-test, instructional

intervention, and post-test. Both the experimental and control groups completed identical pre-tests and post-tests. Statistical analyses included paired-samples t-tests to determine within-group improvement and independent-samples t-tests to compare outcomes between groups. The following hypotheses were tested:
HO1: There is no significant difference in pre-test scores between the experimental and control groups.
HO2: There is no significant difference between pre-test and post-test scores in the experimental group.
HO3: There is no significant difference between pre-test and post-test scores in the control group.
HO4: There is no significant difference in post-test scores between the experimental and control groups.
All procedures adhered to ethical research standards. Participation was voluntary, and informed consent was obtained from all students and their guardians prior to data collection.

Figure 2. Student interaction with PhyFizball during force concept exploration

3. RESULTS AND DISCUSSION

3.1. Pre-test score comparison between group

Data analysis in Table 3 using an independent samples t-test showed no significant difference between the pre-test scores of the treatment group (M =57.33, SD =16.15) and the control group (M =60.93, SD =10.73), with *t*(28) =0.719, *p* =0.478. This result indicates that both groups had similar levels of understanding before the intervention, which validates the equivalence of the groups at the start of the study. An independent samples t-test was conducted to compare the pre-test scores between the treatment group (PhyFizball) and the control group (conventional method). The mean pre-test score for the treatment group was M =57.33 (SD =16.15), while the control group had a mean score of M =60.93 (SD =10.73). The difference was not statistically significant, *t*(28) =0.719, *p* =0.478, indicating that both groups were comparable in their initial understanding of force and motion.

Table 3. Pre-test mean scores for PhyFizball and control group

Group	N	Mean	SD	t-value	Significance
PhyFizball	15	57.33	16.15	0.719	0.478
Control	15	60.93	10.73		

3.2. Learning gains in the experimental group

A paired samples t-test revealed a significant improvement in the treatment group's understanding after using the PhyFizball game, as shown in Table 4. The mean score increased from M =54.73 (SD =13.51) in the pre-test to M =77.40 (SD =18.28) in the post-test, with *t*(14) =3.575, *p* =0.003. This significant change demonstrates that the PhyFizball tool positively influenced student performance in the topic of force and motion. To determine the effect of the PhyFizball teaching tool, a paired samples t-test was conducted within the treatment group. The pre-test score was M =54.73 (SD =13.51), and the post-test score was M =77.40 (SD =18.28). The result was statistically significant, *t*(14) =3.575, *p* =0.003, suggesting that the use of PhyFizball significantly improved students' conceptual understanding of force and motion.

Table 4. PhyFizball group's mean score for pre-test and post-test

PhyFizball	N	Mean	SD	t-value	Significance
Pre-test	15	54.73	13.51	3.575	0.003
Post-test	15	77.40	18.28		

3.3. Learning gains in the control group

A paired samples t-test was conducted to examine the difference in performance between the pre- and post-test scores within the control group. The control group showed no significant improvement from pre-test to post-test, as shown in Table 5. The pre-test mean score was M =60.93 (SD =10.73), while the post-test mean score declined slightly to M =57.27 (SD =15.17), with *t*(14) =1.482, *p*=0.160. This result suggests that conventional instruction did not effectively enhance students' conceptual understanding and may have led to reduced performance, indicating that the conventional teaching method did not produce a measurable improvement in students' understanding of force and motion.

Table 5. Control group’s mean score for pre-test and post-test

Control	N	Mean	SD	t-value	Significance
Pre-test	15	60.93	10.73	1.482	0.160
Post-test	15	57.27	15.17		

3.4. Post-test score comparison between group

An independent samples t-test was conducted to compare the post-test performance of the PhyFizball and the control group, as shown in Table 6. The experimental group, which utilized the PhyFizball game-based teaching tool, achieved significantly higher scores (M =77.40, SD =18.28) than the control group (M =57.27, SD =15.17), with *t*(28) =3.282, *p* =0.003. These findings indicate that the GBL approach significantly improved students’ understanding of force and motion concepts compared to traditional instructional methods.

Table 6. Post-test mean score for PhyFizball and control groups

Groups	N	Mean	SD	t-value	Significance
PhyFizball	15	77.40	18.28	3.282	0.003
Control	15	57.27	15.17		

The purpose of this study was to evaluate the effectiveness of PhyFizball in enhancing students’ conceptual understanding of force and motion. The findings clearly indicate that the experimental group, which engaged with PhyFizball, demonstrated significantly greater improvements in post-test scores than the control group taught using traditional methods. This outcome provides strong support for the study’s hypotheses (HO2 rejected and HO4 rejected), confirming that kinesthetic, GBL can improve conceptual understanding more effectively than lecture-based instruction. By contrast, the lack of substantial improvement in the control group suggests that conventional methods may be less effective in addressing misconceptions related to force and motion (supporting HO3). The pre-test analysis showed no significant differences between groups (supporting HO1), strengthening the validity of these comparative findings.

The improved performance of the experimental group aligns with global research demonstrating that GBL promotes meaningful engagement and supports conceptual reasoning. Students reported that PhyFizball made abstract concepts more concrete and intuitive, echoing findings from [27], [28], who noted that interactive games strengthen understanding through immediate feedback and active exploration. The students’ positive perceptions of motivation, enjoyment, and engagement mirror broader evidence that GBL increases interest in science learning and supports deeper cognitive processing. It is important to note that the pre-test analysis in this study confirmed no statistically significant differences between the experimental and control groups before the intervention. This ensured a valid basis for comparison. The substantial improvement in the experimental group, compared to the limited progress in the control group, highlights the limitations of conventional teaching methods. Traditional instruction, which often relies on textbooks and teacher-led lectures, may not effectively sustain student interest or convey abstract scientific concepts. In contrast, PhyFizball enabled students to engage with the force and motion concept through hands-on and visually rich experiences, providing opportunities for meaningful and contextualized learning. These findings are further supported by previous studies, including those conducted [29]–[31], which reported enhanced academic performance among students exposed to GBL environments. Moreover, the results of this study align with broader literature demonstrating the positive impact of GBL on science education. The authors in [32], [33] report that serious games enhance content mastery, feedback, engagement, and challenge. Wang and Lieberoth [34] found that scoring and audio cues increase motivation and classroom participation, while Kiron and Vassileva [35] demonstrated that peer-based game mechanics strengthen cognitive engagement and cooperation. Ahmed *et al.* [36] similarly noted high levels of student and teacher satisfaction with GBL strategies. Szklanny *et al.* [37] further emphasized the accessibility and educational value of game-based applications in physics instruction.

Designed based on principles of GBL and constructivist pedagogy, PhyFizball provides a kinesthetic, collaborative, and student-centered learning environment. Constructivist approaches have consistently shown strong potential in supporting students' understanding of abstract concepts. For example, Abdikadyr *et al.* [38] found that constructivist methods significantly improved comprehension of mechanics, while Jemberie [39] noted that teachers perceive these methods as aligned with curriculum expectations. Kinesthetic learning also plays an important role in conceptual development. Motion-based systems such as Kinect-based physics platforms [40] have been shown to improve both motivation and conceptual precision, and more recent studies [35], [36] highlight the value of tactile, low-cost educational games in fostering active learning, collaboration, and exploration. Complementary findings from [41], [42] show that multi-representation games and low-cost science, technology, engineering, and mathematics (STEM) tools enhance cognitive performance and overcome limitations in laboratory resources. Together, this body of literature situates PhyFizball within an evidence-based tradition of constructivist and kinesthetic instructional tools.

The hands-on, embodied learning experience provided by PhyFizball appears to be a key mechanism for these improvements. The physical movement of the ball along different pathways allowed students to directly observe principles such as applied force, inertia, friction, and action–reaction. This interactive process aligns with constructivist theory, which posits that students learn best when they actively construct meaning through exploration and reflection. The tool's embedded questioning strategies further promoted conceptual refinement by prompting students to explain the scientific principles underlying each observation. These features helped students confront their misconceptions, leading to more accurate conceptual frameworks. In addition to conceptual gains, the game fostered collaborative learning and the development of soft skills such as communication, teamwork, and shared problem-solving. These outcomes are consistent with the goals of Malaysia's DSKP curriculum, which emphasizes inquiry, communication, and competency-based learning. The alignment between PhyFizball and these curricular priorities strengthens the instructional relevance of the tool and suggests that it can support both cognitive and social dimensions of science learning.

The study's results are also notable in the context of educational equity. Many rural and underfunded schools in Malaysia face limited access to digital learning tools due to infrastructural constraints. The low-cost, non-digital nature of PhyFizball offers a practical alternative for such settings. Constructed from inexpensive and locally available materials, the tool can be replicated easily without reliance on electricity or internet connectivity. This accessibility allows students in resource-limited schools to benefit from interactive learning experiences that are typically available only in better-equipped environments. Moreover, with minimal adjustments to layout or question prompts, the same framework can be adapted to other physics topics such as momentum, energy transformation, or pressure, thereby extending its educational lifespan and supporting interdisciplinary integration across STEM subjects. Sustained adoption also depends on teacher support. Short workshops or peer-sharing sessions can introduce teachers to the tool's construction, gameplay, and facilitation strategies. Such professional development opportunities can strengthen teacher confidence, encourage innovation, and create collaborative spaces for adapting PhyFizball to diverse classroom needs. With administrative support and community involvement, the tool has the potential to evolve from a single-classroom innovation into a scalable, teacher-driven instructional model.

Despite these strengths, several limitations must be acknowledged. First, the small sample size and single-school implementation limit generalizability. Second, the four-week duration may not capture long-term retention or the durability of conceptual change. Third, affective outcomes such as attitudes toward physics, motivation, and enjoyment were not formally assessed, although student comments suggest positive experiences. Future research should therefore consider larger and more diverse samples, longer intervention periods, and the inclusion of qualitative data (such as interviews or classroom observations) to enrich understanding of how and why GBL influences conceptual development. The findings also highlight the importance of teacher preparation and ongoing support.

4. CONCLUSION

This study examined the effectiveness of PhyFizball, a low-cost and kinesthetic GBL tool, in improving Form Two students' understanding of force and motion. The findings demonstrated that students who engaged with PhyFizball achieved significantly higher conceptual gains than those taught through conventional lecture-based instruction. By transforming abstract physics principles into interactive and tangible experiences, PhyFizball helped correct misconceptions, strengthen reasoning skills, and promote active engagement. These outcomes highlight the tool's capacity to enhance learning through hands-on exploration, discussion, and collaborative problem solving. A key strength of PhyFizball lies in its affordability, portability, and practical relevance. Constructed from inexpensive and widely accessible materials, the tool is suitable for diverse classroom contexts, including rural and underfunded schools with limited digital infrastructure. Its design not only supports physics instruction but can also be adapted to teach other topics such as energy, momentum, and pressure, demonstrating strong potential for scalability and curriculum-wide application. Teacher-led orientation sessions or short professional development workshops can further facilitate implementation by equipping educators with strategies for constructing the tool, managing gameplay, and integrating reflective discussions. Beyond content mastery, PhyFizball aligns with broader educational goals such as competency-based education and inclusive learning. Its emphasis on teamwork, communication, and reflective reasoning supports the development of essential 21st-century skills. By offering a non-digital, interactive alternative to conventional instruction, PhyFizball provides equitable access to meaningful learning experiences and contributes to sustainable, inclusive STEM education, particularly in settings where technology-based tools are not feasible.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis

I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
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Vi : **Vi**sualization
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P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been compiled with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [SS], upon reasonable request.

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