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Effect of problem-based learning on students' problem-solving ability to learn physics

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Abstract

A learner's success is supported by the ability to understand real-world problems. This study aimed to examine the effect of problem-based learning on problem-solving ability in the teaching and learning of physics. The study was guided by socio-constructivism theory. A quasi-experiment was conducted with 829 Senior-2 Physics students (age 13–15) from eight (8) selected lower secondary schools in Sheema District, Uganda. Schools were assigned to treatment and control groups using a purposive random sampling technique. Students' problem-solving ability was measured by conducting a problem-solving ability test in each group before and after studying a chapter on simple machines in physics. Repeated measures analysis of variances was applied for data analysis. The study's findings showed a significant improvement in students' problem-solving ability with simple machines in the treatment group compared to the control group ($p < .001$).

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Therefore, educators are encouraged to embrace learner-centred methods that enhance students' problem-solving abilities to help them compete in the world of work.

Keywords: problem-based learning, problem-solving ability, simple machine, Ugandan secondary school

Supplementary material for this article is available online

1. Introduction

Employers need well-equipped individuals with 21st-century skills to handle difficult workplace situations and complex business challenges. Various organizations demand those who can assess the situations and calmly identify solutions. The Ministry of Education and Sports, through the National Curriculum Development Centre in Uganda, reviewed lower secondary curricula to provide opportunities, interactions, tasks, and instructions that bring a learner to the centre of the learning experience. Through developing social, physical, and leadership skills, learners can cultivate personal problem-solving abilities, enhance their information-gathering and interpretation skills, foster independent reading and writing, and engage in self-improvement. Moreover, these skills equip learners to pursue further education in physics and apply their problem-solving capabilities to address community challenges. Consequently, these skills play a vital role in promoting lifelong learning for students, aligning with the objectives of secondary education in Uganda as outlined in the Government's white paper on education (1992) and the Education Sector Strategic Plans, (2009–2017, 2018–2020), which delineate strategies for enhancing the quality and relevance of secondary education.

Understanding physics concepts empowers learners to grasp the inner workings of the world and the reasons behind various phenomena. Physics instruction is structured around chapters and topics emphasizing practical applications and hands-on experiences for each concept, emphasizing real-world relevance and problem-solving skills. It is worth noting that many students find physics a challenging subject [1] despite its status as a mandatory component of the lower secondary school curriculum. Physics education builds upon the foundational concepts and skills developed during primary school and is a robust platform for future studies in science-related disciplines.

In the 21st century, as science and technology continue to advance and shape our lives, physics assumes a pivotal role in education [2]. Consequently, educators must create learning environments that foster the acquisition of scientific and technical skills, catering to all learners' diverse needs and interests.

1.1. Conceptual framework

The present study is guided by social constructivist theory [3]. According to the theory, the child develops individually and socially. The theory plays a fundamental role in the process of cognitive development. The theory works on two principles: the more knowledgeable than the other (MKO) principle and the proximal zonal development (ZPD) principle. MKO refers to anyone with a better understanding or a higher ability level than the learner concerning a particular activity or concept. It is normally considered a teacher, facilitator, peer, or younger person. Problem-based learning (PBL) with related techniques such as group work think pair share, and others take care of all learners: the greatest achievers, moderate and low achievers, and very low achievers. The ZPD is defined as the distance between the actual developmental level determined by independent problem-solving and the level of potential development determined through problem-solving ability under adult guidance of collaboration with more capable peers [3]. Effective teaching involves teachers and students actively participating in the learning process. The teacher's role in facilitating learning can be observed through two key methods (reciprocal and collaboration). Reciprocal teaching: This approach entails interactive dialogues between the teacher and a small group of students. The teacher employs group work techniques during physics class activities to actively engage learners. Subsequently, students take turns acting as the teacher or presenter of their findings. Students gradually develop a deeper understanding of the subject matter through the consistent use of this technique. Peer collaboration: Peer collaboration leverages the benefits of shared social interactions as students collaborate on classroom activities. This collaborative learning approach enhances students' opportunities to interact with their peers and collectively contribute to the learning process.

PBL, a student-centred approach involving collaborative learning in which students work together to solve open-ended problems, can serve as a vehicle to this active learning process. Ali (2019) suggested that the core principles of PBL include learner independence and self-direction, group-based learning, and the teacher serving as a facilitator, with all groups participating equally. PBL has been widely adopted in various educational fields, including medical schools, business, and engineering, as professionals from these disciplines play pivotal roles in serving our communities [4]. The stages of PBL implementation in the classroom includes:

Stage 1 (Finding a Problem): In this stage, the teacher presents a task to the learners, such as investigating why the efficiency of a machine is always less than 100%.

Stage 2 (Organizing Ideas on the Problem): Learners explore the problem and gather ideas about machine efficiency from various sources. The facilitator encourages critical thinking by posing probing questions.

Stage 3 (Group Work): The teacher organizes learners into groups, typically 5–10 or 15–20 students. Each group collaboratively investigates why machine efficiency is less than 100%. Roles, including group leader, timekeeper, scribe, and peacemaker, are assigned to ensure effective teamwork.

Stage 4 (Presenting Findings): Learners present their solutions to the problem (e.g., the reasons for machine efficiency) and receive feedback from peers. The teacher consolidates the learning outcomes and allows self-assessment by students.

Stage 5 (Generalizing): Problem-solving skills developed during PBL are essential for tackling complex, real-world challenges that lack a single correct answer. These skills include problem-solving, creativity (e.g., applying grease and oil to reduce machine friction), communication, cooperation, and innovation. These skills empower learners to become lifelong problem solvers adaptable to the ever-changing demands of the 21st century.

As highlighted by Shakhman and Barak (2019), problem-solving is a fundamental skill in science, engineering, and technology. Exposure to high-level thinking problems during PBL cultivates students into effective problem solvers [5]. Consequently, educators should continually assess students, considering their problem-solving abilities. In the context of physics education, many teachers utilize the Physics Problem-Solving Test (PPST) to design exercises and exams that gauge students' physics achievement [6]. The PPST draws upon revised Bloom's taxonomy, encompassing the cognitive domain (retrieval, comprehension, analysis, and knowledge utilization) and the knowledge domain (declarative and procedural knowledge). Levels of difficulty within PPST questions include:

Retrieval Level: students answer questions similar to those they have encountered frequently. They identify the problem, recall a relevant solution from memory, adapt the idea, and apply it to solve a similar problem.

Diagnosis Level: students handle questions that closely resemble familiar ones but may involve certain variations in presentation. This level is typically encountered in take-home assignments and exercises or as part of a test.

Conceptual Level: learners are required to apply one or more physics concepts related to simple machines to answer questions. For example, they might need to describe applications of simple machines. A strong understanding of concepts is essential to succeed at this level.

Creative-Thinking Level: some problems demand new solutions, as students have never encountered them. This level challenges students to apply knowledge from one topic to innovatively address novel problems.

In this regard, this research aimed to investigate the impact of PBL on students' problem-solving abilities in Ugandan schools, focusing on simple machines in physics. McKenna and Agogino [7] designed a simple machine-learning environment to support reflection, collaboration, and presentation of concepts from multiple perspectives. Simple machines, such as levers, pulleys, ramps, and inclined planes, represent a unique category of physical phenomena often encountered by children during their play with objects [8]. These simple machines are crucial in altering the direction or amplifying the force applied, making various tasks more manageable. They serve as the fundamental building blocks for the creation of more complex objects that we encounter in our daily lives. In this context, the utilization of a simple machine serves the purpose of simplifying work rather than reducing the applied force [9]. For instance, a door, functioning as a lever or a doorknob, which utilizes the principle of a wheel and axle, are examples of everyday objects rooted in these basic mechanical concepts. Simple machines illustrate fundamental physics concepts like force, work, distance, and energy. Remarkably, children participating in this study were naturally familiar with these mechanical principles, seamlessly incorporating them into their play activities [8].

1.2. The rationale of the study

Previous research has shown that PBL enhances students' capacity to solve physics-related problems; however, studies on simple machines, in particular, are limited [7–11]. The current study fills the knowledge gap on PBL and students' problem-solving abilities. Therefore, this study answers the research questions:

- To what extent does PBL enhance students' problem-solving ability in learning simple machine content?
- Is there any significant improvement in problem-solving ability after implementing PBL for the treatment group?

This study focused on improving students' problem-solving ability after implementing a PBL method of instruction during lesson content delivery on simple machines. Therefore, it is hypothesized that there is no significant improvement in problem-solving ability skills after implementing the PBL instruction. The present study contributes to the existing literature on the effect of PBL on students' problem-solving ability with simple machines in Physics.

2. Methodology

2.1. Research design

The study followed ethical guidelines to ensure the protection and welfare of participants. Ethical clearance was obtained from the research and Innovation Directorate at the University of Rwanda-College of Education, the Research Ethics Committee at Mbarara University of Science and Technology, and the Uganda National Council of Science and Technology. In addition, Permission to access the schools was sought from the Ministry of Education and Sports, Office of the Permanent Secretary (PS), who accorded necessary support for the study. This was done following established protocols for research involving subjects. Ethical consideration ensured that the study design, data collection, and participant interactions were consistent with ethical standards. Informed consent procedures were followed. The quasi-experimental research design was employed to investigate the effect of PBL on the problem-solving ability of students studying simple machines in Sheema District, Western Uganda.

Purposive sampling was used to select 829 students from the Eight (8) schools. The selected schools were grouped into a treatment group and a control group. The treatment group (taught with PBL) had 482 students, while the control group (taught in traditional mode) had 347 students. The Treatment groups included 126 students from School A, 101 students from School B, 170 students from School C, and 85 students from School D. The Control group included 88 students from School E, 120 students from School F, 54 students from School G, and 85 students from School H. These schools were located in different town councils at extreme ends of the district and shared similar characteristics suitable for the study. The schools were assigned to the treatment group and control group, respectively. The treatment group was taught using PBL, and the control group was taught using a content-based method. The groups were composed of S.2 students (age range 13–15) who were admitted to the schools.

A pretest-posttest non-equivalent quasi-experimental design was applied. Both groups were pre-tested to establish baseline scores for students' problem-solving abilities. Teachers who taught the treatment group were trained by Lecturers from National Teachers' Colleges (NTCs) on how to use PBL to teach students while the control group was not trained. In addition, teachers in the treatment group were given support supervision by hired NTC lecturers. The lecturers are experts on learner-centred methods like PBL. This was done to ensure the correct use of PBL during the delivery of lessons on simple machines, a physics chapter. The group-work technique was employed alongside PBL. A group consisted of 5–10 learners in every PBL class in the treatment group. Learners shared roles willingly. This promoted discipline in almost all the learners. Each group selected a group leader, secretary, and timekeeper. During the activity, the group discussed tasks on simple machines. An agreement on the possible solutions for the problem was reached. One of the group members presented their work and received feedback from other groups with the teachers help as a facilitator. During the experiment, simple machines were covered as part of the regular curriculum. Students in both groups were exposed to the same content for length. A double lesson took 80 min, and a single lesson took 40 min. After three weeks of teaching and learning, a post-test was administered to the students using the codding system to the treatment and control groups under similar conditions. Classical test theory was used to present item difficulty and discrimination index.

2.2. Data collection tool: physics problem-solving ability test

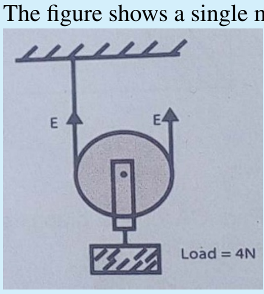
The test aimed to assess students' problem-solving abilities following the completion of the topic on simple machines through the implementation of PBL. This 25 min test comprised ten questions drawn from the practice exercises related to simple machines in physics textbooks designed for senior two or form two secondary learners. The National Curriculum Development Centre and the Ministry of Education and Sports in Uganda approved these textbooks. The test encompassed various topics from the lower secondary curriculum physics syllabus, including concepts and applications of simple machines, mechanical advantage, velocity ratio, and efficiency of machines, levers, pulleys, inclined planes, wheels and axles, gears, and other relevant areas. The test was designed to evaluate students' understanding of a wide range of concepts related to simple machines, as outlined in the Uganda Physics curriculum for Senior-2 students (refer to table 1 for specific content details).

The questions range from a combination of understanding and problem-solving (1, 3, 4a, 4b, 5, 6, 8, 9, 10), primarily problem-solving (7 and 9 sub-questions), primarily understanding (2), and primarily memorization (2). This diverse set of questions encourages students to grasp the fundamental principles of simple machines and apply their knowledge to practical scenarios, fostering a deeper understanding and problem-solving skills in mechanics. A pilot study was conducted with 90 students to evaluate the face validity and reliability of the tool. Two researchers at the University of Rwanda College of Education validated the test items with a background in physics and education. We initially had 20 questions, but evaluators rated ten, similar to what we included in the final administration. Pearson product-moment correlation coefficient of $r = 0.68$ was obtained.

2.3. Teaching intervention and data collection procedures

Permission to access the schools was sought from the Ministry of Education and Sports, Office of the PS, who wrote to the Chief Administrative officer (CAO) with Copies to the District Education officer (DEO) and Resident district commissioner to provide the necessary support for the study. With permission from the CAO, the DEO wrote to school heads and alerted them about the research study. The school heads responded positively and

Table 1. Physics problem-solving ability test: duration: 25 min.

#	Question	Marks
1	Describe how the efficiency of machines can be improved	1
2	Describe one application of simple machines	1
3	Explain what is meant by a first-class lever	1
4	What is meant by each of the following terms as applied to simple machines:	
	a Mechanical advantage	1
	b Efficiency	1
5	Why is the efficiency of any practical machine always less than 100%?	1
6	What is meant by a simple machine's energy input and energy output?	2
7	Illustrate, using a suitable diagram, how a velocity ratio of 4 can be obtained with a system of pulleys.	3
8	''No machine is perfectly efficient,'' Is it true or false? Give a reason to support your answer.	2
9	The figure shows a single movable pulley 	
	a A single movable pulley is used to lift a load (L) of 4 N. Calculate: The effort (E) needed to raise it, hence, find the Mechanical advantage (MA) of the pulley.	3
	b Using a lever, an effort (E) of 50 N moves a load (L) of 200 N through 3 m. If the effort moves a distance of 16 m, Calculate: Mechanical advantage (MA).	3
	c Using a lever, an effort (E) of 50 N moves a load (L) of 200 N through 3 m. If the effort moves a distance of 16 m, Calculate: Efficiency (η) of the machine.	3
10	A box with 800 N is hoisted above a table by Jane, who applies 100 N of force. What is the Mechanical Advantage of the Pulley System?	3

even sent their physics teachers who teach form two to attend a three-day training on how to use PBL. Some days, after the training of the treatment group, there was a briefing of students, physics teachers, school administrators, and the control group at their respective schools on what the intervention would look like.

Before classes began, researchers assisted in developing lesson plans to implement during the teaching of simple machines in physics in physics of S2 students. Two samples of lesson plans have been shared in supplementary material, one for the PBL class (appendix A) and another for the traditional class (appendix B).

After the familiarization process, the physics teachers, researcher, and research assistants administered the pre-test to treatment and control group students using a coding system. Students did not write their names on the scripts, as was highlighted during the briefing. The following week, normal teaching resumed in the treatment and control groups. The first author and research assistants monitored the teaching and learning in the control group, assisted by school administrators. This was done to ensure that the physics chapter about simple machines was being taught according to the syllabus.

Secondary teachers were trained on how to use PBL by Lecturers from NTCs. During the delivery of lessons, the Lecturers gave support supervision to the secondary school teachers to ensure the proper use of PBL. The group work technique was employed alongside PBL. The group was provided with a problem related to simple machines and allowed to discuss it. Each group selected a group leader, secretary, timekeeper, and peacemaker. During the activity, the group discussed tasks on simple machines. The discussion and agreement on the possible solutions for the problem. One of the group members presented their work and received feedback from other groups with the teacher's help as a facilitator. The Group work technique stimulated in-depth learners' knowledge and skills such as teamwork, interpersonal communication, and peer teaching [3]. During the control group learning, students learned normally, where a teacher presented a topic on the blackboard and explained it while students followed and asked questions. The teaching took three weeks, with three periods per week to cover the selected content, making nine periods for three weeks.

2.4. Data analysis

After administering the test, each question was marked on the specified scores above and entered in Microsoft Excel. Before and after the intervention, the overall score from the problem-solving test was considered, and each question was analysed. Students who attended only the pre-test but did not attend the post-test and vice versa were excluded because computing the changes in the score would yield results. Data from problem-solving tests were analysed using descriptive and inferential statistics using Microsoft and the Statistical Package for Social Sciences. The ten structured questions were marked, and marks were awarded according to the numbers. The maximum total score on the test is 25. The scores were scaled to 100% and graded using grading [12]. Based on the acceptable grading scale, the full grading scale is reflected in table 2.

A repeated measure analysis of variances was computed to measure the statistical significance from pre-test to post-test and between control and treatment groups. Tables and figures showing average mean scores were presented and discussed. Histograms and tables showing students' distribution in each grade level were presented to direct the reader further.

Table 2. Grading scale 2022.

80–100	D1	High achievers
75–79	D2	
70–74	C3	
65–69	Credit 3	Average achievers
60–64	Credit 4	
55–59	Credit 5	
45–54	Pass 7	Low achievers
35–44	Pass 8	
0−34	F9	Very low achievers

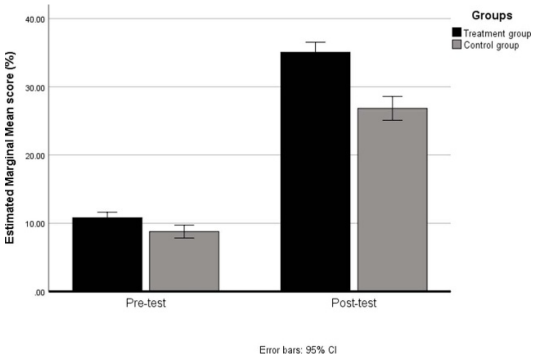


Figure 1. Average score for students in control and treatment groups before (pre-test) and after (post-test) studying simple machines.

3. Results

Descriptive results from the treatment and control groups' pre-test to post-test who learned with the traditional method got an 8.78% average score with an 8.04% standard deviation before intervention and a 26.84% average score with a 16.17% standard deviation after learning. Likewise, students who learned with the PBL approach got a 10.81% average score with a 9.65% standard deviation before intervention and a 35.07% average score with a 16.79% standard deviation after learning. The results showed that the average score increased after learning simple machines more in the treatment group; however, the standard deviation was the same in both groups. Thus, the scores were scattered similarly in the treatment and control groups. This means none of the methods was best for gathering students on average scores and avoiding outliers.

Figure 1 presents descriptive results in visual form. It informs that the shift in performance arises after studying despite the intervention

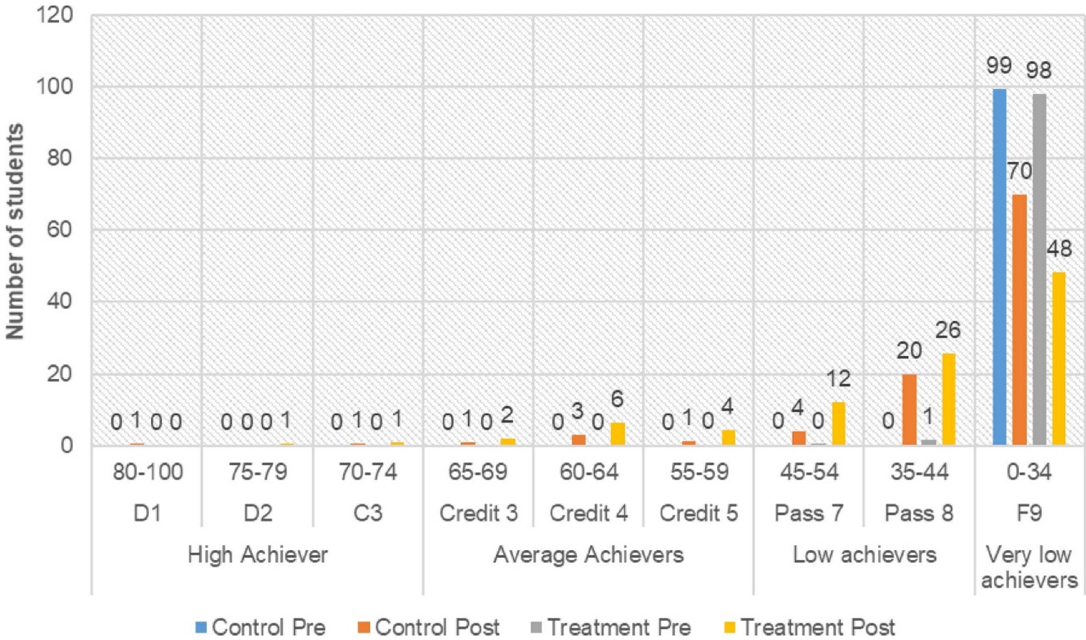


Figure 2. The figure shows the number of students in scores distribution, grades and achievement levels before and after studying simple machines. The treatment group experienced a significant decrease in the number of very low achievers as seen in figure 2 . As a result of the intervention, many students in the treatment group improved in academic performance leading to reduced very low achievers. Therefore, the positive outcome highlights the effectiveness of PBL in improving the academic achievements of students in our education sector.

provided. However, such a shift was still under 50% of performance. Thus, although students were taught with PBL or traditional methods, none of the groups reached 50% of the average score on the provided test despite it being administered twice (pre- and post-test).

Inferential results from the pre-test to the post-test and between treatment and control groups shows that there was a very high statistically significant difference ($F = 1043.44$, d$f = 1$, $p < .001$) between pre-and post-test scores, in favour of post-test with a large effect size (.558). Likewise, Tests of Within-Subjects Contrasts showed that a very high statistically significant difference ($F = 22.35$, d$f = 1$, $p < .001$) rose between the control group and treatment groups (considering pre-and post-test) in favour of students that learned with PBL (treatment group) though the effect size was small (.026).

A more robust analysis took place in score distribution across the grading to measure the shift of problem-solving ability of low and higher achievers. The physics problem-solving ability test provided was difficult even after learning the content of a simple machine to achieve high levels was problematic. For instance, many students still rise in 0–34 of very low achievers as seen in figure 2. However, a contribution of PBL alongside the traditional method was visualized. Few students learned with PBL compared to those who learned traditionally at this level of very low achievers. And their numbers continue rising at upper levels compared to the traditional method.

Tables 5 and 6 in supplementary material present item difficulty and the number of students that got a particular score on each item.

4. Discussion

The changes in the problem-solving ability in the treatment group were significantly found to be higher than those in the control group ($p < .001$). Therefore, the null hypothesis was rejected. Hence, there was an improvement in students' problem-solving ability after the implementation of PBL instruction (Treatment group) and the currently used approach of instruction (Control group) used by the physics teachers of form two (2) in lower secondary schools of Sheema District. This means problem-solving ability improved after implementing PBL. The results of this research resemble that of the study conducted by Sani (2017), which investigated the effect of PBL on students' problem-solving ability in physics, a case study on simple machines. The study found that students in both the treatment and control groups had similar knowledge levels before learning physics problem-solving. Post-learning, the treatment group showed greater changes in problem-solving ability, indicating that PBL improved students' ability. This was attributed to active group work, peer interaction, and social constructivism theory [13].

The current study findings agree with the results of another study, which revealed that students with a higher problem-solving ability also exhibited higher academic achievement than average [14]. However, our unique finding was that such academic achievement was classified into the achievement grade that is currently used in the Ugandan system. Despite the intervention's effort, the achievement was not classified into high levels. Thus, few students attained the low, average, or high achievers category. A study on the mathematics problem-solving approach concluded that PBL impacts learners' problem-solving ability [15] regarding understanding the problem, planning ways to approach the problem, monitoring the progress, and reviewing the solution process. Our study did not envisage such procedures, which may be why students did not get above-average scores (>50%). Students need to clearly understand the problem, be able to plan ways to approach that problem, be knowledgeable about monitoring the progress while tackling the problem, and possess the skills to review the solution process in order to check whether all conditions of the problem have been satisfied. Question-nine (q10) showed the figure with a single movable pulley (see figure 3) used to lift a load (L) of 4 N.

Few students (4% in the treatment and 1% in the control group) could get at least 3 out of 9 scores before learning the content of simple machines. Similarly, a few (2% in the treatment

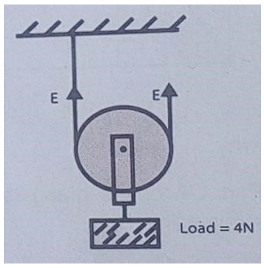


Figure 3. Single movable pulley-related question asked in q10.

and 4% in the control group) got 9 out of 9 scores on this question after studying. The lack of skills teachers might have caused this to train their students to solve problems systematically. Therefore, Ugandan teachers need to be trained in indicators (understanding the problem, planning the solution strategy, implementing the plan, and interpreting or checking the solution obtained [15]) of problem-solving approaches. Furthermore, students must be settled into useful and systematic tasks [16] and interactive activities [17]. Scientific problems can be solved only when engaging methods of instruction are employed during the teaching and learning of physics. The skills help learners integrate scientific knowledge into real-life experiences; therefore, they should be used in teaching and learning physics.

When students are subjected to high-level thinking problems, they become problem-solvers [5]. Therefore, teachers should always think of ways to assess learners by catering to their abilities concerning problem-solving ability. The students work out a complex relationship by deciding to find a solution, such as a graphical representation of a solution, dividing a subsystem into components, or comparing it with a borderline. For example, using a lever, an effort (E) of 50 N moves a load (L) of 200 N through 3 m. If the effort moves a distance of 16 m, the learner must identify that the effort moves a load through 16 m; the load moves 3 m because the learner decides on a series of stages to solve a problem.

5. Conclusions

There was a slight increase in students' problem-solving ability for the treatment group as compared to the control group after studying simple machines. Therefore, we recommend that the Ministry of Education and Sports, under the Directorate of Basic and Secondary Department, train teachers on using problem-based and learner-centred learning methods. This will help equip the learners with skills to solve real-life problems even after school. (b) Teachers need to empathize with active participation and promote students' problem-solving abilities. The study recruited lower secondary schools in the Sheema District. This was done due to financial constraints and time, so the study can be done with more students from other classes like Form Three and Form Four in the district, and even considering other districts in Uganda.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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