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The Development of Students' Critical Thinking Skills in Solving Torque and Rigid Body Equilibrium Problems Through STEM Learning Using Infusion-Based Collaborative Problem Solving

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A B S T R A C T

This study investigated how students use critical thinking skills in solving problems in Torque and rigid body equilibrium before and after using STEM learning Infusion based- Collaborative Problem Solving model. Embedded Design Experimental Model was used. The research instrument was eight essay questions in torque and equilibrium of rigid objects that had been validated. Quantitative data were obtained from the pretest and post-test score, pretest and post-test data were analyzed using N-gain to determine the improvement of students' critical thinking skills. Qualitative data was obtained from students' answers in the pretest and post-test. Data were analyzed descriptively to compare students' critical thinking skills before and after the intervention. The average critical thinking skills of students increased from 7.61 (pretest) to 38.84 (post-test) with an N-gain of 0.34, the improvement is categorized as moderate. The findings indicate that critical thinking skills can be cultivated through physics lessons using STEM learning with Infusion-Based Collaborative Problem Solving. Following the intervention, students demonstrated systematic critical thinking in answering questions.

1. Introduction

The advancement of technology in the 21st century provides a vast array of information sources that are available to anyone with internet access (Halpern, 2014; Paul & Elder, 2002). Consequently, the public requires critical thinking skills to effectively evaluate information, enabling them to become responsible consumers of information (Quines, 2017). Critical thinking is commonly seen as a personal trait and a crucial aspect of cognitive growth (Morris, 2017). This process entails evaluating statements and forming a profound comprehension of

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particular meanings and interpretations (Costa, 1991). Critical thinking refers to reasoning that is logical, purposeful, and focused on achieving specific objectives (Halpern, 2010). This type of thinking is assessed from multiple viewpoints, considering evidence, concepts, methods, criteria, and context, to deliver logical explanations and facilitate sound decision-making (Serrat, 2017), In the end, this increases the likelihood of attaining the expected results (Halpern, 2014). Thus, developing critical thinking skills is crucial to equip students to face the challenges of the 21st century (Putra, B. K. B., Prayitno, B. A., & Maridi, M, 2018; Goldman & Zielezinski, 2016; Mutakinati dkk., 2018; Quines, 2017; Semerci, 2011).

Critical thinking skills can be effectively cultivated through educational experiences (Reid, 2010). In physics education, the emphasis on developing critical thinking skills is becoming increasingly important (Wenno et al., 2022). Traditionally, the teaching of physics has emphasized the presentation of theoretical material and the application of mathematical equations, frequently overlooking the cultivation of higher-level cognitive abilities in students (Burkholder et al., 2021; Maries & Singh, 2023). However, research indicates that implementing a more holistic approach to physics education that highlights the significance of studying scientific practices and intellectual skills can substantially improve critical thinking skills (Wenning & Vieyra, 2020). One effort to develop critical thinking skills is to train these skills alongside the learning material (Tiruneh et al., 2018). Research indicates that embedding critical thinking skills within the educational content (Infusion) effectively improves students' critical thinking skills (Lin, 2018; Vardi, 2015).

Lin (2018) utilized the Infusion method in teaching English as a Foreign Language. Based on Lin's (2018) research findings, the Infusion approach increased the frequency with which students used critical thinking skills in writing. Aizikovitsh & Amit (2010) assessed the infusion method for teaching critical thinking skills in mathematics, employing the California Critical Thinking Disposition Inventory (CCTDI). The research findings indicate that the infusion approach is effective in enhancing students' critical thinking disposition and skills. In physics education, Tiruneh et al. (2016) designed a lesson on electricity and magnetism using the infusion approach for students enrolled in a Basic Physics course. The assessment of students' critical thinking skills was conducted through the CTEM (The Critical Thinking in Electricity and Magnetism Test). Based on the study by Tiruneh et al. (2016), students who engaged in instruction with the infusion approach attained better critical thinking skill scores in electricity compared to students in the control class. Afroz (2024) Continuing Professional Development is provided institutionally, teachers will get the opportunity to develop professionally, and students will also be benefited through it.

Besides employing the infusion approach, critical thinking skills can be cultivated through STEM learning (Siekmann & National Centre for Vocational Education Research (Australia) (NCVER), 2016). In their study, Mutakinati et al. (2018) developed students' critical thinking skills through STEM education using a Project-Based Learning approach for first-year junior high school students in

Japan. it was found that post-instruction, students on average fell into the Average Thinker category, indicating that they had sufficient skills to critically evaluate plans in a systematic manner and develop realistic critiques. Language is an important tool to express and communicate with the others (Sari, 2023).

In this study, the authors combined STEM education with the infusion approach to train students' critical thinking skills on the topics of Torque and Equilibrium of Rigid Bodies. Torque and Equilibrium of Rigid Bodies were selected due to their inclusion of Science, Engineering, and Mathematics aspects, while Technology is utilized as an information source. Furthermore, this material presents learning assignments within real-world contexts, and the principles discussed are vital in civil engineering, architecture, and mechanical engineering (Serway & Jewett, 2004). The instructional model employed to ease the implementation of STEM and Infusion is Collaborative Problem Solving. This article will explore how students' critical thinking skills in addressing issues related to Torque and Equilibrium of Rigid Bodies were evaluated prior to and following the intervention.

2. Methodology

The objective of this study is to investigate how students apply critical thinking skills in solving questions on Torque and Equilibrium of Rigid Bodies prior to and following the application of STEM education with an Infusion-based Collaborative Problem Solving approach. The study took place at the UM Laboratory High School in the 11th grade, involving 31 students over the course of six meetings, each lasting between 60 and 80 minutes. The research design utilized an Embedded Design Experimental Model that combines qualitative and quantitative research methods (Creswell & Plano Clark, 2011). The research design is illustrated in Figure 1. The design is detailed based on the framework proposed by Creswell and Plano Clark (2007).

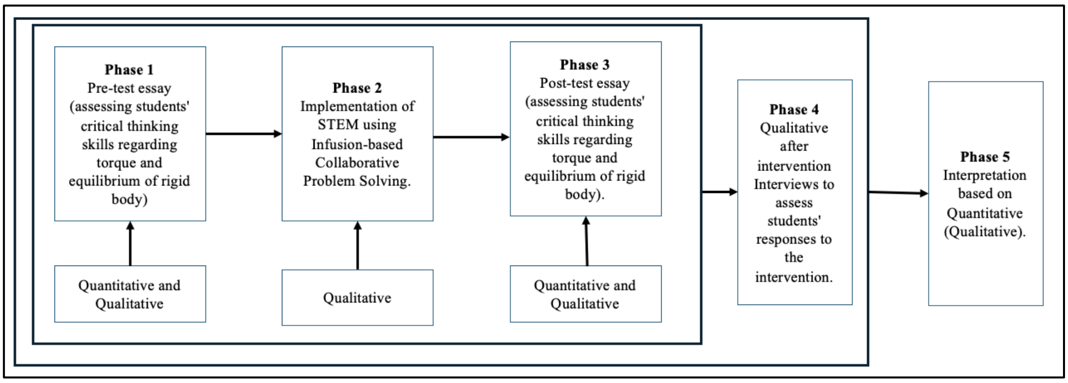


Figure 1. Outline of the Research Design Implemented

The data regarding students' critical thinking skills in responding to questions on Torque and Equilibrium of Rigid Bodies were collected by administering critical thinking exercises related to these subjects. A total of 8 test items were developed based on the sub-indicators proposed by Tiruneh et al. (2017) for the topics of Electricity and Magnetism. The critical thinking questions were validated by two specialists, modified according to their recommendations, and subsequently tested empirically. The eight test items are valid and reliable. The reliability category of the test items is high, with a Cronbach's Alpha value of 0.743, making them suitable for assessing students' critical thinking skills in solving questions on Torque and Equilibrium of Rigid Bodies. Data analysis was conducted using descriptive methods. The collected data are qualitative, consisting of students' open-ended answers to the test questions. The students' answers are subsequently categorized by their pattern similarities and transformed into quantitative scores. The improvement in critical thinking skills is analyzed using the following N-gain formula.

$$(g) = \frac{s_f - s_i}{100 - s_i}$$

S_{prt} represents the average critical thinking skill score on the pretest, and S_{pst} represents the average score on the post-test. The interpretation is based on the criteria provided in Table 1.

Table 1. N-gain Classification Criteria

Range	**Criteria**
$(g) \geq 0{,}7$	High
$0{,}3 \leq (g) \leq 0{,}7$	Medium
$g < 0{,}3$	Low

(Source: Hake, 1998)

The qualitative analysis to determine students' challenges in solving critical thinking questions related to torque and rigid body equilibrium is carried out by grouping their pretest and post-test responses and analyzing them based on how they apply critical thinking skills in solving the torque and rigid body equilibrium problems. The mean score is converted to a 4-point scale and grouped according to the students' critical thinking skills categories, as shown in Table 2.

Table 2. Classification of Categories and Criteria for Critical Thinking

Categories	**Criteria**
$3{,}51 - 4{,}0$	*Master Thinker*
$3{,}11 - 3{,}50$	*Advance Thinker*
$2{,}41 - 3{,}10$	*Practicing Tninker*
$1{,}71 - 2{,}40$	*Beginning Thinker*
$1{,}01 - 1{,}70$	*Challenged Thinker*
$0 - 1{,}0$	*Unreflective Thinker*

(Source**:** Paul and Elder (2009) in Mutakinati, Anwari, & Kumano, 2018)

3. Results and Discussion

During the lessons, students learn about topics such as torque, rigid body equilibrium, centre of gravity, and forces in structures, which they then implement in a project to build a balanced tower crane. During the learning process, the teacher informs students about the critical thinking skills that will be used during their studies. The project is designed to involve all four components of STEM—Science, Technology, Engineering, and Mathematics—and requires active collaboration within groups. During the learning process, students are divided into 8 heterogeneous groups to encourage collaboration and discussion among them. The purpose of this activity is to offer practical experience in engineering design and to enhance their critical thinking abilities. The tower crane project is conducted over two sessions, with a completion period of 10 days between the two sessions. Throughout this time, students are urged to utilize the knowledge they have learned in designing and constructing prototypes. The learning process includes an analysis of student work, which allows students to assess and improve their skills in a practical and collaborative environment.

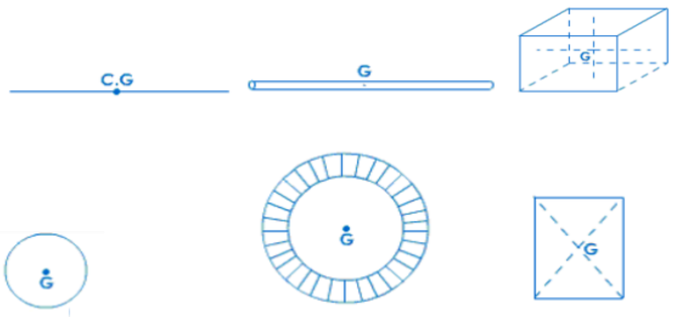
Collaborative Problem Solving activities in STEM learning create a dynamic and interactive classroom atmosphere. Students are engaged in the task of designing and building a tower crane prototype using ice cream sticks, where they apply physics concepts, particularly torque and rigid body equilibrium. This activity engages students because they believe they can directly apply what they have learned to a tangible project. The classroom atmosphere is filled with discussions among students in groups, although their collaboration remains limited to exchanging basic information and simple ideas.

Some students faced difficulties with algebra operations, especially when asked to calculate torque and apply equilibrium conditions. However, with guidance from the teacher, they ultimately succeeded in completing the calculations needed to ensure that the crane they built was strong and stable. The teacher actively encouraged students to use various sources of information, but students were more inclined to ask the teacher directly for answers.

While collaboration between students is not entirely optimal, the classroom environment reflects a high level of enthusiasm, with students actively participating in project-based learning (learning by doing). They appear to be exchanging ideas and opinions, although in some instances, discussions are still led by the teacher. This learning approach allows students to enhance their critical thinking and problem-solving skills in real-world contexts, although it takes longer compared to traditional teaching methods.

Based on the results of the descriptive analysis of students' critical thinking skills before (pretest) and after (post-test) the intervention, it was found that the average score of students' critical thinking skills in the post-test (38.84) was higher than their critical thinking skills in the pretest (7.61). The improvement in students' critical thinking skills using STEM learning through Infusion Collaborative Problem Solving is categorized as moderate, with an N-gain value of 0.34. An example of a test item for critical thinking skills on the topic of Torque and Rigid Body Equilibrium is shown in Figure 2.

Berikut ditampilkan beberapa benda dengan bentuk berbeda. Titik berat benda ditunjukkan oleh tanda G.



Berdasarkan beberapa Gambar yang telah ditampilkan, dapatkah kamu menyimpulkan bahwa "letak titik berat selalu berada pada bagian tengah"? jelaskan

Figure 2. Sample Question Item for Critical Thinking Skills

The question item in Figure 2 assesses the sub-skill of critical thinking in Argument Analysis: understanding that more information is needed to draw conclusions and deducing the correct statement from a provided data set. In addition, the sub-skill of critical thinking in Hypothesis Testing involves examining the adequacy of sample size and the potential for bias when generalizing. The question item displays a collection of data in the form of pictures of symmetrical objects, along with a conclusion statement derived from the images provided. Students are expected to understand that to draw conclusions, images of symmetric objects alone are inadequate and do not represent a sample of asymmetric and non-homogeneous objects. The changes in students' responses before and after the intervention are presented in Table 3.

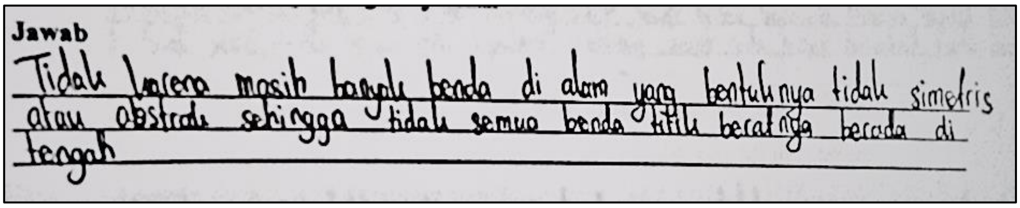
Table 3. Pretest and Post-test Answer Comparison.

Answer	*Pretest*	*Post-test*
• Cannot determine; the image above only shows the centre of gravity for symmetric objects, and the provided image does not represent asymmetric objects. For asymmetric objects, the centre of gravity is not always in the centre of the object. (fully correct)	0%	51%
• Cannot determine; if the object undergoes changes, the centre of gravity will not be in the centre. (Partially correct)	0%	17%
• Cannot determine, because the centre of gravity is the pivot point, and the image contains one object whose centre of gravity can rotate around one end or the midpoint. (Partially correct)	0%	6%
• Can determine, because in the image, all centres of gravity are at the centre or all objects are symmetric. (Incorrect)	3%	14%
• Applicable to all symmetric or asymmetric objects. (Incorrect)	0%	3%
• Can determine, because the centre of gravity is the point of equilibrium. (Incorrect)	36%	3%
• Can determine, because the centre of gravity is the centroid of the object, or the centre of gravity divides the object into two symmetrical parts with equal weight. (Incorrect)	16%	0%

Answer	*Pretest*	*Post-test*
● Does not state whether it can or cannot. For symmetric objects, the centre of gravity can be found by locating the intersection of the diagonal lines of the angles. (Incorrect)	0%	3%
● Can determine, because the centre of gravity is always in the centre. (Incorrect)	13%	0%
● Can determine, for other reasons. (Incorrect)	16%	0%
● Explaining the concept of the centre of gravity.	0%	3%
● No answer	6%	0%
Total	100%	100%

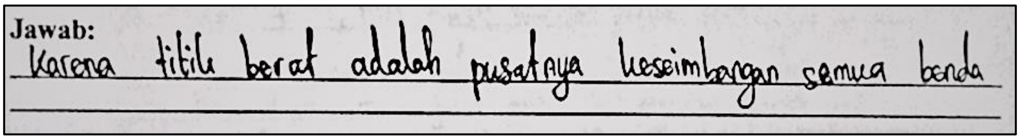
The improvement in students' critical thinking skills in answering test items is moderate, with an N-gain of 0.7. Table 3 shows that prior to the intervention, there were no students who indicated that it could not be concluded from the image that all centres of gravity of the objects are in the middle. This is because students have not yet realized that the information is insufficient, and the image does not represent the sample of objects found in nature (assuming all students understand that not all objects shaped symmetrically are represented in the question image). After the intervention, 51% of students recognized that there are both symmetric and asymmetric objects, and that the objects presented in the question image cannot represent asymmetric objects in decision-making. The difficulty students faced in answering the question was due to their assumption that the centre of gravity is the same as the point of equilibrium, thus it would always be in the centre. A comparison of students' pretest and post-test responses can be seen in Figure 3 as an example.

Pretest


Jawab

Tidak karena masih banyak benda di alam yang bentuknya tidak simetris atau abstrak sehingga tidak semua benda titik beratnya berada di tengah

Post-test


Jawab:

Karena titik berat adalah pusatnya keseimbangan semua benda

Figure 3. Comparison of Student Answers Before and After the Intervention.

From Figure 3, the differences in student responses in the pretest and post-test are evident. In the pretest, students did not express agreement or disagreement and argued that the centre of gravity is the equilibrium point for all objects. following the intervention, students recognized that the images in the questions were all symmetric, which prompted them to understand that many objects in nature are not symmetric or are abstract. As a result, they could assert that not all centres of gravity are situated in the middle. The proportion of improvement in students' critical thinking skills when responding to sample questions is illustrated in Figure 4.

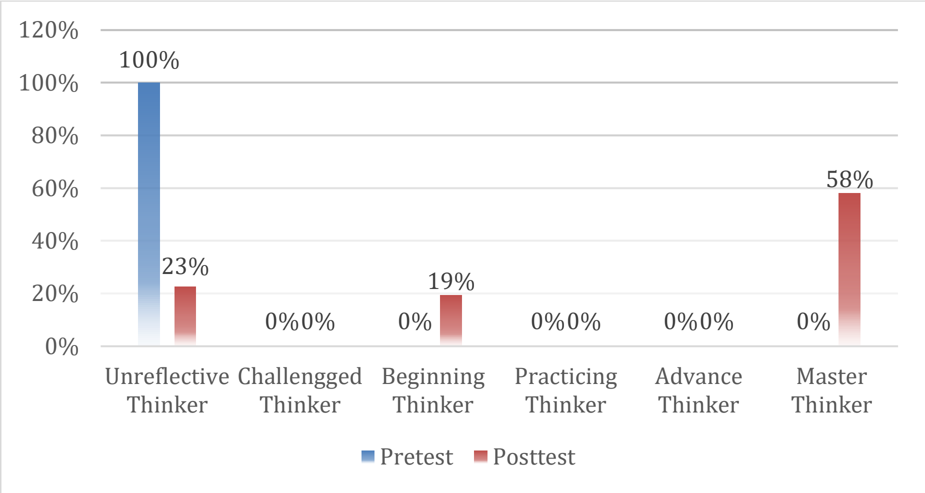


Figure 4. Classification of Critical Thinking Skills in Students.

Before the intervention, all students (100%) were categorized as Unreflective Thinkers when responding to the sample questions. Following the intervention, only 23% of students were still classified as Unreflective Thinkers, 19% had moved up to the Beginning Thinker category, and 58% had become Master Thinkers in applying critical thinking skills (as aimed for in the questions) to answer the items.

The results of the study indicate that students' critical thinking skills after engaging in STEM learning through Infusion-Based Collaborative Problem Solving were higher than their critical thinking skills prior to the learning experience. The increase in students' critical thinking skills with STEM learning using Infusion-Based Collaborative Problem Solving is categorized as a moderate improvement. This indicates that critical thinking skills can be developed by integrating them into physics education (Reid, 2010; Tiruneh et al., 2018; 2018). Nevertheless, to cultivate critical thinking skills, commitment is essential because the development of these skills does not happen spontaneously or subconsciously; it must stem from the students' own efforts (Paul & Elder, 2014). STEM education that implements Infusion-Based Collaborative Problem Solving can be used to train students' critical thinking skills. This can be achieved by fostering students' awareness of the importance of critical thinking and providing them with opportunities to apply those skills in the learning process, which can lead to an increase in their critical thinking abilities (Tiruneh et al., 2018; Krishna Rao, 2005). Critical thinking skills need to be ingrained in students, so that they become proficient in using thinking strategies to complete their tasks in an acceptable and rational manner (Tiruneh et al., 2016).

4. Conclusion

Infusion-Based Collaborative Problem Solving in STEM education can be used to help students apply critical thinking skills in problem-solving (specifically in this research on Torque and Equilibrium of Rigid Bodies), as indicated by the improvement in the average scores of students' critical thinking skills, which are categorized as moderate. The comparison of student responses also reveals a shift in their thinking patterns in addressing problems before and after the intervention. After the intervention, some students were able to answer systematically, understanding that reaching conclusions necessitates additional information and accurately deducing statements from the provided data, while also assessing the sample size to ensure that their generalizations are not biased.

There are several limitations in this study, one of which is the number of research groups involved. This research solely employed a single group to illustrate the influence of STEM education through infusion-based collaborative problem solving. It is suggested that future studies incorporate a control group to provide a comparative analysis of the intervention's effects on students' critical thinking abilities.

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