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Research Article

Reducing gender gaps in physics achievement: The role of constructivist methods

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ABSTRACT

This study investigates the impact of constructivist teaching methods on achievement and misconceptions in mechanics, with a focus on gender differences. The research involved 88 first-year physics students enrolled in the physics teacher training program. Using a quasi-experimental design, students were divided into experimental (constructivist teaching) and control (traditional teaching) groups, with each group completing a pre- and post-test to assess changes in understanding and misconceptions around key mechanics concepts, particularly the concept of force. Results reveal that the constructivist intervention significantly improved achievement scores, especially for female students, thus reducing the gender gap in physics achievement. However, persistent misconceptions were observed in specific, abstract topics, such as motion in frictionless environments and rocket propulsion, which were less effectively addressed by the constructivist approach alone. These findings contribute to the literature on gender-sensitive instructional strategies and points out that constructivist approaches can be further optimized to support conceptual understanding in complex scientific domains.

Keywords: constructivist teaching, physics education, misconceptions in physics, physics achievement

INTRODUCTION

This study explores the effectiveness of constructivist teaching methods in improving achievement and addressing misconceptions in physics, with a particular focus on gender differences in student outcomes. Constructivist teaching, grounded in the theories of Piaget (1970) and Vygotsky (1978), emphasizes active learning where students build prior knowledge through exploration, collaboration, and inquiry-based activities. This approach contrasts with traditional, lecture-based instruction and aims to foster a deeper, more meaningful understanding of scientific concepts by encouraging students to actively construct their knowledge (Fosnot, 2005). Constructivist strategies have been shown to promote engagement and comprehension in STEM subjects by creating learning environments where students can connect new information with their existing cognitive frameworks (Driver et al., 1994). Given the historical underrepresentation of women in physics and other STEM fields, constructivist methods hold particular promise for promoting inclusive education by addressing barriers to female students' engagement and success in science (Lorenzo et al., 2006; Rose, 2018).

The importance of this study lies in its potential to contribute to educational practices that close gender gaps and improve physics learning outcomes. Despite efforts to address gender disparities, research indicates that male students often outperform female students in physics, which may be partially attributed to differences in engagement and self-efficacy developed early in educational trajectories (Dubrovskiy et al., 2022; Sadler & Sonnert, 2016). Misconceptions in physics, such as misunderstandings about motion or force, further complicate these challenges, as they are often deeply rooted in students' intuitive experiences and can hinder effective learning if not adequately addressed (Hestenes et al., 1992; McDermott, 1991). By examining how constructivist teaching methods impact achievement and misconceptions across gender, this study seeks to identify strategies that could foster a more equitable and effective physics learning environment. Understanding the role of constructivist methods in reducing misconceptions and promoting achievement is essential for designing instructional practices that serve to diverse learning needs in STEM fields (Baviskar et al., 2009; Zacharia & Olympiou, 2011).

We hypothesize that constructivist methods, with their focus on active learning and student engagement, will help reduce misconceptions in physics and improve achievement, particularly among female students.

Although constructivist teaching methods, rooted in theories by Piaget (1970) and Vygotsky (1978), have been well-established in educational practices globally, their implementation is relatively recent in post-Soviet countries like Kazakhstan. Traditionally, Kazakhstani education, influenced by Soviet pedagogical approaches, emphasized teacher-centered methods and rote learning (Mehisto et al., 2014). With education reforms and increased emphasis on interactive, inquiry-based learning, constructivist methods are now being incorporated in classrooms to encourage students' critical thinking and problem-solving skills (Baviskar et al., 2009).

LITERATURE REVIEW

The purpose of this literature review is to analyze the existing research on constructivist teaching methods, assessment tools such as the force concept inventory (FCI) and three-tier tests, gender differences in science education, and common misconceptions in mechanics within the context of physics education. This literature review aims at exploring how constructivist approaches are applied in physics education, synthesizing current knowledge about its application, and filling the gap by focusing both on local and international contexts. According to Watkins and Mazur (2013), students are facing challenges in applying physics problems in real life situations, in other words, students are experiencing difficulty in transferring theory into practice. In a similar vein, Folashade and Akinbobola (2009) revealed that students find it difficult to study physics, as it is reflected in their poor academic achievement.

Constructivism in Education

Constructivist teaching methods are based on the idea that learning takes place through interaction, reflection, engagement, and experience. The literature review demonstrates that two major theories of learning by Piaget (1970) and Vygotsky (1978) are the central ideas of the constructivist teaching methods. Aina (2017) differentiates two descriptions of constructivism as social and cognitive ones. Social constructivism based on Vygotsky's (1978) theory requires social environment, interaction with peers, and teachers to construct knowledge. According to social constructivism, learning is situation-specific and context-bound (Aina, 2017). On the other hand, cognitive constructivism, based on Piaget's (1970) theory, sees learning as an individual process when students construct their knowledge by connecting the new information to their past knowledge and prior experience. In a similar vein, Weil-Barais (2001) highlights a teaching approach based on Piaget (1970) theory, which emphasizes student-centered learning, practical activities, and inquiry-based experiments, to move away from traditional didactic teaching methods.

The literature review revealed numerous articles that focus on constructivist teaching methods in science education. To begin with, Baviskar et al.'s (2009) provide a critical review of empirical studies that focus on this topic and offer criteria for conceptualizing constructivist teaching methods. Baviskar et al. (2009) reviewed five different empirical studies that claimed to apply a constructivist approach in teaching science at different educational levels. Baviskar et al. (2009) came up with a conceptual framework consisting of four criteria that include: activating prior knowledge, creating cognitive dissonance, application of new knowledge and reflection on learning that can be applied to measure constructivist teaching methods. For instance, Baviskar et al. (2009) analyzed studies of Huffman et al. (2003), Bostock (1998), Klionsky (1998), Burrowes (2003), and Banet and Ayuso (2003) to demonstrate their application of constructivist teaching methods. According to Baviskar et al. (2009), the empirical studies conducted by Huffman et al. (2003), Bostock (1998), and Klionsky (1998) did not meet the criteria of constructivist teaching method because participants in Huffman et al.'s (2003) study lacked cognitive dissonances, application of new knowledge, and reflection stages. Bostock's (1998) study also failed to meet the criteria of constructivist teaching methods because the teacher did not elicit students' prior knowledge nor created dissonance in learning as students lost their interest in learning as was reported by the scholar (Baviskar et al., 2009). Another study conducted by Klionsky (1998) also did not meet the criteria provided by Baviskar et al. (2009), even though the research participants reported improvements in science learning and comprehension. According to Baviskar et al. (2009), Klionsky's (1998) study deviated from constructivism as it did not focus on eliciting students' prior knowledge, did not provide any evidence for cognitive dissonance, and no examples for reflection were made. Overall, Baviskar et al. (2009) claim that constructivist teaching methods should focus on these four stages in order to promote inquiry-based, student-centered, and interactive learning in constructing knowledge.

Regarding constructivist teaching methods, studies conducted by Burrowes (2003) and Banet and Ayuso (2003) exemplify the implementation of this teaching approach. An experimental study conducted by Burrowes (2003) applied the constructivist learning model by Yager (1991), the '5E' model by Bybee (1993), and cooperative learning by Lord (1994) to the experimental group, whereas the traditional group studied only using note-taking and lecturing formats. The results of the study showed improved students' academic performance, the development of higher order thinking skills, and a positive change in students' attitudes toward science learning. In a similar vein, an experimental study conducted by Banet and Ayuso (2003) implemented the constructivist teaching method in a biology class. The implementation of this method started with identifying students' prior knowledge and their misconceptions through surveys and pre-tests. Furthermore, the cognitive dissonance was created through applying problem-solving tasks to students' misconceptions. Overall, the results of the post-test were significantly better compared to pre-tests.

Constructivism in Physics Education

A number of studies investigated the application of constructivist teaching methods in physics education in relation to students' academic achievement (Adak, 2017; Rose, 2018; Ukozor, 2011) and students' beliefs about teaching strategies (Chang, 2002). For instance, Rose (2018) explored the impact of constructivist teaching methods on secondary school students' academic achievement in physics and the impact of school location, rural and urban, on students' academic performance. The study applied an experimental approach with 118 participants. It was revealed that students in the experimental group who studied through the constructivist teaching method had a higher mean score than those who were in the control group. Furthermore, the results indicate that urban school students performed better than their rural counterparts (Rose, 2018). Similarly, Adak (2017) found a positive relationship between students' academic achievement and teachers' application of the constructivist approach. The students who were exposed to constructivism had significantly higher achievements compared to students who studied through a traditional approach. According to Adak (2017), constructivist teaching methods promote content knowledge through applying higher-order thinking tasks. In terms of self-efficacy, Ukozor (2016) identified that implementation of the constructivist teaching method in teaching physics had significantly greater impact on students' self-efficacy compared to the traditional method of teaching as lecturing. Although the literature analysis demonstrated a positive connection between constructivist teaching methods with students' higher academic achievement, Chang (2002) proposes modifications to the constructivist teaching program. Chang (2002) identified that research participants in traditional group and constructivist teaching programs preferred superficial learning strategies to achieve good grades.

Measuring Tools in Physics Education

FCI is a multiple-choice test tool designed to measure students' comprehension and understanding of basic and fundamental concepts in Newtonian physics developed by Hestenes et al. (1992). It aims at identifying students' common misconceptions regarding basic physics principles. According to Hestenes et al. (1992), many physics students have common sense beliefs about physics concepts which are inconsistent with Newton's laws. Furthermore, traditional teaching methods such as memorization and superficial problem-solving without proper understanding of the underlying laws lead to misconception and challenging issues in physics education. Therefore, FCI is used to explore students' understanding of Newtonian laws and effectiveness of different teaching methods in physics (Hestenes et al., 1992). Moreover, Stoen et al. (2020) claim that FCI can be employed as a summative assessment tool for students' understanding, comprehension and conceptualization of introductory physics. Overall, FCI can be employed as a diagnostic tool to adjust teaching methods to target the areas students struggle with most.

The literature review revealed widespread use of FCI as a measuring tool of students' comprehension of physics concepts (Docktor & Heller, 2008; Nieminen et al., 2010; Savinainen & Viiri, 2008; Stoen et al., 2020). Moreover, the literature analysis uncovered the comparison of traditional methods with interactive teaching methods where FCI was used to measure the students' understanding of physics concepts (Hake, 1998; Savinainen & Scott, 2002). The quantitative research conducted by Hake (1998), that involved 6,542 students across different educational organizations, compared the effectiveness of traditional teaching with interactive engagement (IE) teaching methods in physics education. Hake (1998) employed FCI to measure students' understanding of physics conceptualization and concluded that students who are taught using IE methods demonstrated significantly higher learning results compared to those who were taught through traditional instruction. The study emphasized that IE methods, which involve active student participation and conceptual problem-solving, are more effective at improving students' mastery of physics concepts than passive lecturing format. In a similar vein, another study conducted by Savinainen and Scott (2002) concluded that employing interactive methods that promote communication among students and teachers help the development of students' conceptual development of physics concepts, and FCI is a tool that facilitates in providing summative assessment of students' understanding.

Another collection of assessment tools known as the three-tier test, was designed to evaluate students' conceptual understanding of Newton's laws (Kaltakci-Gurel et al., 2017). Kaltakci and Didis (2007) outline a three-tier questioning framework: in the first tier, students are interrogated about concepts; in the second tier, they must elucidate their rationale for the first-tier responses; and in the third tier, they are tasked with assessing their confidence level regarding the answers provided in the first and second tiers. The purpose of this three-tier test is to identify students' misconceptions, knowledge and errors. The literature analysis uncovered a number of studies that examine the use of three-tier tests in physics education to measure students' conceptual understanding of physics concepts.

For instance, a recent mixed method study conducted by Japashov et al. (2024) employed FCI and three-tier tests to measure students conceptual understanding of mechanics. The study revealed gender gap and discovered common physics misconceptions of Kazakhstani students. Having a deep understanding of physics concepts is crucial and a significant phase of physics learning. The ability to understand physics thoroughly builds the skills necessary for solving complex physics problems later in further courses. In the same vein, Pramesti et al. (2021) did a mixed method study to investigate the students' level of understanding geometric optics using three-tier tests. It was revealed that some students had misconceptions of geometric optics. The rationale for conducting the three-tier test was to assess students' learning so the teacher is aware of students' strength and weaknesses regarding the topic and take effective actions in learning process. Following a similar approach, the studies conducted by Caleon and Subramaniam (2010) and Kirbulut and Geban (2014) employed three-tier tests to measure students understanding of waves and states of matter, respectively. For instance, Caleon and Subramaniam (2010) designed three-tier tests to measure students' understanding of waves by modifying wave diagnostic instruments. The research aims were to create three-tier tests to assess students' understanding of waves, strengthen previous research with a more sophisticated data analysis, and classify students' alternative conceptions on waves for further investigation. The study's results indicate that students exhibit significant overconfidence in their incorrect responses, suggesting that they possess robust alternative conceptions that educators must address. In terms of Kirbulut and Geban's (2014) study, the three-tier test was recognized as a useful instrument for assessing students' comprehension of physics concepts, identifying their misconceptions, and determining their knowledge gaps. The study results indicated that students misinterpreted the concept as condensation, suggesting a possible gap in its comprehension.

Physics Education in Kazakhstan

In Kazakhstan, physics education starts in the 7th grade in public schools as per the official educational program, whereas natural science is introduced from the 1st grade to serve as the foundation for the physics curriculum. In the frame of trilingual education, secondary schools should offer two of these subjects "informatics", "chemistry", "biology", "physics" in English depending on schools' choice from 2019–2020 (Road Map, 2015). However, the implementation of trilingual education tends to have better educational outcomes and financial support in privileged schools such as Daryn schools, Nazarbayev Intellectual School and Bilim-Innovation Lyceums (Irsaliev et al., 2017; Mehisto et al., 2014). Overall, the Ministry of Education has assigned the physics course books and physics curriculum. Each class has two physics lessons weekly, focusing on theoretical concepts and problem-solving, while laboratory practice occurs bi-monthly. In grade 10 and grade 11, schools may opt to specialize in either the humanities or the natural sciences. The initial group, engaged in the humanitarian area, often undergoes physics classes twice weekly, characterized by moderate difficulty. The second group, studying in the natural sciences, has physics three times a week, focusing on challenging problem-solving issues. To conclude, science education in Kazakhstan has started to gain popularity among students and development by the Ministry of Education.

In terms of recent studies, the literature review revealed a limited amount of research that investigated physics education provision within the local context. For instance, Daineko et al. (2020) and Mukhtarkyzy et al. (2022) investigated the usage of augmented reality (AR) and virtual reality (VR) for physics lessons. It was found that AR and VR tools serves as a profitable solution for laboratory works. The results of these studies show that the implementation of AR and VR tools improves students' attitudes towards physics education in general. Another set of studies regarding physics education concern the use of information and communication technology in physics education (Akimkhanova et al., 2020) and students' experimental research competences in physics (Kurbanbekova et a., 2016).

Misconceptions in Physics Education

According to Resbiantoro and Setiani (2022), misconceptions refer to the discrepancy between students' understanding in relation to scientific conceptions. It is interesting to note that the literature review revealed numerous articles discussing common misconceptions in physics education. Moreover, the literature review uncovered various factors that affect students' misconceptions in physics learning. To begin with, the impact of teaching approaches on students' learning was already mentioned earlier above. Traditional lecture-based teaching methods can hinder students' understanding and comprehension, whereas, constructivist teaching methods, active engagement and inquiry-based learning correct students' misunderstanding in physics education (Adak, 2017; Hammer, 1996; Rose, 2018; Ukozor, 2011). Secondly, an earlier study conducted by McDermott (1991) highlight the relationship of physics curriculum between students' misconceptions. McDermott (1991) argues for the modification of physics curriculum focusing more on how students learn rather than what students learn. Thirdly, the complexity of physics concepts tends to impact on students' comprehension, thus leading to misconceptions (Hestenes et al., 1992). Gafoor and Akhilesh (2008) discovered, using the concept attainment test in physics, that the domains of density, velocity, gravity, and sound had a greater prevalence of misunderstandings. Furthermore, Hestenes et al. (1992) claim that students established common sense beliefs on physics concepts, topics like force, energy, and motion, derived from their personal experience, which may contradict scientific conceptions. Such misunderstandings and students' prior experience may be some of the factors that affect students' misconceptions in physics learning.

Furthermore, gender differences might be another set of factors impacting students' misconceptions. Research suggests that male and female students approach physics problem solving differently. Furthermore, physics is typically perceived to be a male-dominated discipline, restricting female students' participation and distorting their preconceptions (Sadler & Sonnert, 2016). Gender differences in physics are extensively studied with male students generally surpassing female students in performance (Balta et al., 2023; Lorenzo et al., 2006). This performance disparity may be affected by cultural and environmental variables, including stereotypes, resource availability, pedagogical approaches and levels of confidence. Research by Lorenzo et al. (2006) shown that gender discrepancies may be mitigated by the application of IE techniques and constructivist teaching methods in physics education. The results of the research suggested that female students' conceptual understanding of physics topics increased dramatically in the experimental group. The experimental group was taught using IE methods including peer instruction, real-time feedback, and active learning strategies. Lorenzo et al. (2006) argue that the gender gap and misconceptions in physics may be addressed by enhancing pedagogical approaches which include student-centered, collaborative, and interactive teaching techniques. Overall, past research has demonstrated that constructivist teaching approaches can assist in closing the gender gap in physics education by improving performance and reducing misconceptions. Constructivist teaching approaches encourage active learning, collaboration, authentic problem solving, and engagement, resulting in a stronger conceptual grasp and a learning environment that addresses misconceptions.

School locations are believed to have an impact on students' experience in learning physics. Students in rural areas often face limited access to resources such as laboratory equipment and less exposure to extracurricular activities, and probably less qualified physics teachers may be some of the reasons for students' misconceptions (Cervetti et al., 2005). For instance, Gafoor and Akhilesh (2008) found that rural students had higher rates of misconceptions in topics such as velocity, mass, and sound compared to urban counterparts. It is remarkable to see that a number of meta-analyses investigated the misconceptions in physics education (Neidorf et al., 2020; Resbiantoro & Setiani, 2022). A number of measuring tools were utilized as interviews, open-ended questions, and multiple-tier tests. To conclude, these studies highlight the importance of teaching strategies for conceptual change. Overall, the literature review displayed various factors that affect students' misconceptions in physics education suggesting further research and examination to overcome those issues.

METHODS

Study Design

The study employed a quasi-experimental design to investigate the impact of constructivist teaching methods on students' achievement and the correction of misconceptions in the subject of mechanics. The research was conducted over the course of the 2023–2024 academic year at the department of physics, faculty of physics and mathematics, at South Kazakhstan Pedagogical University. Students were divided into experimental and control groups, with each group receiving different instructional approaches. The experimental groups were taught using constructivist teaching methods, designed to encourage deeper understanding and student engagement. These groups participated in interactive lectures and practical classes, where theoretical tasks related to key concepts in mechanics were assigned to foster problem-solving skills and to address conceptual misconceptions. In contrast, the control groups followed a more traditional lecture-based teaching method, where instruction was primarily teacher-centered with less emphasis on student interaction.

To measure the impact of the teaching methods, a pre-/post-test design was used. At the beginning of the experiment, all students took a pre-test to assess their initial understanding and identify misconceptions regarding the concept of force in mechanics. This provided a baseline for comparing the effectiveness of the different instructional approaches. After the instructional intervention, a post-test was administered to evaluate the changes in students' understanding and to identify any remaining misconceptions. The results from the pre- and post-test were analyzed both quantitatively and qualitatively to assess the effectiveness of the constructivist teaching method in improving students' achievement and addressing misconceptions.

Context and Participants

The research was conducted at South Kazakhstan Pedagogical University, named after Ozbekali Zhanibekov, which is situated in the center of Shymkent, Kazakhstan. This institution provides high-quality education with a strong focus on pedagogy, serving over 6,598 students with a teaching staff of 415 members. The university is comprised of six faculties, which include: faculty of natural sciences, faculty of philology, faculty of physics and mathematics, faculty of history and pedagogy, faculty of arts and education, faculty of physical education and sports. The university offers a diverse range of academic programs, including 33 undergraduate programs, 21 master's programs, and 12 doctoral programs. Admission to the institution can be achieved through paid contracts or government scholarships.

The experiment was conducted within the department of physics at the faculty of physics and mathematics, focusing on first-year undergraduate students enrolled in the physics teacher training and physics-informatics teacher training programs. These students, aged between 17 and 18, had recently graduated from secondary schools in the Turkestan region of southern Kazakhstan. The study targeted students who will eventually become physics teachers after completing their degree programs.

The research focused on the course "mechanics", which is taught in the first semester, followed by "laboratory practice in mechanics" in the second semester. Both courses are offered in the Kazakh language, with two lectures and two practical lessons each week for the mechanics course, and two laboratory lessons each week for the laboratory practice course. Throughout their education, the students also study various other courses, such as molecular physics, electricity and magnetism, optics, quantum mechanics, and physics teaching methodology. Each theoretical course is followed by laboratory practice in the same subject during the next semester, enhancing the students' understanding of the material.

The participants in this study were 88 first-year undergraduate students from two distinct programs: the physics teacher training program and the physics-informatics teacher training program. These students were divided into experimental and control groups. The experimental groups consisted of 44 students, with 21 students from the physics teacher training program and 23 students from the physics-informatics teacher training program. Similarly, the control groups included a total of 44 students, with 22 students from the physics teacher training program and 22 students from the physics-informatics teacher training program. The experimental groups were taught using a constructive learning approach, while the control groups followed a traditional teaching method.

Implementation of Constructivist Method

The implementation of constructivist teaching methods in this study accounted for its inherently time-consuming nature. Lesson plans for the experimental group were adjusted to ensure sufficient time for interactive activities, discussions, and reflective exercises without compromising the overall content coverage. In contrast, the control group adhered to a traditional lecture-based format, where the same amount of content was delivered more concisely, focusing on teacher-led explanations. Both groups were taught by the same instructor, ensuring consistency in teaching delivery, expertise, and familiarity with the course material. The teacher received prior training to proficiently implement both the constructivist approach in the experimental group and the traditional method in the control group. While the constructivist method required additional time per topic to accommodate interactive learning, both groups were provided with equivalent overall instructional hours. To maintain fairness, the extra time allocated for constructivist activities in the experimental group was balanced by focused review sessions for the control group, ensuring that both groups received equal attention and resources.

The constructivist teaching intervention implemented in this study was structured around four key phases as outlined by Baviskar et al. (2009): activating prior knowledge, creating cognitive dissonance, applying new knowledge, and encouraging reflection. These phases were designed to promote active student engagement, enabling them to construct their understanding of physics concepts by interacting with and exploring content deeply.

Activating prior knowledge

The intervention began by encouraging students to draw on relevant prior experiences related to the physics concepts being studied. This phase involved discussions and concept mapping, allowing students to connect new topics with their pre-existing knowledge and frameworks. This step set the stage for deeper learning by helping students recognize the relevance of their background knowledge to the new material.

Creating cognitive dissonance

To challenge students' initial assumptions, the instructional activities included scenarios that introduced information contradicting their intuitive understandings. This cognitive dissonance prompted students to question their assumptions and engage actively with the content, fostering critical thinking. By facing conflicting ideas, students became motivated to seek clarity, a key principle of constructivist learning.

Application of new knowledge

After resolving cognitive conflicts, students were guided to apply their new understanding through hands-on activities, simulations, or problem-solving exercises. These applications were designed to reinforce theoretical knowledge by allowing students to observe or test principles in practical scenarios, bridging the gap between abstract concepts and real-world experiences. This active engagement supports the constructivist notion of learning as a process of constructing knowledge through meaningful interaction.

Reflection on learning

Finally, students reflected on their learning process, consolidating their insights and noting how their understanding had evolved. This reflection phase included group discussions, journaling, or individual assessments where students could articulate their revised understandings, address any remaining questions, and reinforce the cognitive gains achieved throughout the lesson.

An example of a constructivist teaching method is provided in **Appendix A**. **Appendix B** shows list of activities.

Data Analyses

The analyses conducted in this study involve a combination of descriptive statistics, independent samples t-tests, and analysis of variance (ANOVA). Descriptive statistics were used to summarize the key characteristics of the data, including the means and standard deviations for pre- and post-test achievement and misconception scores, broken down by gender. The Shapiro-Wilk test was performed to assess the normality of the data distributions. Independent samples t-tests were employed to compare the control and experimental groups across different test scores, determining whether there were any statistically significant differences between the groups in terms of pre- and post-test scores. This test was used for both achievement and misconception scores.

Additionally, ANOVA was utilized to explore the effects of group (control vs. experimental), gender, and the interaction between group and gender on post-test scores. This method allowed for the examination of not only the main effects of group and gender, but also whether the intervention had a different impact depending on the participants' gender. ANOVA was performed for both post-test achievement and post-test misconception scores to determine if there were significant differences or interactions influencing the outcomes. Finaly, a heat map was generated to visualize the misconceptions across 30 items of FCI.

RESULTS

The results section begins with descriptive statistics (**Table 1**). Pre-test scores are compared across groups to confirm baseline similarities. t-tests or ANOVA then examine post-test achievement and misconception scores, identifying any significant differences attributed to the intervention. Gender differences in scores are analyzed within each group, followed by two-way ANOVA to explore potential interaction effects between gender and group type. Lastly, a heatmap analysis details item-level changes in misconceptions, highlighting areas of improvement and persistent challenges, especially in complex topics.

Table 1. Descriptives statistics for achievement and misconception scores

	Gender	N	M	SD	Shapiro-Wilk	
					W	p
Pre-test achievement scores	Female	37	4.49	2.67	0.95	0.070
	Male	17	6.24	3.56	0.80	0.002
Pre-test misconception scores	Female	37	14.05	5.47	0.98	0.574
	Male	17	13.59	5.68	0.98	0.944
Post-test achievement scores	Female	37	7.73	3.01	0.95	0.099
	Male	17	10.18	4.97	0.90	0.057
Post-test misconception scores	Female	37	12.08	5.78	0.97	0.434
	Male	17	15.29	4.74	0.96	0.714

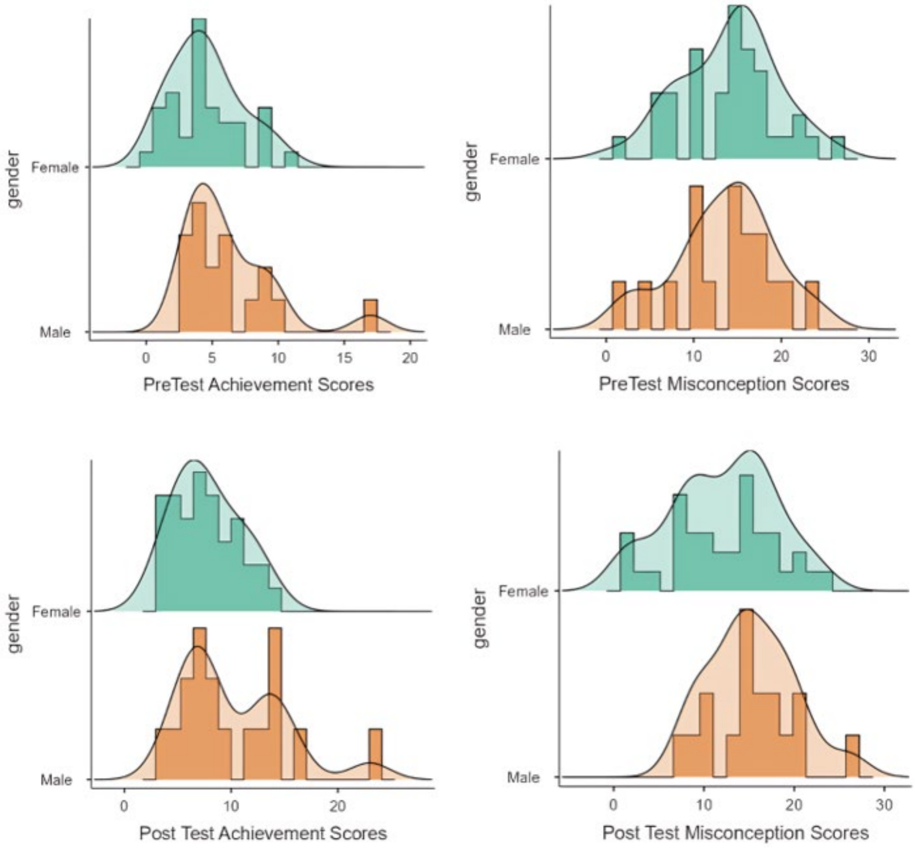


Figure 1. Plots for achievement and misconception scores (the authors' own work)

The descriptive statistics results show the comparison of pre- and post-test achievement and misconception scores between male and female participants. Female participants had lower average pre-test achievement scores (mean [M] = 4.49, standard deviation [SD] = 2.67) compared to males (M = 6.24, SD = 3.56), with males showing a significant deviation from normality (p = 0.002). For pre-test misconception scores, both genders had similar averages (females: M = 14.05, SD = 5.47; males: M = 13.59, SD = 5.68), with no significant normality issues.

Post-test achievement scores show an improvement in both groups, with males (M = 10.18, SD = 4.97) scoring higher than females (M = 7.73, SD = 3.01), and no significant deviations from normality for either group. Finally, post-test misconception scores slightly decreased for both groups, with males (M = 15.29, SD = 4.74) maintaining a higher mean than females (M = 12.08, SD = 5.78), while normality was not a concern for either (**Figure 1**).

Across all test scores (pre-test achievement, pre-test misconception, post-test achievement, and post-test misconception), none of the comparisons between the control and experimental groups show statistically significant differences. All p-values are above 0.05, indicating that there is no strong evidence to reject the null hypothesis (which suggests no difference between the groups) (**Table 2**).

Table 2. Independent samples t-test

	Statistic	df	p
Pre-test achievement scores	1.55	52.00	0.127
Pre-test misconception scores	–0.58	52.00	0.561
Post-test achievement scores	–0.64	52.00	0.528
Post-test misconception scores	–1.59	52.00	0.118

Table 3. ANOVA: Post-test achievement scores

	Sum of squares	df	Mean square	F	p
Group pre-test	3.15	1	3.15	0.24	0.628
gender	91.01	1	91.01	6.89	0.011
Group pre-test * gender	56.94	1	56.94	4.31	0.043
Residuals	660.77	50	13.22		

Table 4. ANOVA: Post-test misconception scores

	Sum of squares	df	Mean square	F	p
Group pre-test	49.49	1	49.49	1.64	0.206
Gender	92.48	1	92.48	3.07	0.086
Group pre-test * gender	0.19	1	0.19	0.01	0.938
Residuals	1,507.63	50	30.15		

The ANOVA results for post-test achievement scores show that there is no significant difference between the control and experimental groups based on pre-test scores alone (p = 0.628). However, gender has a significant effect on post-test achievement scores (p = 0.011), indicating that male and female participants differ significantly in their performance. Additionally, the interaction between group and gender is significant (p = 0.043), indicating that the effect of being in the control or experimental group depends on gender. This implies that both gender and the combined effect of group and gender contribute to the variation in post-test achievement scores, while the group effect alone is not enough to explain the differences (**Table 3**).

The ANOVA results for post-test misconception scores show that neither the group pre-test nor the interaction between group and gender has a statistically significant effect on the scores, with p-values of 0.206 and 0.938, respectively. Gender approaches significance with a p-value of 0.086, indicating a marginal, though not statistically significant, influence on misconception scores. This suggests that while there might be slight differences based on gender, neither group assignment nor the combined effect of group and gender significantly impacts post-test misconception scores. In other words, the factors tested do not have a strong influence on the outcome (**Table 4**).

Interaction Effect

The interaction between gender and group (control vs. experimental) in terms of achievement scores shows a significant impact of the intervention, particularly for females. In the control group, males outperformed females, with a mean score of 12.00 compared to 6.83 for females. However, in the experimental group, the gap narrowed, with females improving to a mean score of 8.58 while males scored 9.18. This crossing of lines in the achievement scores shows that the intervention had a more pronounced positive effect on females, helping to reduce the gender disparity observed in the control group. The improvement in female scores in the experimental group indicates that the intervention was successful in fostering better achievement outcomes for them, leveling the playing field between genders.

The interaction effect between gender and group for misconception scores, however, shows a different pattern. In both the control group and the experimental group, males consistently scored higher in misconceptions than females, indicating that they retained more misconceptions after the intervention. In the control group, males had a mean misconception score of 13.86, slightly higher than females' 11.06. In the experimental group, both genders saw an increase in misconception scores, with males scoring 15.50 and females scoring 13.05. This suggests that the intervention did not effectively reduce misconceptions for either gender and may have even slightly increased the gender gap in misconceptions, as the difference between males and females widened in the experimental group. In other words, the intervention was less effective at addressing misconceptions, particularly for males.

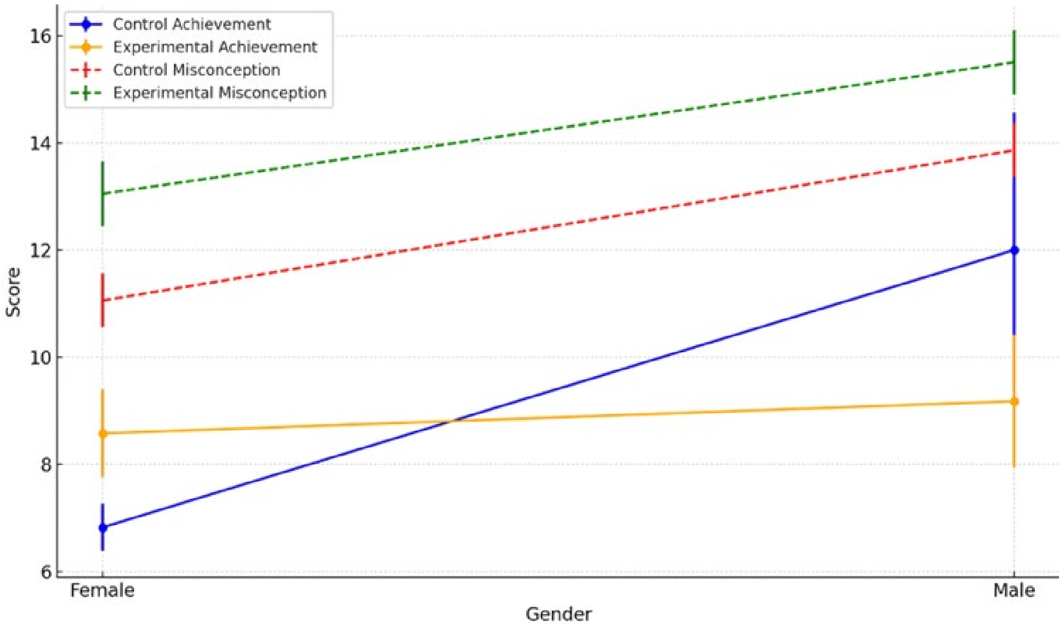
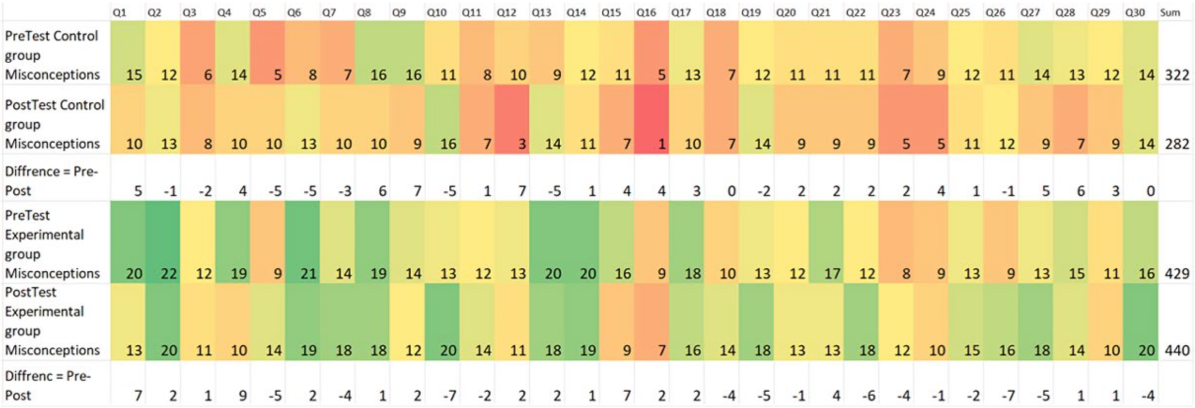


Figure 2. Interaction effect for group and gender (the authors' own work)



	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23	Q24	Q25	Q26	Q27	Q28	Q29	Q30	Sum
PreTest Control group Misconceptions	15	12	6	14	5	8	7	16	16	11	8	10	9	12	11	5	13	7	12	11	11	11	7	9	12	11	14	13	12	14	322
PostTest Control group Misconceptions	10	13	8	10	10	13	10	10	9	16	7	3	14	11	7	1	10	7	14	9	9	9	5	5	11	12	9	7	9	14	282
Diffrence = Pre-Post	5	-1	-2	4	-5	-5	-3	6	7	-5	1	7	-5	1	4	4	3	0	-2	2	2	2	2	4	1	-1	5	6	3	0	
PreTest Experimental group Misconceptions	20	22	12	19	9	21	14	19	14	13	12	13	20	20	16	9	18	10	13	12	17	12	8	9	13	9	13	15	11	16	429
PostTest Experimental group Misconceptions	13	20	11	10	14	19	18	18	12	20	14	11	18	19	9	7	16	14	18	13	13	18	12	10	15	16	18	14	10	20	440
Diffrenc = Pre-Post	7	2	1	9	-5	2	-4	1	2	-7	-2	2	2	1	7	2	2	-4	-5	-1	4	-6	-4	-1	-2	-7	-5	1	1	-4	

Figure 3. Heatmap for misconception scores (the authors' own work)

Figure 2 shows an interaction effect for achievement scores but no interaction effect for misconception scores. In the achievement scores, the control group shows a larger increase from females to males compared to the experimental group, where the scores are more stable across genders. For misconception scores, both groups show consistently higher misconception scores for males than females, indicating that while misconceptions are generally higher among males, this difference is consistent across both the control and experimental groups.

Comparison of Misconceptions at Item Level

The heatmap provides a visual comparison of pre-test and post-test misconceptions across 30 questions for both the control and experimental groups. It illustrates how misconceptions varied before and after the intervention, highlighting areas where misconceptions were reduced or persisted in each group. The color scale ranges from green to red, where green represents lower misconception scores, indicating fewer misconceptions, and red represents higher misconception scores, indicating more misconceptions for a given question.

In the heatmap (**Figure 3**), higher numbers indicate a greater number of misconceptions. For the control group, misconceptions generally decreased from pre- to post-test across most questions, with notable improvements in several key areas. For instance, in Q8, students showed a better understanding of how an object moves in a circular path, reducing misconceptions about the forces that keep an object in circular motion (centripetal force). In Q9, there was a significant reduction in misconceptions regarding how objects move at a constant velocity when no net force is acting on them. Similarly, in Q12, students gained a better understanding of how the application of force affects an object's acceleration, particularly with Newton's second law of motion. Q28 also saw improvements as students improved their understanding of how forces balanced out to result in no motion, particularly when dealing with stationary objects.

However, misconceptions increased in certain areas, most notably in Q5, where students seemed to struggle with the concept of gravitational force, possibly misunderstanding its effect on objects of varying masses. Q6 also saw an increase in misconceptions about friction and motion, suggesting that students had difficulty grasping how friction opposes motion. Q10 showed a significant increase in misconceptions about how objects move on a frictionless surface. Here, students seemed to misunderstand that in the absence of friction, an object would continue moving indefinitely at a constant velocity once a force is applied, indicating confusion about Newton's first law of inertia.

For the experimental group, the heatmap revealed a more mixed outcome. Some improvements were observed in several areas. In Q1, misconceptions about how objects of different masses fall under gravity improved, indicating a better understanding of free fall. In Q4, the group showed strong gains in understanding how forces act during collisions, likely correcting the misconception that larger objects exert greater forces. Q15 also improved as students demonstrated a better understanding of Newton's third law, learning that forces exerted between two interacting objects are equal and opposite.

However, several other questions showed either minimal change or an increase in misconceptions post-test. Q10 again stood out, with students showing more confusion about motion on a frictionless surface, similar to the control group. Many students may have misunderstood the idea that in a frictionless environment, an object continues moving indefinitely at a constant velocity without slowing down, in accordance with Newton's first law. Q22 saw an increase in misconceptions regarding rocket propulsion in space, as many students struggled to understand that once propulsion ceases in the vacuum of space, a rocket will continue moving at a constant velocity due to the lack of external forces such as friction or air resistance. In Q26, students had difficulty grasping how applying more force to an already moving object affects its speed or acceleration, indicating a persistent misunderstanding of the relationship between force and acceleration.

DISCUSSION

This study investigated the impact of a constructivist teaching intervention on students' achievement and misconception scores in physics, with specific focus on gender differences. The findings suggest that the constructivist approach had a differential impact across gender, showing greater effectiveness for female students in the experimental group, who demonstrated higher gains in achievement scores compared to the control group. This improvement reduced the gender gap in achievement, which was more pronounced in the control group. However, misconception scores across both groups revealed persistent misunderstandings in complex topics, particularly regarding concepts like motion in frictionless environments and rocket propulsion.

These findings align with previous research on constructivist teaching methods, which emphasize active engagement, inquiry, and experiential learning as effective means of enhancing comprehension in science education (Vygotsky, 1978; Weil-Barais, 2001). Constructivist approaches, which are grounded in Piagetian and Vygotskian theories, encourage students to build on prior knowledge through interactive and student-centered activities (Aina, 2017; Piaget, 1970). Research indicates that such methods not only improve learning outcomes but also help reduce gender disparities by fostering a collaborative learning environment that supports all students (Applefield et al., 2001; Rose, 2018). The observed reduction in the gender gap within the experimental group supports findings by Lorenzo et al. (2006) and Hake (1998), who report that constructivist approaches like active learning can close gender gaps by promoting equal engagement. However, the persistence of misconceptions regarding complex topics aligns with findings by Hestenes et al. (1992) and McDermott (1991), who emphasize that deeply rooted intuitive misconceptions in physics are challenging to address and often require targeted instructional strategies beyond traditional methods.

An unexpected result was the increase in misconception scores for certain items, particularly on concepts like motion on a frictionless surface (Q10) and rocket propulsion in space (Q22). Given that the constructivist intervention aimed to address conceptual understanding, these results were surprising. Constructivist approaches, while effective in promoting exploration, often require students to dismantle pre-existing misconceptions–a complex and gradual process (Resbiantoro & Setiani, 2022; Smith et al., 1994). Students may struggle with counterintuitive ideas, such as the persistence of motion without friction, due to everyday experiences that conflict with Newtonian mechanics (Balta & Asikainen, 2019; Balta et al., 2019). This persistence of misconceptions, as documented by Hammer (1996), shows that constructivist methods could benefit from supplemental tools, such as digital simulations, to provide clearer, concrete representations of abstract concepts (Agyei & Agyei, 2021; Baviskar et al., 2009).

CONCLUSIONS

In conclusion, this study highlights the potential of constructivist teaching methods in physics education, particularly for reducing gender disparities and supporting female students' achievement in physics. While the constructivist approach demonstrated effectiveness in narrowing the gender gap, persistent misconceptions in specific physics topics suggest the need for additional support in complex areas. These findings contribute to the existing literature by reaffirming the value of constructivist, gender-sensitive approaches in science education and indicating that further refinement of constructivist strategies, potentially through the integration of simulations and other experiential tools, may enhance their effectiveness in addressing deeply rooted physics misconceptions.

This study adds to the existing literature by stressing the potential of constructivist teaching methods to reduce gender disparities in physics education and by highlighting the importance of integrating varied instructional tools for challenging topics.

While this study points out the importance of constructivist teaching in physics education, several limitations should be noted. Conducting the research in a single institution limits the generalizability of the findings, as students from different backgrounds may respond differently to constructivist interventions. Additionally, the reliance on quantitative measures, such as achievement and misconception scores, may not fully capture students' cognitive and conceptual development. Studies points out that qualitative approaches, including interviews or reflective journaling, could provide deeper insights into students' thought processes and learning challenges (Smith et al., 1994). Future research could benefit from a mixed methods approach to gain a more nuanced understanding of students' conceptual growth within constructivist frameworks.

Building on these findings, future research could examine the effects of integrating simulations and hands-on activities into constructivist instruction, especially for complex and abstract physics concepts (Stoen et al., 2020; Zacharia & Olympiou, 2011). Studies could also explore the long-term effects of constructivist teaching on both male and female students' understanding and retention in STEM subjects, to assess whether the observed gender differences in achievement and misconceptions persist over time (Sadler & Sonnert, 2016). Additionally, cross-institutional studies could evaluate how constructivist methods perform in varied educational contexts, while longitudinal research could assess whether these methods have lasting impacts on students' conceptual understanding and interest in STEM fields.

In summary, this study specifies that constructivist teaching has the potential to improve student outcomes in physics and reduce gender gaps, but certain physics concepts may require additional support. Policymakers, curriculum designers, and educators could enhance STEM learning by integrating constructivist practices with targeted instructional tools, thereby making science education more accessible and effective for all students.

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Ethics declaration: This study was reviewed and approved by the Institutional Review Board of South Kazakhstan Pedagogical University named after Ozbekali Zhanibekov under Report No. 2, dated September 9, 2023. All participants were informed of the study's purpose, procedures, and their rights, including voluntary participation and confidentiality. Informed consent was obtained before data collection, and all research activities adhered to the ethical principles outlined by the IRB. There were no conflicts of interest, and participant data was handled with strict confidentiality and anonymity.

Declaration of interest: The authors declared no competing interest.

Data availability: Data generated or analyzed during this study are available from the authors on request.

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APPENDIX A: WEEK 7 ACTIVITY–EXPLORING FORCES AND STABILITY IN A SYSTEM OF CYLINDERS

In this scenario, students activate their prior knowledge of forces and stability, experience cognitive dissonance by encountering the paradox of continuous acceleration in a static system, apply their new understanding to predict the behavior of the setup, and reflect on their learning. The added discussion on changing friction levels further enriches their understanding of stability and friction, promoting a comprehensive grasp of dynamics and static equilibrium principles.

Learning Objective

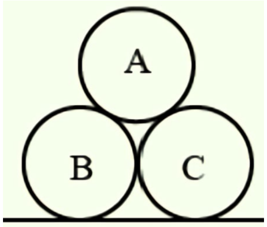
Students will understand the role of frictional forces, torque, and stability in a multi-object system by analyzing a setup with three cylinders stacked in a triangular formation.

Step 1: Activate Prior Knowledge

Begin by asking students if they have any experience with stacking objects or balancing items (e.g., books, blocks) and discuss what makes them stable or unstable.

Ask students to create a quick concept map with terms like “friction,” “force,” “torque,” and “equilibrium.” They should note how they think these concepts interact when objects are stacked.

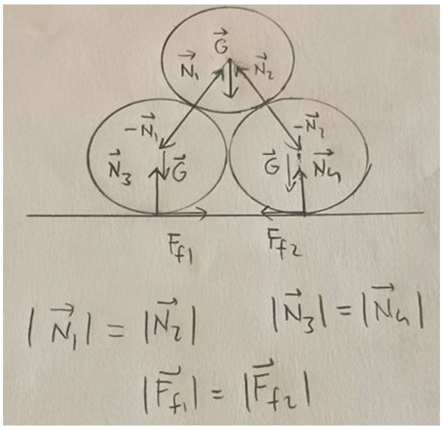
Show them three cylinders stacked as in the diagram. Ask, “What do you think will happen to this setup over time? Will it stay balanced, or will something move?”



Step 2: Create Cognitive Dissonance

Begin by asking students to calculate the torques generated by the weight of the upper cylinder and the friction forces at the base of the lower cylinders. Guide them to show that both forces indeed create torque in the same direction, which, if left unopposed, would theoretically cause the lower cylinders to speed up.

The friction force on the ground does not balance the torque created by the component of the weight of the cylinder above. What kind of movement occurs here?



Once students have determined that both forces produce torque in the same direction, ask them:

“If both forces are creating torque in the same direction, what does that imply for the motion of the lower cylinders?”

“Would this result in continuous acceleration or speeding up?”

“Is this realistic? Wouldn’t this imply a violation of the conservation of energy?”

These questions introduce cognitive dissonance by making students realize that the unopposed torque would mean continuous acceleration in a static setup, which is impossible without an external input of energy.

Allow students time to think about why this result doesn't make sense. Guide them towards understanding that in a static scenario, an unbalanced, continuously accelerating motion would violate the conservation of energy, as there's no external source to supply continuous energy to the system.

After students grapple with the impossibility of continuous acceleration, prompt them to consider what forces or conditions might actually prevent the system from accelerating indefinitely. Guide them to the idea that static friction is what holds the system in place, creating an equilibrium that prevents continuous motion.

Step 3: Application of New Knowledge

Guide students through analyzing the forces and torques in the system, discussing the role of static friction at each contact point and the effect of the weight of the upper cylinder.

If you have access to similar cylindrical objects, let students try stacking them in a triangular formation to observe the forces in real life. They should see that, rather than causing continuous rolling, the structure becomes unstable and leads to separation or stays in equilibrium if there is sufficient friction.

With the experiment or through guided discussion, help students conclude that the weight of the upper cylinder likely overcomes the friction holding the lower cylinders together, causing them to separate and the upper cylinder to fall.

Ask students, "What do you think would happen if we change the friction between the bottom cylinders and the ground?"

If feasible, change the surface under the bottom cylinders to simulate different friction levels (e.g., use a smoother surface like plastic for low friction and a rougher surface like sandpaper for high friction).

Have students observe the difference in stability with low and high friction and discuss how friction affects the tendency of the cylinders to separate. Higher friction helps hold the cylinders together, while lower friction makes the system more prone to separation.

Step 4: Reflection on Learning

Have students write a journal entry about their initial predictions, how their understanding changed, and why continuous rolling could not occur in this setup.

Facilitate a discussion where students share thoughts like why static friction plays a critical role in preventing the impossible acceleration and how they would analyze similar setups in the future.

Ask each student to summarize one concept they learned (e.g., the role of static friction, equilibrium analysis) and write down any questions they still have about forces and torque.

Thoughts on the Implementation of This Activity

This example includes multiple factors, such as, moment of inertia, combined translational and rotational motion, the center of gravity of the bodies, and friction at various contact points. These factors were intentionally introduced to challenge students' understanding and encourage deep exploration of the concepts. During the implementation of this activity, students were guided through a structured inquiry process to identify and analyze these factors. For example; students explored the impact of the moment of inertia on the system's dynamics through hands-on experiments with different objects; the interaction between translational and rotational motion was illustrated using simulations; frictional forces, both between the rollers and the ground and between the rollers themselves, were analyzed in group discussions, emphasizing their roles in the system's equilibrium and motion.

Observations revealed a variety of approaches about students' methods of solving the task, often influenced by initial misconceptions. Common misconceptions included; the assumption that friction acts only at the base and not between the rollers, misunderstanding the interplay between rotational inertia and translational motion, incorrect predictions about the stability of the system due to neglecting the center of gravity.

The teacher addressed these misconceptions through targeted feedback and follow-up activities. For instance, when students incorrectly analyzed the system's motion without considering rotational inertia, teachers guided them to calculate the torque for individual components and compare it with experimental results. Similarly, the role of friction between rollers was clarified using demonstrations and conceptual discussions.

APPENDIX B

Table B1. Activities

Week	Topics	Activity	Source
1	Introduction: Concepts of motion	No activity	
2	Kinematics in one dimension 2.1 Uniform motion 2.2 Instantaneous velocity 2.3 Finding position from velocity 2.4 Motion with constant acceleration 2.5 Free fall 2.6 Motion on an inclined plane 2.7 Instantaneous acceleration	Drop ball and paper Simultaneous freefall Galileo's experiment–Inclined plane	https://www.physics.uci.edu/~demos/entries/1C20.16.html https://demos.smu.ca/demos/mechanics/125-simultaneous-freefall https://www.youtube.com/watch?v=KEXqAVfoTEU&t=247s
3	Vectors and coordinate systems 3.1 Vectors 3.2 Properties of vectors 3.3 Coordinate systems and vector components 3.4 Vector algebra	Vector addition Vector components and resultant	https://phet.colorado.edu/en/simulations/vector-addition https://www.youtube.com/watch?v=b1hqcbCLWTw
4	Kinematics in two dimensions 4.1 Acceleration 4.2 Two-dimensional kinematics 4.3 Projectile motion 4.4 Relative motion	Monkey demonstration Projectile motion Relative motion Bulldozer on the moving sheet	https://www.youtube.com/watch?v=RdoXc7kZqfQ https://phet.colorado.edu/sims/html/projectile-motion/latest/projectile-motion_en.html https://www.purdue.edu/freeform/me274/course-material/animations/relative-motion/ https://yppsweb2.its.yale.edu/physics/demos/demomain.asp?task=viewdemo&id=1E10.10
5	Circular motion 4.5 Uniform circular motion 4.6 Velocity and acceleration in Uniform circular motion 4.7 Nonuniform circular motion and angular acceleration	Circular motion Foam ball on string Pail of water	https://www.youtube.com/watch?v=XGllrlzbR1Y https://www.youtube.com/watch?v=DqBBxSGX8CQ https://yppsweb2.its.yale.edu/physics/demos/demomain.asp?task=viewdemo&id=1D50.40
6	Force and motion 5.1 Force 5.2 A short catalog of forces 5.3 Identifying forces 5.4 What do forces do? A virtual experiment 5.5 Newton's second law 5.6 Newton's first law 5.7 Free-body diagrams	Inertia with pendulums First law disc stack The inertia ball Breaking a rod: Combining impulse and inertia	https://spark.iop.org/inertia-pendulums https://www.youtube.com/watch?v=PVkrpmv0CpU https://yppsweb2.its.yale.edu/physics/demos/demomain.asp?task=viewdemo&id=1F20.10 https://www.ase.org.uk/system/files/SSR_June_2020_056-057_Balta.pdf
7	Dynamics I: Motion along a line 6.1 Equilibrium 6.2 Using Newton's second law 6.3 Mass, weight, and gravity 6.4 Friction 6.5 Drag 6.6 More examples of Newton's second law	Stability in a system of cylinders Atwood machine Inseparable phone books demonstration	Our own demonstration https://yppsweb2.its.yale.edu/physics/demos/demomain.asp?task=viewdemo&id=1G10.40 https://iopscience.iop.org/article/10.1088/1361-6552/aa5f89/meta
8	Newton's third law 7.1 Interacting objects 7.2 Analyzing interacting objects 7.3 Newton's third law 7.4 Ropes and pulleys 7.5 Examples of interacting-object problems	Push me pull you carts Fan cart and sail	https://yppsweb2.its.yale.edu/physics/demos/demomain.asp?task=viewdemo&id=1H10.10 https://yppsweb2.its.yale.edu/physics/demos/demomain.asp?task=viewdemo&id=1H10.20
9	Dynamics II: Motion in a plane 8.1 Dynamics in two dimensions 8.2 Uniform circular motion 8.3 Circular orbits 8.4 Fictitious forces 8.5 Nonuniform circular motion	Locating the center of gravity: The dance of normal and frictional forces Coriolis effect Oscillations of a meterstick on two rotating shafts	https://pubs.aip.org/aapt/pte/article-abstract/50/8/456/318696/Locating-the-Center-of-Gravity-The-Dance-of-Normal?redirectedFrom=fulltext https://www.youtube.com/watch?v=dt_XJp77-mk https://pubs.aip.org/aapt/pte/article-abstract/54/3/145/277822/Oscillations-of-a-Meterstick-on-Two-Rotating

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