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Innovative Educational Kit for Manufacturing: A Study of Student Engagement and Learning Outcomes

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Abstract

Principles of fluid mechanics are a key subject introduced early in engineering education. In the manufacturing sector, fluid power is indispensable for driving hydraulic and pneumatic systems that operate a wide array of machinery such as presses, conveyors, robotic arms, and material handling systems. These systems are crucial for automation in modern manufacturing processes, ensuring precision, repeatability, and energy efficiency. Hydraulic systems provide the power needed for heavy lifting and forming operations, while pneumatic systems offer speed and simplicity for tasks like assembly and packaging. Fluid power's application extends to sectors like automotive manufacturing, aerospace, and construction, where precision-controlled motion and force are essential to the production and assembly of components. Early exposure to such topics is crucial in shaping students' perceptions of engineering and fostering their developing sense of identity as engineers, which influences their future career paths. This paper investigates how implementing a lab kit, along with five educational modules, enhances students' understanding of fluid power and its applications in manufacturing. By incorporating hands-on experiences into an introductory fluid power course, we assess how these practical modules impact students' engagement with the subject, their engineering identity, and their comprehension of core concepts. Each of the five modules targets specific learning objectives, bridging the gap between theory and practice. Students engage with core principles through activities like constructing grippers and deadweight testers, mastering data acquisition with Arduino, sensor calibration, and data visualization on LCD screens. Data collection will focus on measuring changes in students' engagement in the material, confidence in self-identification as engineers, and overall comprehension of the material. Surveys were administered after a regular lab session to act as a baseline and following the completion of the lab kit modules to evaluate students' engagement and perception of engineering identity. Our findings highlight how a single kit with five hands-on modules positively impacts students' understanding of the material, enhances their engineering identity, and strengthens their ability to apply theoretical knowledge to practical manufacturing applications.

Keywords: Fluid Power, Laboratory Kit, Manufacturing Technology Education, Engineering Technology Education

1. Introduction

The development of innovative educational kits for manufacturing education has become a cornerstone in addressing the challenges of student engagement and improving learning outcomes. These kits serve as valuable resources to close the gap between theoretical ideas and real-world applications. In fluid power, an important aspect of mechanical, aeronautical, and manufacturing engineering, providing students practical experience is essential to developing the skills needed for the present-day engineering sectors. To this end, adopting educational lab kits presents an effective means to address ongoing challenges with resource accessibility and student engagement [1], [2].

Despite advancements in fluid power education, traditional laboratory practices face challenges in engaging students and fostering meaningful learning. Students often approach labs with external motivations, such as completing tasks quickly or achieving high grades, resulting in surface-level engagement where they prioritize finishing experiments over understanding principles [3], [4]. Traditional labs rely on structured tasks with predetermined outcomes, leaving little room for creativity or exploration [5], [6]. This rigid approach limits connections to real-world engineering and fails to accommodate diverse learning styles, disengaging students who benefit from hands-on methods [4], [7], [8].

Prior research supports hands-on, student-centered approaches to improve engagement and learning in engineering education. Active participation fosters deeper understanding, critical thinking, and greater satisfaction [9]. Tailored educational tools, as highlighted by Zakaria et al. [10] and Chang [11], enhance motivation and engagement while aligning with Astin's theory of involvement, which links active participation to positive outcomes [12]. Examples of successful hands-on learning tools include low-cost robotic kits [13], Lean Six Sigma experiments [14], and modular robotic tools [15]. These tools bridge theoretical concepts with real-world applications, encouraging creativity, collaboration, and problem-solving.

The lab kit introduced in this study provides a cost-effective, adaptable, and associated modules for exploring fluid power concepts. Designed for junior and senior engineering technology students, it includes five modular experiments focusing on actuation, sensor calibration, and data acquisition. Surveys before (in a regular lab session) and after its use measured student engagement and engineering identity across emotional, physical, and cognitive dimensions, as well as recognition, interest, and performance/competence. Results showed improvements in confidence and cognitive engagement, particularly in out-of-lab activities (+11.3%) and performance/competence (+10.7%). The lab kit's design ensures adaptability for future use, making the kit an effective tool for improving manufacturing education.

This study highlights the lab kit's ability to bridge theoretical concepts with practical applications, fostering deeper engagement and enhancing learning outcomes. The findings underscore its potential to improve student confidence, cognitive engagement, and engineering identity while offering a scalable, cost-effective solution for manufacturing education.

2. Related Work

Several studies have explored the role of innovative laboratory kits in enhancing engineering education by bridging theoretical concepts with real-world applications. Reck and Sreenivas [16] developed an affordable controls education kit that improves accessibility and engagement through low-cost components. Gawade et al. [17] demonstrated similar benefits with the Lean Lego Lab, which enhanced student achievement, even in remote learning. Woods et al. [18] and Martin and Betser [19] emphasized hands-on learning through case-based activities and informal maker clubs, respectively, fostering engineering identity and collaboration. The GOAL Engineering Kit Initiative [20] further validated the effectiveness of low-cost kits in STEM education by boosting technical confidence and identity in K-12 students.

In fluid power education, previous kits focused on basic fluid mechanics concepts (Zorro et al. [21], Mishler et al. [22]) but lacked modern electronic controls and data acquisition. Recent advancements address these gaps: Starks et al. [23] replicated traditional lab outcomes remotely, while Mandal et al. [24] combined physical kits with simulations to improve engagement and skills. Sustainability-focused kits, such as Chiou et al. [25], also integrated robotics and infrared imaging for renewable energy education. These efforts align with broader findings (Feisel and Cook [26], COVID-19-era studies [27], [28]) highlighting lab kits' role in enhancing problem-solving, engagement, and accessibility.

Distinct from prior work, our lab kit prioritizes cost-effectiveness and adaptability, bridging theoretical and practical learning in fluid power education while addressing student engagement and engineering identity.

3. Lab Kit and Modules

The lab kit introduced in this study was developed to provide students with hands-on experience in fluid power concepts, particularly focusing on pneumatic systems that are often underrepresented in traditional curricula. Designed to be cost-effective (priced at approx. $70), the kit includes key components such as a pneumatic gripper, pressure transducer, Arduino microcontroller, and LCD screen, which collectively enable students to explore concepts like actuation, sensor calibration, and data acquisition (Figure 1). The kit is designed to be affordable for institutions with limited budgets, enabling the integration of comprehensive fluid power modules, and allowing educators to expand its use for additional fluid power experiments and related topics.

The kit includes five structured modules [31] each focusing on specific learning objectives. In the first module, students assemble and control a pneumatic gripper to learn about actuation and basic control techniques, a secondary objective is to introduce fundamental concepts in electric circuit prototyping and simple programming using an Arduino microcontroller. The second module introduces a deadweight tester for understanding pressure, force, and area relationships based on Pascal's principle, in it, the student builds with their hands a structure to hold a piston to lift a load using a syringe on one end and another syringe to lift the load when pressed by hand. Modules three and four are part 1 and 2, focused on data acquisition and calibration of a pressure transducer. These modules, built on the constructions from modules 1 and 2, are used for teaching students to collect and display real-time data using Arduino-based circuits. The fifth module integrates the concepts of pressure measurement and system monitoring, providing students with a comprehensive understanding of dynamic instrumentation in pneumatic systems, it adds instructions on how to connect and operate an LCD screen with the Arduino, and how to report the data from a pressure transducer in it. These modules emphasize hands-on engagement, helping students bridge theoretical knowledge with practical applications. This structured yet flexible, hands-on approach fills a significant educational gap, aligning student experiences more closely with industry needs. The specific activities developed by the student in the laboratory are described in section 3.1 below.

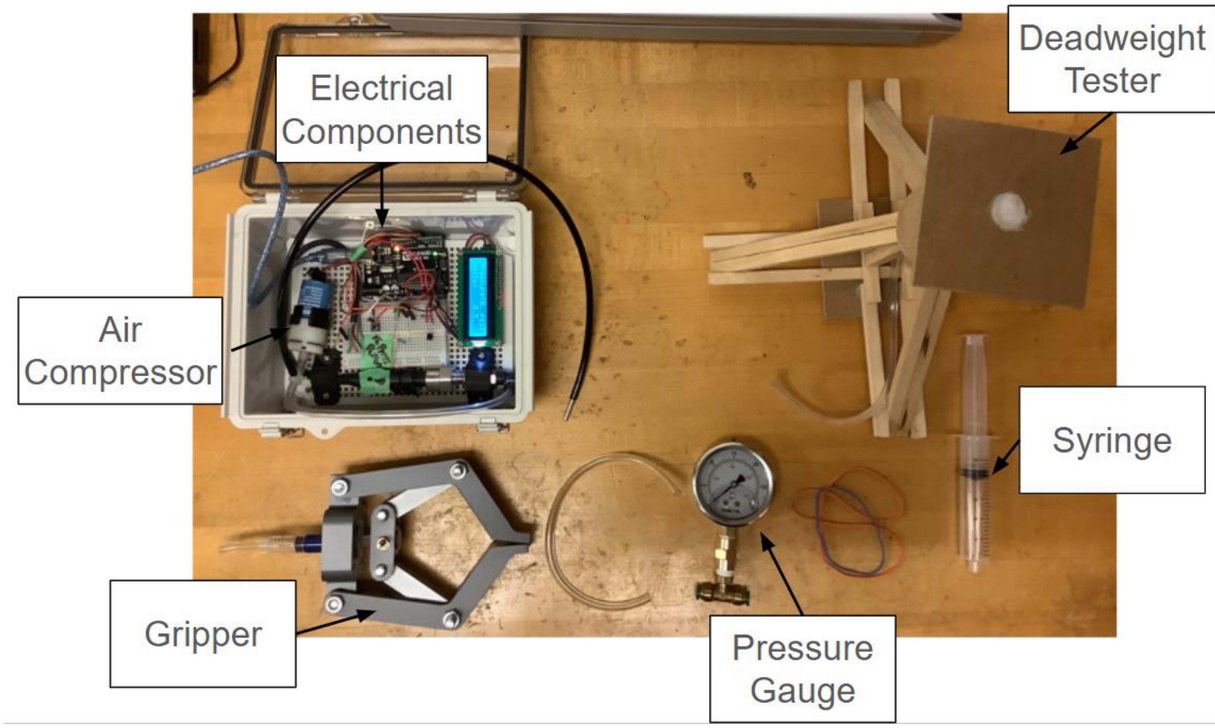

Figure 1. Complete Lab Kit Setup for Hands-On Fluid Power Instruction.

3.1. Lab Modules

The five lab modules were designed to progressively introduce students to key fluid power concepts through structured, hands-on experimentation. Each module builds on the previous one, allowing students to engage with pneumatic actuation, pressure measurement, sensor calibration, and real-time data acquisition in increasingly complex ways. The first module focuses on the assembly and control of a pneumatic gripper, where students integrate an Arduino microcontroller and mini air pump to observe actuation principles and develop basic programming skills. Next, students construct a deadweight tester using balsa wood, a syringe, and calibrated weights to explore Pascal's principle by analyzing force, pressure, and area relationships in pneumatic systems. In the third module, students utilize the deadweight tester to calibrate a pressure transducer, establishing a voltage-to-pressure conversion equation, while a manual pressure gauge serves as a reference for measurement accuracy.

Building on calibration techniques, the fourth module integrates an LCD screen with the Arduino circuit to display real-time pressure readings, allowing students to investigate system dynamics, including how hose length and pump power affect system stability. The final module expands on these principles by incorporating the pressure transducer with the pneumatic gripper, enabling students to collect and analyze pressure variations during actuation. This hands-on experience reinforces sensor integration, data reliability, and system monitoring, bridging theoretical knowledge with practical applications. These modules not only enhance students' technical competencies but also encourage problem-solving and critical thinking, ensuring they gain a comprehensive understanding of fluid power systems relevant to modern engineering applications.

3.2. Traditional Lab

In the regular or traditional lab that was preceding the implementation of the lab modules described in section 3.1, an experimental setup was built for the students. The purpose of that laboratory was to demonstrate how an industrial grade electronic pressure regulator is used to control the displacement of a pneumatic cylinder; a second experiment was setup for the students to experiment with the same electronic pressure regulator to control the speed of rotation of an air driven turbine. The goal of this laboratory was to demonstrate an open loop control system where pressure is used as an input to the system and linear displacement, or rotational speed are measured and recorded to describe the response of a pneumatic system.

More specifically, for this laboratory experience, the electronic controller, the input pneumatic power and electric connections were prepared by the instructor. Similarly, the sensors used for measuring speed and distance were calibrated by the instructor prior to the laboratory, the students were tasked with adjusting the pressure command on the electronic pressure regulator and recorded the output data read by the sensors. This setup illustrates a cause an effect relationship between input pressure and the desired output, distance or speed. However, the students did not participate in the process of assembling the system or setting it up to read the responses of said system to the input pressure. In this sense the role of the student was more passive than that taken in the modules lab presented in this paper.

4. Engineering Identity & Engagement Assessment Tools

Two survey instruments, each utilizing a Likert scale from 1 to 5, were developed and administered during the course to evaluate the impact of the lab kit on the participation of 23 students and their engineering identity. The first survey, conducted after a standard lab session without the lab kit (referred to as the regular lab session survey), served as a baseline. The second survey, administered following the use of the lab kit modules, focused on students' experiences with the third, fourth, and fifth modules, which emphasized data acquisition, calibration of a pressure transducer, and pressure measurement with system monitoring. Drawing on the validated frameworks of Burch et al. and Godwin [29], [30], both surveys were designed to measure students' perceptions across key areas: emotional and physical engagement, cognitive engagement (in-lab and out-of-lab), and the engineering identity components of recognition, interest, and performance/competence.

Because of their demonstrated applicability in engineering education, engagement and engineering identity were chosen as the study's primary constructs. Academic achievement and learning retention are significantly correlated to engagement, which includes emotional, physical, and cognitive aspects. Meanwhile, students' persistence and sense of belonging in engineering fields are greatly influenced by their engineering identity, which is characterized by recognition, interest, and performance/competence beliefs. This study aims to evaluate how well the lab kit improves both short-term learning experiences and long-term professional growth by looking at these characteristics.

The surveys used in this study are adapted from well-established tools in engineering education research. The engineering identity survey developed by Godwin et al. [29] has been rigorously validated, ensuring reliable measurement of recognition, interest, and performance/competence constructs. Similarly, the engagement survey by Burch et al. [30] has demonstrated strong psychometric properties, including internal consistency and factor validity for assessing various dimensions of student engagement. Due to the robustness of these tools, further validation was deemed unnecessary for this study.

5. Data Analysis

In the engagement section, cognitive engagement in out-of-lab activities showed the most significant improvement (+11.30%), while physical engagement increased slightly (+3.50%). Emotional engagement remained stable, but cognitive engagement in-lab decreased (-6.60%), possibly due to the lab session being conducted at the end of the semester, when students were preoccupied with final coursework. For engineering identity, performance/competence improved the most (+10.70%), while recognition (+1.60%) and interest (+0.20%) saw minor increases. These findings suggest that the lab kit enhanced students' confidence in their engineering abilities and reinforced their engineering identity.

Table 1. Comparison of Engagement Metrics Between a Regular Lab and Lab Kit Surveys

Engagement Metric	**Regular Lab Average (Scale 1-5)**	**Lab Kit Average (Scale 1-5)**	**Improvement**
Emotional Engagement	3.83	3.81	-0.02
Physical Engagement	3.70	3.84	+0.14
Cognitive (In-Lab)	3.97	3.71	-0.26
Cognitive (Out-of-Lab)	3.23	3.68	+0.45

Table 2. Comparison of Eng. Identity Metrics Between a Regular Lab and Lab Kit Surveys

Eng. Identity Metric	**Regular Lab Average (Scale 1-5)**	**Lab Kit Average (Scale 1-5)**	**Improvement**
Recognition	4.07	4.13	+0.05
Interest	3.88	3.89	+0.01
Performance/Competence	3.57	4.00	+0.43

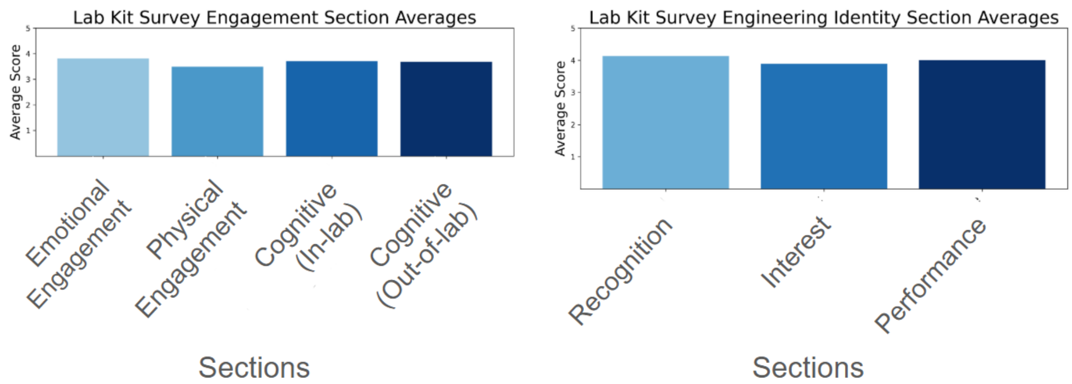

Figure 3. Lab Kit Survey Section Averages for Engagement and Engineering Identity.

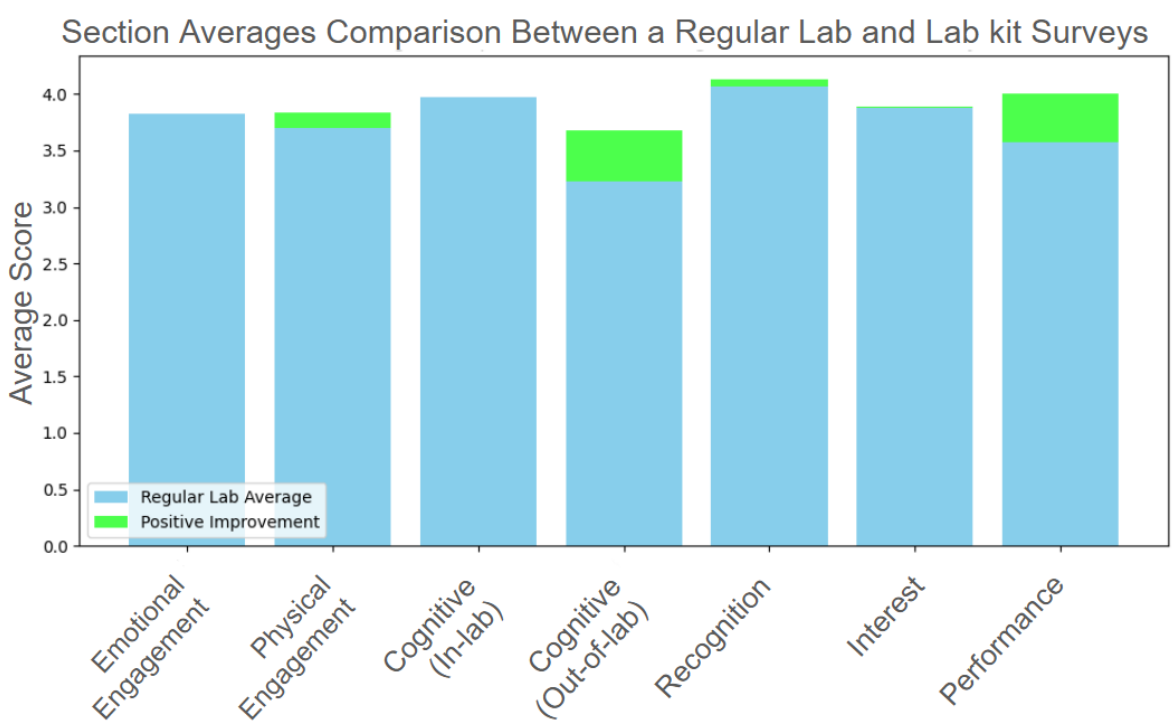

Figure 2. Section Averages Comparison Between a Regular Lab and Lab Kit Surveys.

Correlation analysis (Table 3) further supports these results, showing strong links between engagement and identity. Students who were more enthusiastic about using the lab kit (r = 0.90) were also more focused during lab activities, while those who put in greater effort (r = 0.85) were more likely to assist peers in pneumatic experiments. Additionally, concentration on lab tasks (r = 0.83) correlated with feelings of fulfillment, and attentiveness while using the lab kit (r = 0.71) was associated with perceived skill improvement in engineering.

Table 3. Strongest Correlations from the Lab Kit Survey

Correlation Pair	**Correlation Value**	**Question 1**	**Question 2**
Question 1 and Question 14	0.90	I am enthusiastic about working with the lab kit.	When I am in the lab using the lab kit, I concentrate fully on the activities.
Question 9 and Question 27	0.85	I devote great efforts toward using the lab kit.	Others ask me for help in pneumatic modules and related experiments.
Question 14 and Question 28	0.83	When I am in the lab using the lab kit, I concentrate fully on the activities.	I feel fulfilled when completing pneumatic systems projects.
Question 16 and Question 21	0.82	When I am in the lab using the lab kit, I devote a lot of attention to the activities.	When I am studying material related to the lab kit, I devote a lot of attention to it.
Question 16 and Question 30	0.71	When I am in the lab using the lab kit, I devote a lot of attention to the activities.	I feel that working on pneumatic systems projects improves my skills as an engineer.
Question 25 and Question 30	0.79	I am interested in continuing work in engineering projects involving pneumatic systems.	I feel that working on pneumatic systems projects improves my skills as an engineer.

Figure 4 highlights survey questions that saw the greatest improvement, particularly in effort, energy exertion, attention to material, and peer collaboration. These results reinforce the effectiveness of the lab kit in promoting hands-on engagement and fostering a stronger engineering identity among students.

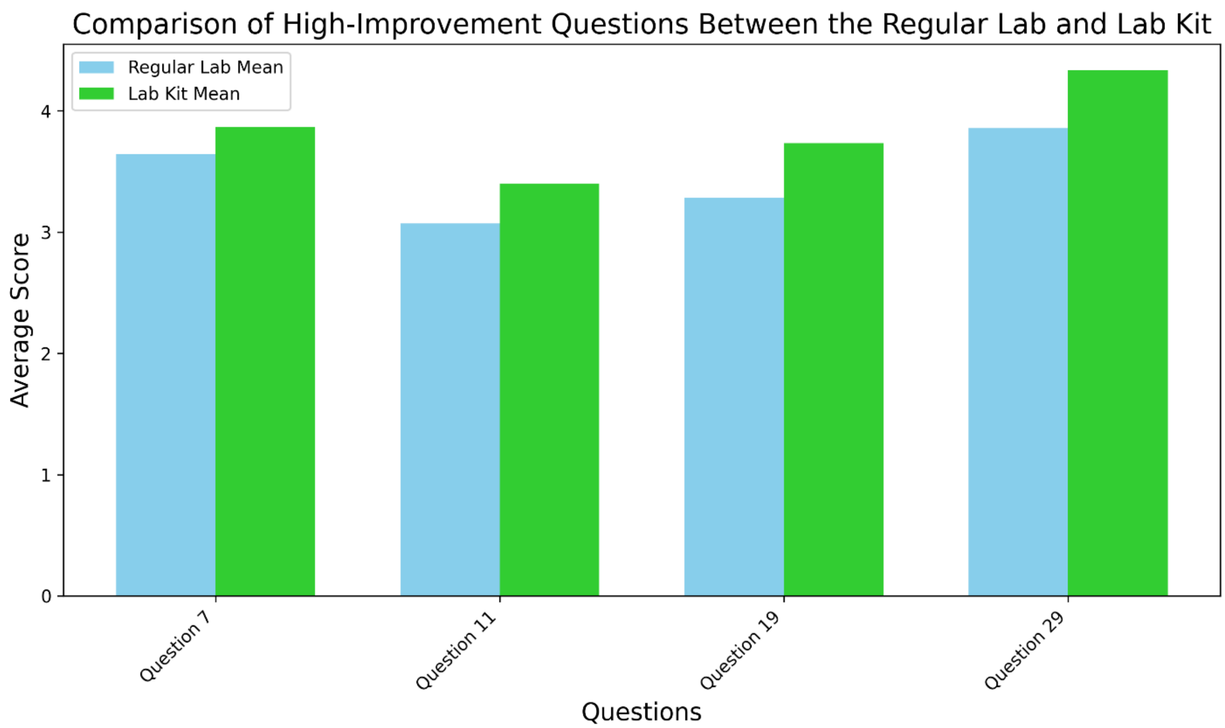

Figure 4. Comparison of High-Improvement Questions Between the Regular Lab and Lab Kit

6. Discussion

The lab kit's first-generation design demonstrated promising outcomes, particularly in fostering cognitive engagement during out-of-lab activities and improving performance/competence as part of engineering identity. The findings of this study highlight the potential of using the lab kit with its associated modules to address persistent challenges in traditional fluid power education. By incorporating hands-on activities, the lab kit provided students with opportunities to engage with fluid power concepts beyond procedural tasks. The findings show that while cognitive engagement improved significantly out-of-lab, a decline in in-lab engagement was observed, possibly due to the timing of the lab kit session as the final activity of the semester. Future iterations should consider introducing the lab kit earlier to mitigate these factors. Additionally, the strong correlations between specific engagement and engineering identity metrics—such as enthusiasm for lab activities correlating with improved concentration and recognition—underscore the kit's potential to integrate theory and practice effectively. The lab kit's associated modules proved effective in bridging theoretical knowledge with practical applications. However, being a first-generation design, further enhancements are needed to optimize its impact. This includes redesigning certain modules, incorporating advanced data acquisition tools, and expanding the instructional scope to cater to diverse learning needs. Increased participant numbers in future studies will also provide more robust validation of the kit's effectiveness. Overall, while the lab kit has successfully laid a foundation for improved student engagement and engineering identity development, the iterative design process will play a crucial role in realizing its full potential as a transformative educational tool.

7. Limitations

Although the study's findings are encouraging, a few limitations should be mentioned. There was only a one-week gap between the regular lab session and the lab kit session, and the lab kit session was the final lab of the semester. This timing may have influenced the results, as students might have been affected by end-of-semester fatigue or other external factors. Introducing the lab kit earlier in the semester could potentially yield more significant results. Additionally, the brief one-week gap between the two sessions may not have provided sufficient time to observe a meaningful difference in student responses between the regular lab and the lab kit sessions. Furthermore, the study included only 23 students, which limits the generalizability of the findings. While the results are promising, a larger sample size would enhance the validity of the conclusions and provide a more comprehensive understanding of the kit's impact.

8. Conclusion

This study introduces a first-generation lab kit designed to enhance fluid power education through hands-on, modular activities that bridge the gap between theoretical concepts and practical applications. By addressing key areas of engagement and engineering identity, the kit provides students with opportunities to develop deeper understanding, confidence, and the ability to apply their knowledge to real-world scenarios. The results demonstrate that the lab kit positively impacts student outcomes, particularly in cognitive engagement during out-of-lab activities and performance/competence in engineering identity. While overall improvements in engagement metrics were modest, the findings underscore the potential of this low-cost, adaptable solution to enhance traditional laboratory practices. With its scalable and flexible design, the lab kit not only meets diverse instructional needs but also serves as an effective tool for preparing students to tackle practical challenges in manufacturing and engineering fields.

9. Future Work

The lab kit presented in this study represents a first-generation design, and while the initial results are promising, there is room for improvement. Future iterations of the lab kit should focus on refining its design, enhancing its modules, and addressing any limitations identified through student feedback. Additionally, expanding the scope of participant surveys and incorporating more detailed metrics can provide deeper insights into the kit's effectiveness in fostering engagement and engineering identity. Future studies with larger sample sizes and extended implementation periods are essential to validate the observed benefits and further refine this innovative educational tool. Researching the kits application in other fluid power classes in both this school as well as others is also desired.

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