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Evaluating Robotics-Enabled Active Plus Experiential Learning of Mechanical Engineering Concepts

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Abstract

The objective of this paper was to evaluate the effectiveness of a special type of educational robotic platform (an all-in-one robotic STEM learning platform) that was developed to teach various fundamental mechanical engineering concepts such as drawing and drafting, hydraulics, pneumatics, manufacturing processes, engraving, dynamics, vibration, etc. to engineering students in an active plus experiential learning setup. Two (02) groups of engineering students (mechanical major, sophomore year), each group consisting of 10 students, participated in the study. The instructor (the author) randomly selected three fundamental mechanical engineering concepts (pneumatics, energy conversion and vibration) to teach the students as part of a mechanical design course. The instructor followed two distinct but interrelated pedagogical approaches for that purpose: (i) active learning for one group of students, and (ii) active plus experiential teaching for the other group of students. For the active learning group, for teaching each concept, the pedagogy was such that the instructor supplied reading materials to the students, wrote and drew relevant diagrams illustrating the concept on the board, explained the concept verbally, demonstrated relevant animation videos illustrating the concept, asked questions to students, staged brief bilateral dialogues between students and asked students to complete brief worksheets. For the active plus experiential learning group, the instructor followed the same pedagogy as used for the active learning group. In addition, the instructor developed relevant demonstrations of each concept using the robotic platform as an experiential learning tool and demonstrated robot-based illustration of each concept to the students. The instructor also collected relevant data from the robotic illustration and analyzed the data to support the instruction of the concept to the students. The learning outcomes in terms of content knowledge (subject matter knowledge) and interdisciplinary knowledge of the students, and student engagement and enthusiasm between the two pedagogical approaches were determined based on examinations and observations, and then the learning outcomes between the two pedagogical approaches were compared. The results showed that the active plus experiential learning approach outperformed the active learning approach significantly. Then, based on the experience, the instructor identified potential sources of misconceptions associated with robotic illustration for each lesson, which could adversely affect the learning outcomes. Then, the instructor identified the challenges and burdens that an instructor might face for designing and implementing the robotics-enabled instructional model and then determined necessary training and institutional support for instructors applying robotics-enabled instructions. The results helped identify the boundary between active and experiential learning. The results can inspire and guide STEM instruction designers in applying robotics-enabled experiential plus active learning methods to STEM courses.

1. Introduction

1.1 Background and Motivation

In many cases, mechanical engineering concepts are abstract in nature. As a result, students may face difficulty in comprehending such concepts, which can significantly affect their learning outcomes and professional careers [1]. The mechanical engineering concepts that are somewhat abstract in nature may include torque, pneumatics, moment, force, hydraulics, vibration, energy conversion and conservation, machine intelligence, theory of machines, machine kinematics, mechanical logic, etc. Students in their early stages of higher education such as freshmen and sophomore students may face such difficulty more intensely [2]. This is why it is realized that it would be better in terms of learning outcomes if such abstract mechanical engineering concepts could be taught to students in special arrangements that are somewhat advanced from existing traditional classroom settings [1]-[3].

Researchers have different opinions regarding what the special arrangements should be. One of the approaches of such special instructional arrangements has created serious impact on current STEM researchers. Such a special approach is that suitable robotic platforms can be used as kinesthetic experiential tools to illustrate different abstract concepts to students under an experiential teaching and learning setup [1]-[13]. The robotic platforms are usually flexible in design. So, a single robotic platform can be configured in many ways to illustrate multiple abstract concepts to students [3]-[6]. Robotic platforms are currently not so expensive, and they may motivate students intrinsically and extrinsically, which may also be a reason for the higher prospect of robotic platforms to be used as experiential teaching and learning tools [2]-[3].

However, there are a few issues with the applications of robotics as kinesthetic experiential teaching and learning tools, which need to be addressed before robots can be widely used in classrooms for this purpose. For example, most existing robotic platforms are stand-alone systems that may help students learn robotic technology itself, but they may not come to great help in learning specific mechanical engineering concepts such as vibration, pneumatics, energy conservation, etc. together through robot-based illustrations in a single robotic setup [14]. As a result, examples of dedicated stand alone and combined (all-in-one) robotic platforms are necessary that can be used to teach multiple concepts to students easily on a single platform. The state-of-the-art robotics-enabled education efforts usually focus on STEM education in K-12 classes [1]-[6], but such robotics-enabled educational approaches are rarely used to teach STEM concepts such as mechanical engineering concepts in higher education [2]-[4], [13]. The pedagogical methods for robotics-enabled education are still not well-defined. Robotics-enabled illustrative education can fall under the experiential teaching and learning approach [15]. However, it needs to investigate how such experiential approach can be implemented in conjunction with active learning approaches [16]. Recently, an initiative was taken to instruct basic mechanical engineering concepts through robotics-enabled experiential learning [23]. However, the initiative did not combine experiential learning with active learning, and the approach needed substantial evaluations addressing its challenges and burdens, generalizability and possibility of generating misconceptions and misrepresentations. It is realized that appropriate integration of experiential learning with active learning may produce significantly better learning outcomes. Furthermore, extensive evaluations of robotics-illustrated experiential teaching and learning are necessary to truly understand the learning outcomes of such an approach, identify and remove any misconceptions and determine the challenges and burdens of such an approach [3]. However, the state-of-the-art research output in this area does not address these issues properly and adequately.

1.2 Objectives

Considering the above background and motivational information, the objectives of this paper were to (i) design and develop an all-in-one robotic platform to teach a few selected abstract mechanical engineering concepts to sophomore students following robotics-enabled active plus experiential teaching and learning approach, (ii) evaluate the instructional outcomes properly, (iii) compare the outcomes with that of the specially designed active teaching and learning approach that does not include robotics-enabled illustrations of the mechanical engineering concepts, and (iv) identify the sources of misconceptions and misrepresentations, and challenges and burdens in robotics-enabled active plus experiential STEM education, so that all these can guide education policy makers and interested instructors to implement robotics-enabled active plus experiential teaching and learning approach in actual classroom settings.

1.3 Organization

The rest of paper has been organized in the following way: Section 2 analyzes the state-of-the-art related work. Section 3 presents the materials and methods of the research. This section introduces the participants selected to participate in the studies, the lessons developed for the instruction, the developed pedagogical approaches, robotics-based illustrations of the selected concepts, the research design, research procedures, and research results and analyses. Section 4 discusses various critical issues related to the research. Section 5 presents conclusions and the future research work in this research direction. Then, the acknowledgement, references and an Appendix are presented.

2. Analysis of Related Work

The literature shows growing interest in research regarding technology-enhanced, especially robotics-enhanced STEM teaching and learning. As the literature shows, Rahman et al. illustrated the design and execution of a professional development (PD) program for K-12 STEM teachers for teaching STEM in middle schools centering on robotic illustrations of STEM concepts [1]. The authors conducted a detailed study to identify and verify the prerequisites (required knowledge, skills, and attitude) of K-12 students for participating in robotics-enabled math and science lessons so that they could obtain optimum learning outcomes [2]. The research revealed that students' computational thinking ability was a vital requirement before they could attend robot-based STEM lessons, though there was a great possibility that robotics-based lessons could also enhance the computational ability of the students [2]. A teaching and learning framework called technological-pedagogical content knowledge (TPACK) was implemented in conjunction with robotics-based experiential instructions of STEM lessons to experientially teach math and science lessons to middle school students [3]. The impacts of such a robotics-based TPACK framework on student outcomes compared to traditional classroom-based teaching were investigated and the dynamic nature of the TPACK framework for robotics-enabled instructions were studied [3]-[4]. The robotics-enabled STEM instructions were augmented with the application of systems approach to analyzing the instructional outcomes [5]. How students develop trust and mistrust in robotics-enabled experiential learning was investigated in [6]. In addition to STEM learning, robots were used as experiential tools to enhance English language learning outcomes of students [7]. A LEGO robot-based teaching and learning framework was proposed for students to solve critical problems and enhance lesson engagement [8]. Students' interest in using robots as experiential learning tools is very important before robots can be put in classrooms to illustrate STEM lessons. Considering this, a dedicated study was conducted to enhance students' interest in robot-enabled STEM studies in high schools [9].

In addition to functional robots such as the LEGO robot, it was found that social robots can also be used in classrooms to enhance learning outcomes. Social robots possess human-like behavioral and emotional attributes that can mimic human instructors. As a result, social robots' prospects in education were investigated and favorable outcomes were obtained [10]. A review study was conducted that showed that robotics-based STEM teaching and learning is more suitable for young and child learners than adult learners, though adult learners can also benefit from robotics-based instruction [11]. More studies are found in literature that present various survey results highlighting teaching and learning prospects in schools using robots [12]. Creativity is a key objective in higher education. Studies showed that, like K-12 education, robotics can be employed as experiential teaching and learning tools in higher education as well [13], [23].

The above literature analysis reveals that most of the research conducted around robotics-enabled teaching and learning focused on K-12 education. However, the literature shows that higher education, especially college level STEM education, can also benefit from robotics and technology-enhanced teaching and learning. However, currently adequate efforts are not put into investigating the prospects of robotics-enabled college level STEM education. In addition, more comprehensive evaluations of robotics-enabled college STEM education should be conducted to evaluate robotics-enabled instructional outcomes, identify potential misconceptions raised by robotics-based education, and the challenges and barriers toward the implementation of robotics-enabled instructions in college education. This paper aims to address these points.

3. Materials and Methods

3.1 Participants

Twenty (20) mechanical engineering sophomore students were selected to participate in the study. The students were enrolled in a mechanical design dissection course. Those students were the learners for the research study presented herein. The students were randomly divided into two groups, each consisting of ten (10) students. In addition, six senior mechanical engineering students and one mechanical engineering graduate student were selected to serve as observers and evaluators of the research studies. The participants participated in the studies voluntarily, and they were informed before their participation in the studies.

3.2 Lesson development

The lesson included various fundamental mechanical engineering concepts that were abstract in nature, and students might feel difficulty in comprehending those concepts. The selected abstract mechanical engineering concepts were pneumatics, energy conversion and mechanical vibration. The selected three topics were taught by the instructor in a 50-minute class period as a special module of a mechanical design analysis course for sophomore mechanical engineering students.

3.3 Pedagogical approaches

Two distinct but interrelated pedagogical approaches were designed to teach the selected abstract mechanical engineering concepts to the selected students: (i) active teaching and learning, and (ii) active plus experiential teaching and learning. Two groups of students were taught the selected topics in two separate sessions. One group was randomly selected to be taught following the active teaching and learning approach. The other group was selected to be taught following the active plus experiential teaching and learning approach. For the active teaching and learning approach, the instructor supplied reading materials to the students, wrote and drew relevant diagrams illustrating the concept on the board, explained the concept verbally, demonstrated relevant animation videos illustrating the concept, asked questions to students, staged brief bilateral dialogues between students and asked students to complete brief worksheets. For the active plus experiential teaching and learning approach, the instructor followed the same pedagogy as used for the active teaching and learning approach, but in addition, the instructor developed relevant demonstrations of each concept using a robotic platform as an experiential teaching and learning tool and demonstrated robotics-based illustration of each concept to the participating students. The application of robotic illustration was the main difference between the two pedagogical approaches.

3.4 Research design

The research methodology was observation of instruction and comparison of instructional outcomes between two different pedagogical approaches: (i) active teaching and learning, and (ii) active plus experiential teaching and learning. Here, the pedagogical approaches were independent variables, and the instructional outcomes were dependent variables. Since the application of robotic illustration was the main difference between the two pedagogical approaches, the variations in instructional outcomes were sufficient to prove the impact of robotic illustrations on the instructional outcomes.

3.5 Robot-illustrated experiential learning module

A Dobot magician robotic arm (education version) along with its various accessory modules was used to develop robotics-based illustrations of the selected mechanical engineering concepts. The Dobot magician robotic arm was used for this purpose because this robotic system was flexible in its configuration and the same robotic platform could be used to design and develop illustrations for all three mechanical engineering concepts. Figure 1 shows how the robotic system was used to illustrate the concept of pneumatics in a real-world scenario. As the figure shows, the robot used its pneumatic suction-type gripper to pick a thin plate from a table surface and place it at a different location on the table surface. A pneumatic pump was connected to a long tube. The tube was connected to the gripper end. The robot used pneumatic power to grip and pick the thin plate. Then, the air suction was stopped, the pneumatic power stopped also, and the thin plate was released (placed on the table surface).

Figure 2 shows how the robotic system was used to illustrate the concept of vibration in a real-world scenario. In the scenario, the robotic system was used as the vibration source, and the table was used as the vibration base. The robot was used to pick and place a metal block on the table surface using the jaw-type robotic gripper. The speed of the robot manipulator at the time of manipulation was varied by changing the arm manipulation speed in the software. Arm speed directly impacted on the vibration of the robotic manipulator at the time of manipulation. Higher arm manipulation speed increased the vibration of the robotic arm as well as of the whole robotic system placed on the table (machine base). Paper sheets and rubber pads were placed between the robot base and the table to illustrate how vibration could be suppressed or absorbed.

Figure 3 shows how the robotic system was used to illustrate the concept of energy conversion in a real-world scenario. The Dobot robotic system was used to illustrate the laser engraving process. The robotic system used the laser end-effector module, and the laser was used to engrave a pattern or text on cardboard. In this case, the robot converts electrical energy into light energy (laser). The light is then converted into heat energy that burns cardboard for engraving the text by the subtractive machining process, which converts heat energy into mechanical energy. The energy amount can be adjusted by adjusting the programming in the robotic software, which also can impact the mechanical phenomena (engraving features).

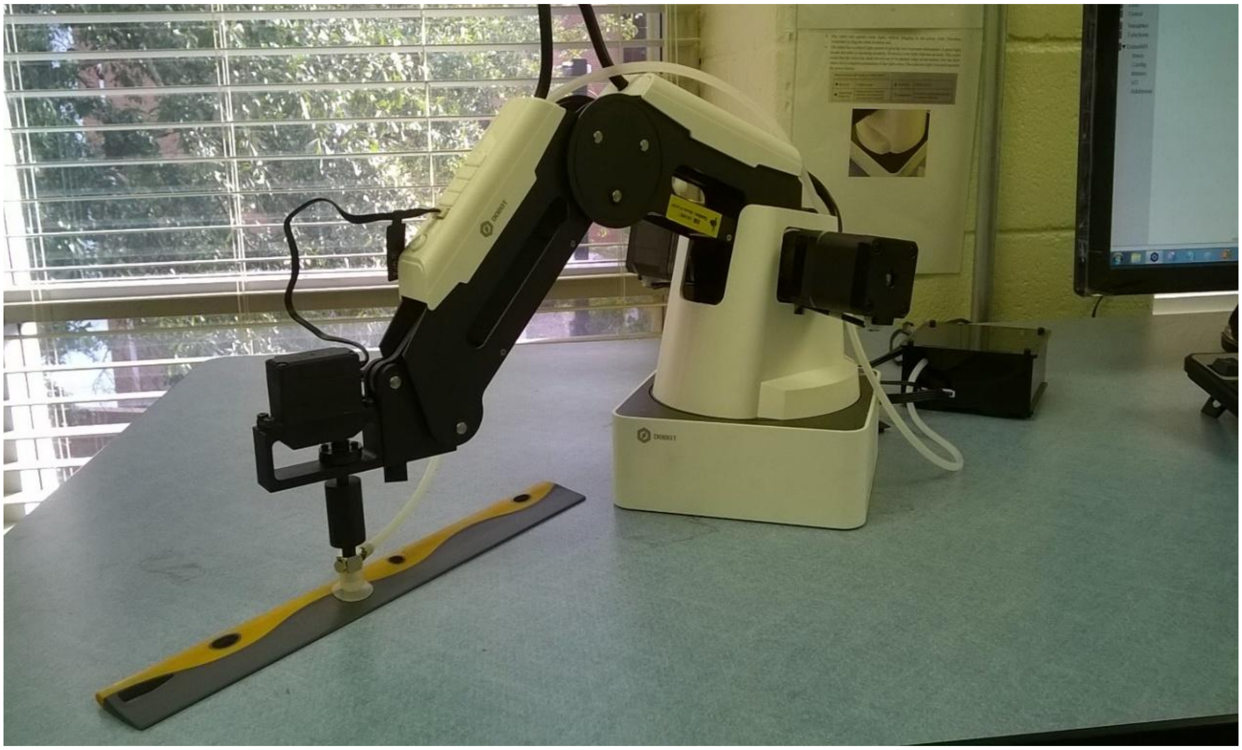

Figure 1. The robotic system developed to illustrate the concept of pneumatics in a real-world scenario.

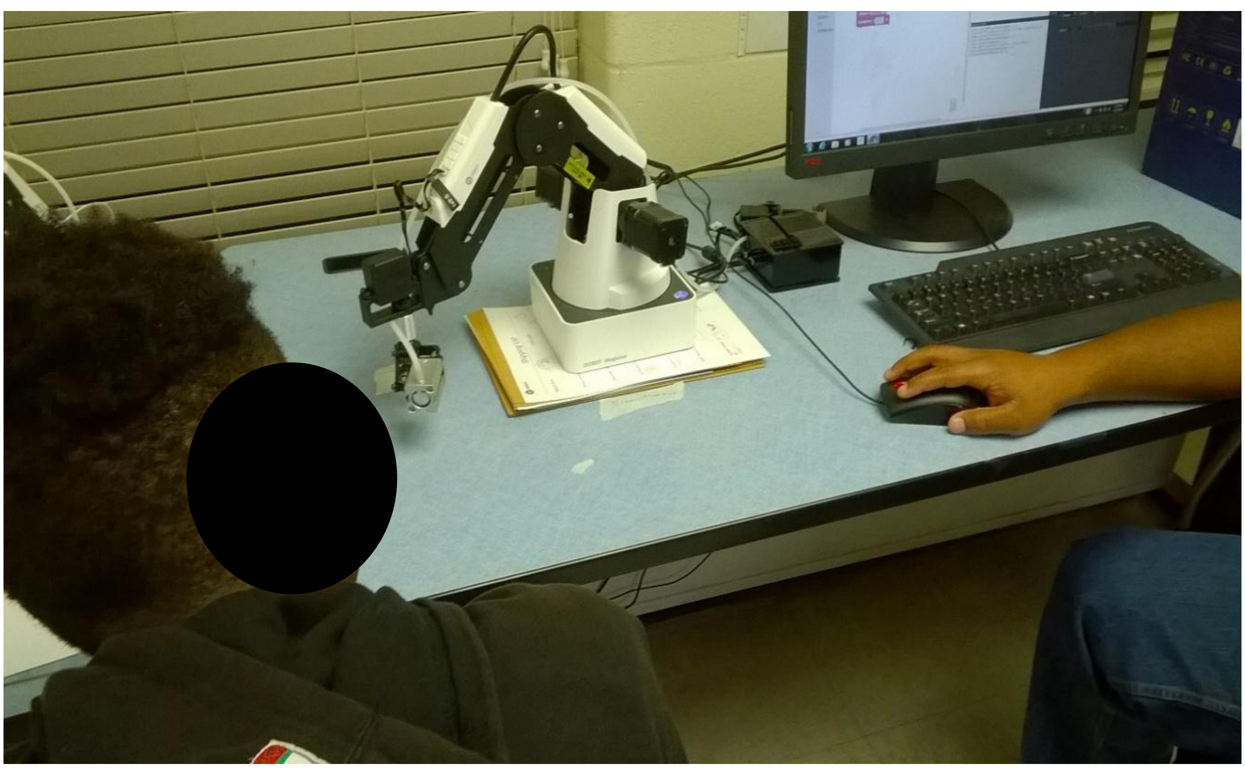

Figure 2. The robotic system developed to illustrate the concept of vibration in a real-world scenario.

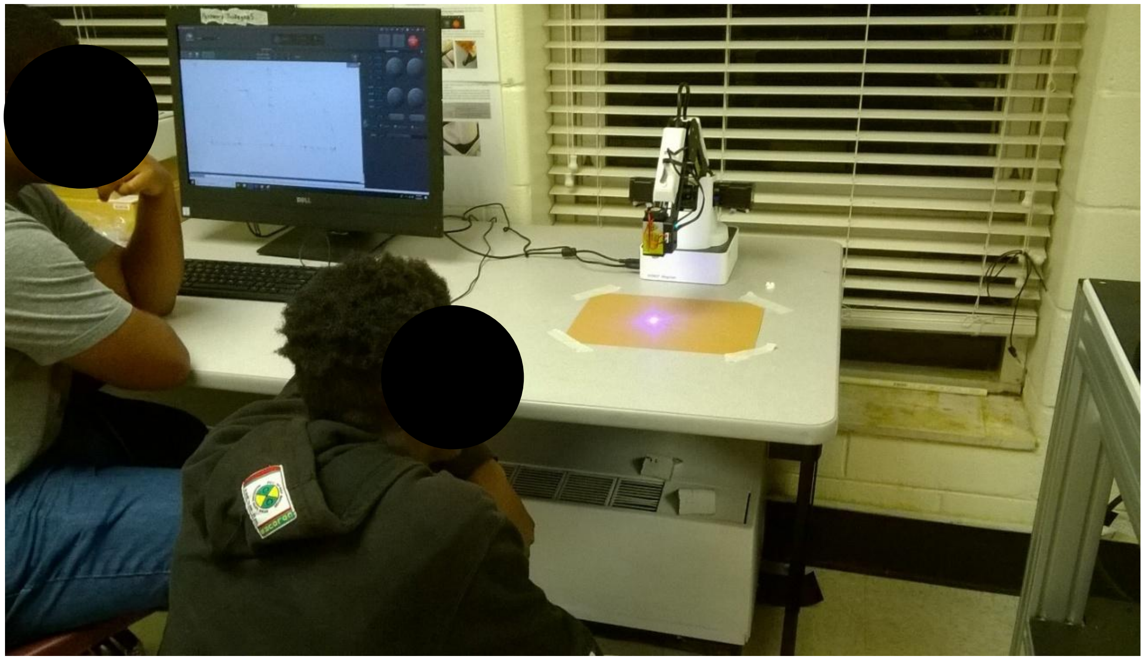

Figure 3. The robotic system developed to illustrate the concept of energy conversion in real-world scenario.

3.6 Research procedures

In the first phase of the study, the instructor instructed the mechanical engineering concepts to a group of students following the active teaching and learning approach in a classroom plus laboratory setting. The duration of the teaching and learning period was 50 minutes. Seven evaluators (six senior mechanical engineering students and one mechanical engineering graduate student) observed the instructions. Then, the instructor conducted an examination to evaluate the learning outcomes of the students based on a set of questionnaires developed by the instructor as presented in Appendix A. Then, the independent evaluators evaluated the answers of the students and determined the learning outcomes of the students. In the second phase of the study, the instructor instructed the mechanical engineering concepts to the other group of students following the active plus experiential teaching and learning approach in the same classroom plus laboratory setting. The duration of the teaching and learning period was also 50 minutes. Seven independent evaluators also observed the instruction in the same way as they observed the active teaching and learning approach. Then, the instructor conducted an examination to evaluate the learning outcomes of the students based on the same set of questions developed by the instructor as presented in Appendix A. Then, the independent evaluators evaluated the answers of the students and determined the learning outcomes of the students. In both study phases, the evaluators evaluated the students for their engagement and enthusiasm based on their observations on the students during the lesson using a 7-point Likert scale (1 indicated the least and 7 indicated the most positive results). The evaluators received brief training and instructions from the instructor so that they were able to evaluate the students on the same ground. The evaluators submitted the evaluation results to the instructor. The evaluation results were anonymous. The confidentiality of the results was maintained.

In the second phase of the study, the students observed robotic illustrations of the concepts developed and operated by the instructor. The students did not need to interact with the robotic system directly. In both study phases, the evaluators did not need to ask questions to the students verbally or directly to evaluate the instructional outcomes. Instead, the evaluators evaluated the students based on their question answers written on examination sheets and on their observations on the students during the instruction sessions. In both phases of the instruction, the instructor instructed the concepts to the students in such a way that the correct answers to the questions shown in Appendix A were embedded in the instruction and it was possible for the students to know the answers to the questions in Appendix A clearly.

3.7 Research results and analysis

Table 1 shows the mean exam score for each question (standard deviation in parenthesis) between the two student groups. A paired *t*-test was conducted on the evaluation scores between the two student groups. The results showed that the evaluation scores between the two student groups were statistically significant ($p<0.05$). The results show that the instructional outcomes significantly improved for the active plus experiential teaching and learning approach compared to the active teaching and learning approach. It is to note that the instructional outcomes for active teaching and learning group were also high, but the outcomes for the active plus experiential teaching and learning group were higher. It happened because the active teaching and learning approach was also a good instructional approach, but the active plus experiential teaching and learning approach proved to be a better instructional approach due to the addition of robotic illustrations. It is assumed that robotic illustrations augmented the effectiveness of active learning by adding the advantages of experiential learning to active learning. Thus, robotic illustrations broadened the scope and effectiveness of active learning [15]-[17].

Table 2 shows the mean evaluation scores of engagement and enthusiasm rated by the evaluators for the two student groups. The results showed that engagement and enthusiasm also significantly improved due to the inclusion of the robotic system as an experiential tool in the instructional method [18]. The paired *t*-test results showed that the assessment scores between the two student groups were statistically significant ($p<0.05$). It is assumed that robotic illustration created a physical environment that attuned the students with the system and enhanced their physical engagement with the system [18]. Physical engagement enhanced their mental engagement as well.

Table 1. The mean exam score for each question (standard deviation in parenthesis) between the two student groups.

Question number	Active teaching and learning group scores	Active plus experiential teaching and learning group scores	Difference between the scores
1	8.52 (0.16)	9.18 (0.24)	+0.66
2	8.33 (0.33)	9.06 (0.22)	+0.73
3	8.62 (0.24)	9.31 (0.16)	+0.69
4	8.74 (0.19)	9.28 (0.24)	+0.54
5	8.17 (0.14)	8.98 (0.31)	+0.81
6	8.63 (0.38)	9.12 (0.09)	+0.49
7	8.86 (0.43)	9.46 (0.26)	+0.60
8	8.37 (0.11)	9.14 (0.20)	+0.77
9	8.56 (0.35)	9.10 (0.17)	+0.54
10	8.44 (0.17)	9.38 (0.23)	+0.94

Table 2. The mean engagement and enthusiasm assessment scores (standard deviations in the parentheses) between the two student groups.

Assessment Criteria	Active teaching and learning group scores	Active plus experiential teaching and learning group scores	Difference between the scores
Engagement	5.63 (0.12)	6.59 (0.19)	+0.96
Enthusiasm	5.51 (0.28)	6.44 (0.15)	+0.93

Robotics is an exciting technology and experiential learning based on such exciting technology might enhance students' enthusiasm during the lesson for the active plus experiential teaching and learning approach. It might happen as the students might be motivated by the robotics-based illustrations [19], they might trust the experiential results [20], robotics-based illustrations might reduce their cognitive workload in learning [21], and they might find robotics-based illustrations safe for learning [22].

4. Discussion

4.1 Limitations of the studies

Ten students participated in each group. The number of students was adequate to investigate the superiority of the active plus experiential learning approach over the active learning approach. However, inclusion of more students as well as independent evaluators could further enhance the generality and reliability of the results. Only three mechanical engineering concepts were taught in the studies. It is believed that teaching more mechanical engineering concepts as well as concepts from other engineering disciplines could further enhance the effectiveness of the proposed robotics-illustrated instructions. Application of multiple robotic platforms to illustrate the same concepts could further enhance generality and effectiveness of the results [11].

4.2 Potential misconceptions and their impacts

Misconceptions and lack of trust may develop in students due to robotic illustrations if the illustrations are not developed and executed properly [20]. Misconceptions may arise if robotic illustrations do not truly and completely reflect the engineering concepts, or if robotic illustrations misrepresent the concepts. Therefore, it is necessary to investigate if any misconceptions develop in robotic illustrations, and the misconceptions should be minimized through iterations in illustration design [1]. Similarly, performance of the robotic system in illustrating the concepts may develop students' mistrust or over trust in the robotic system [20]. Therefore, it is also necessary to design the performance level of the robotic system so that it can generate optimum level of trust in students [6].

4.3 Prospects, challenges, burdens and support

The prospects of the proposed active plus experiential learning are clear based on the results presented herein. The active plus experiential learning surely enhances students' learning outcomes, their engagement and enthusiasm in learning. Nonetheless, this approach also has a few challenges. For example, the instructor needs more resources such as robotic systems and laboratory setup in the classroom [4]. The instructor needs additional time and expertise to develop and operate robotic illustrations properly, avoiding misconceptions and misrepresentations. The class period also needs to be extended to accommodate robotic illustrations. Students may be over-interested in robots, which may distract them from other teaching and learning methods and arrangements. The robotic systems may cause safety hazards for the students [22]. As a result, the instructor needs to be aware of the safety hazards and implement safety procedures during class hours. Thus, the instructor needs additional commitments from the instructor himself/herself and additional support from the institution to make the active plus experiential teaching and learning approach successful.

4.4 Reduction in abstractive ability

The main objective of the presented research was to help students comprehend abstract concepts through physical and experiential learning approach. The results showed that the proposed active plus experiential learning approach enhanced students' ability to comprehend the abstract concepts. However, it needs to be investigated if experiential learning practice gradually impacts students' abstractive and cognitive abilities adversely. It means that students may be accustomed to experiential learning and they may fail to understand and think the topics that cannot be taught experientially. A detailed study of such impact can help justify the impact of the proposed experiential learning more clearly [15].

5. Conclusions and Future Work

In this article, two independent studies of instructing three fundamental and abstract mechanical engineering concepts were conducted. The mechanical engineering concepts were pneumatics, energy conversion, and vibration. In one study, the mechanical engineering concepts were taught to a group of 10 sophomore mechanical engineering students following a specially designed active teaching and learning approach. In another study, the same concepts were taught to another group of 10 sophomore mechanical engineering students following a specially designed active plus experiential teaching and learning approach. The main difference between the instructional approaches was that the concepts were illustrated using robotics-based illustrations for the active plus experiential teaching and learning approach, but such robotics-based illustrations were not used for the active teaching and learning approach. Both approaches were implemented in the same classroom plus lab setting separately. Both approaches were observed by a team of evaluators. The evaluation team also evaluated the instructional outcomes for both groups of students based on a specially designed brief examination and subjective assessments. The results showed that the student group that was taught the concepts following the active plus experiential teaching and learning approach learned the concepts more effectively than the student group that was taught the concepts following the active teaching and learning approach. The prospects, challenges, limitations, and burdens of the active plus experiential teaching and learning approach were then discussed, and the support required for the approach was identified. The results presented herein can come to the help of related instructors and STEM education policy makers in incorporating robotics and similar technologies as experiential kinesthetic teaching and learning tools to teach abstract and difficult STEM concepts to students.

In the near future, an advanced version of the studies will be conducted by removing or reducing the limitations discussed earlier. Number of student participants and independent evaluators will be increased. More mechanical engineering concepts including other STEM concepts will be taught using active plus experiential teaching and learning approaches involving multiple different robotic platforms. Research will be conducted to remove or reduce the challenges, burdens and misconceptions of active plus experiential teaching and learning approaches involving robotic platforms. More innovative qualitative and quantitative observation methods to observe and evaluate classroom performance for the active plus experiential teaching and learning approach will be used.

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Appendix A

Each student needed to write answers to each of the following questions. Maximum obtainable point for each question was 10.

1. Briefly explain what you mean by pneumatics.
2. How is force or torque generated in pneumatics?
3. What internal and external factors can affect pneumatic performance?
4. Briefly explain what you mean by energy conversion and energy conservation.
5. Write how the conversion of different forms of energy occurs in the laser engraving process.
6. What internal and external factors can affect the laser engraving process and the energy conversion process?
7. Briefly explain what you mean by mechanical vibration.
8. What are the causes of vibration?
9. What are the factors that can affect vibration of the machine (robot)?
10. How can you suppress or reduce vibration in the machine (robot) system?