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Does Performance-Based Assessment in an Introductory Circuits Laboratory Improve Student Learning?

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Abstract

Undergraduate engineering students regularly participate in laboratory experiences in introductory circuit theory courses. Based on instructor experience, it can be observed that students often struggle to remember how to use test and measurement equipment or important software from week to week, making long term retention of necessary skills inadequate. The facilitators of this study searched for strategies to improve student retention of important skills, and drew inspiration from performance-based assessment strategies used in the healthcare profession. In particular, physical therapy students are often subject to skills checks, where they must demonstrate competency in standard techniques for physical therapy practice. This approach was adapted to an introductory circuit theory lab, in which students were given regular skills checks to test competency with hardware and software standard in circuit theory courses. Data were collected for three years by asking students to complete anonymous Likert scale surveys designed to allow students to self-assess their achievement of the laboratory learning outcomes. The first year was a control group in which performance-based assessment was not used, while year two and three were separate experimental groups which were subject to skills checks. As a result of the addition of skills checks to the laboratory experience, student self-assessment of achievement of laboratory learning outcomes increased dramatically. This result is promising for the inclusion of skills checks in engineering laboratories to improve student competency using hardware and software common to engineering practice.

Introduction

Laboratory experiences are a commonality in undergraduate engineering curricula. Since the primary goal of engineering is the design and analysis of physical devices and phenomena for the benefit of humankind, it is logical that most engineering students require hands-on experience as a part of their education[1]. Not only does hands-on experience yield improved understanding, it also provides students with technical skills useful in engineering practice, such as the use of test and measurement equipment and certain software.

One particularly useful skill set in electrical engineering, and for students interacting with electrical equipment, is the use of electrical test and measurement equipment including multimeters, function generators, and oscilloscopes. Another skill valuable to a variety of engineering disciplines is the ability to prototype and construct circuits[3]. Even if students don't use test and measurement equipment or prototyping in their future careers or senior design experiences, it is valuable for these students to have an appreciation for how measurements are performed to the limitations and sources of error associated with using equipment to record data.

Standard circuit laboratories require students to use such equipment but often do not provide a method for a direct measurement of student ability to use it. Most commonly, assessment strategies include graded laboratory reports or checks that circuits function as expected[3]. A shortcoming of these methods is that work is often completed in groups, thereby failing to ensure that each student is capable of using the equipment at a competent level. As a result, some students may get by on the knowledge or ability of an academically stronger partner, or defer their learning to a more capable student. Through experience instructing circuit theory labs, the facilitators of this study have observed that students' deferral to more capable partners results in poor retention of important skills for later laboratory experiences and downstream courses. This motivates the desire to directly measure each student's ability to perform specific skills, which is the primary problem this research aims to address.

In the search for a viable alternative assessment method to augment existing strategies, the authors drew inspiration from the performance-based assessment strategy in medical professional programs. In the medical field, it is essential to test that each student is able to perform specific skills related to professional practice. The strategy of using performance- (or ability-) based assessment techniques have been implemented in medical education for decades[4-6]. One benefit of this strategy is that graduates from medical professional programs are expected go into medical practice. Since the stakes are high when dealing with human wellness, being able to complete a skill or ability with only 75% accuracy is insufficient! Students should be able to maintain a high competency level with each skill.

One particular tool used in physical therapy (PT) education is the performance-based assessment method called the skills check[4]. As a requirement to graduate, Doctor of Physical Therapy students are regularly subjected to skills checks to test competency, in which there were a set of abilities learned through class and laboratory hands on experiences that must be performed on a patient and assessed by an instructor. This particular method is the primary inspiration for the work in this paper.

This paper presents a study on the effect of adding skills checks as a form of performance-based assessment to standard laboratory instruction in an introductory Circuit Theory laboratory course at Roger Williams University. Cohorts from three consecutive years participated to provide a relatively large sample size (n=155). This study proposes that the employment of performance-based assessment by using skills checks improves student ability to complete specific tasks related to the use of test and measurement equipment and standard software used in engineering. Detailed within this paper is a review of relevant literature, specifics of experimental design, the set of laboratory learning outcomes, the topics covered in skills check, and the assessment of the effectiveness of this method.

Literature Review

The literature has shown that the inclusion of hands-on activities (i.e. laboratories) in engineering education is important for a number of reasons. In their paper, Feisel and Rosa[1] point out that the role of the laboratory today is to provide an opportunity for students to engage in hands-on learning activities, so that they can gain some physical intuition for concepts that they might not otherwise gain while in school. Miller et al[7] reported work performed to determine why hands-on activities are important. They also underscored the importance of the laboratory, since students today, upon entering higher education, have typically had fewer opportunities to learn by doing compared to those students who came before them. In addition, they suggest that hands-on activities also serve to get more students interested in engineering in the first place –

which is to say they are a recruitment tool. In fact, Aguirre-Munoz et al[8] reported, perhaps not surprisingly, that kindergarten students engage more readily with engineering concepts when they are presented in a hands-on, active manner. Hands-on components to education have also been reported in the popular press[9] as a means to improve retention once students enter engineering programs. Finally, we note that although they can be valuable in teaching selected concepts, computer simulations designed to mimic physical systems are not as effective as physical hands-on activities[10].

To its core, treatment of patients by medical professionals consists of the medical professional's correct implementation of a treatment that will improve the health of the patient. As such, it should be expected that one focus in the education of medical professionals is on the techniques or skills used for treating patients. As mentioned previously in this paper, a common way to assess students' mastery of these techniques is the so-called skills check. The literature reports use of the skills check in a variety of medical fields, including medical schools[6,11-15], physical therapy programs[4], nursing programs[16], and physician's assistant's programs[17].

The literature reports fewer examples of the use of the skills-check assessment method in engineering education. In fact, as we define the skills-check, there seem to be no examples. Given the less critical nature of engineering practice (i.e. it is not as often that engineers need to apply skills in life-altering situations) this is perhaps not surprising.

The studies which are reported in literature can be collected into a few general groups, understood in the context of the ABET program outcomes[18]. Some studies focus on assessment of ABET "technical skills"[19-22] some on professional skills"[23-24], and one on both[25]. It is the first group that is most relevant to this work. Of that group, the studies more closely related to the current are Suits et al and Salim et al who describe assessing students' laboratory skill at the end of the semester, rather than at multiple times during the semester as in the case of the current work.

Methods

This study proposes that the employment of performance-based assessment by using skills checks improves student ability to complete specific tasks related to the use of test and measurement equipment and standard software used in engineering. To test this hypothesis, an experiment was designed in which a control group did not complete skills checks, and two experimental groups completed skills checks. These students were asked to self-assess their ability to complete these tasks for all groups, and the results were compared.

This study considered three consecutive offerings of an introductory Circuit Theory course in the undergraduate focused engineering program at Roger Williams University. The control group consisted of students in the Fall 2014 offering of the course. Students in the control group participated in a standard laboratory experience, in which the only assessment strategy employed was evaluation of submitted lab reports. A total of 24 students participated in the study as a part of the control group. There were two separate experimental groups, consisting of the 2015 and 2016 offerings of the course. These groups saw the addition of skills checks as a method of performance-based assessment. The experimental group from 2015 consisted of 68 engineering students, while the group from 2016 was composed of 63 engineering students. The total number of students involved in this study was 155.

The experimental groups each completed four skills checks centered around the following topics:

1. Building a circuit on a breadboard, using a digital multimeter, and using a DC power supply.
2. Simulating a circuit in SPICE.
3. Solving for circuit values in MATLAB.
4. Using a function generator to produce a disturbance signal and an oscilloscope to measure signal values.

Skills checks are scheduled to take place two to three lab periods after a new skill is introduced, requiring students to retain and recall abilities that they have previously learned. Skills checks are typically administered towards the beginning of a laboratory period, after the laboratory assignment is introduced. A station is set up with equipment necessary to complete the skills check, and students are brought over one-by-one to perform the necessary skill. While the instructor is engaged in performance-based assessment, the instruction of the laboratory falls to lab assistants. Since the early lab time frame is typically spent performing calculations, this has not been observed to result in deficient lab instruction.

An example of a skills check assignment and grading rubric is shown in Figure 1. A list of tasks is provided for assessment, and students are required to demonstrate proficiency in each task. Lab instructors are directed to let students attempt each skill on their own, but to provide help as needed so that each student successfully completes each task. This provides an opportunity for each student to receive one on one instruction. The grade assigned is at the discretion of the lab instructor, whose job is to consider the degree of help that was offered to each student in assigning a grade. As a result, student grades are not a valid method of assessing the efficacy of this method, as grades are a subjective measure.

SKILLS CHECK 4: Function Generator and Oscilloscope

In this skills check, you will be tested on your ability to use the function generator and oscilloscope. Complete the following tasks on the first try for full credit, receive help for lower credit. To do this, connect the function generator to the oscilloscope using a BNC cable.

Skill	**Complete**
Set function generator to a 10 Hz sine wave	
Set function generator to 5 Vpp	
Adjust the O-scope vertical scale to fit signal	
Adjust the O-scope horizontal scale to show single period	
Use x-cursors to measure frequency	
Use y-cursors to measure amplitude	
Score (0-5 pts, based on completeness)	

Figure 1 Example of a skills check and rubric.

In designing the course evaluated, the following lab learning outcomes were established. Upon completion of the Circuit Theory Laboratory, students should be able to:

1. Construct a circuit on a breadboard.
2. Set a DC voltage using a power supply.
3. Use a digital multimeter to measure voltage and current.
4. Use a function generator to inject a signal.
5. Use an oscilloscope to display signals.
6. Use an oscilloscope to make measurements.
7. Solder.
8. Check your answers using SPICE software.
9. Use MATLAB to numerically solve sets of linear equations.

To assess the achievement of these lab learning outcomes, students involved in this study were asked to complete a Likert scale survey, rating their perceived ability on a scale of 1 to 5, with 1 corresponding to Strongly Disagree and 5 corresponding to Strongly Agree. This method of assessment is an indirect assessment method. In search of a direct method, it was determined that the most viable direct method of assessing of student understanding was evaluation of student laboratory grades or student skills check grades. These are both problematic: in both cases, grades tend to be subjective and can vary from instructor to instructor. Furthermore, a direct evaluation of student ability to perform these tasks is only accomplished by employing skills checks, which is the subject of this study, and eliminates the possibility of a control group.

To evaluate the student responses, the Cohen Size Effect is applied to measure the significance in size difference between sets of data. The Cohen Size effect is a metric used to measure if there is a significant difference between two sets of data. The Cohen size effect is calculated as

$$d = \frac{\mu_{Group1} - \mu_{Group2}}{\sqrt{(\sigma^2_{Group1} - \sigma^2_{Group2})/2}}$$

where Group 1 for this case are the experimental groups of 2016 data or 2015 data, and Group 2 are the 2014 control group data. As a metric, a size effect of 0.8 is considered large, and thus represents a significant change (one that could be observed with the naked eye). Size effects <0.2 are considered small, and thus the differences can only be observed through detailed study. Size effects between 0.2 and 0.8 are considered medium[26]. In addition, a null-hypothesis single sided t-test is applied with a significance value of α =0.01.

In addition to quantitative assessment means, the resulting data are plotted in a diverging stacked bar chart, which is shown to be the preferred method for visualizing the results of Likert scale surveys by Robbins et al[27]. In this chart, the neutral answer is shown in yellow, and is centered around 0%, while responses indicating a positive response are shown as positive percentages in shades of green, and responses indicating negative responses are shown as negative percentages in shades of red. This plotting strategy allows observation of the percentage of positive versus negative responses, which may help to interpret the resulting data.

Finally, as an additional measure of the value of skills checks, the 2016 Experiment Group was asked to qualitatively assess the efficacy of this assessment method on retaining ability with test and measurement equipment. These results are categorized into four sets, students who felt the skills checks were helpful, those who felt skills checks were somewhat helpful, those who felt they were hurtful, and those who abstained from providing an answer.

Results

A Likert scale survey was administered, which asked students to rate their achievement of lab learning outcomes. The same survey was completed by all 155 students participating in this study. As mentioned in the methods section, this study considered three consecutive offerings of an introductory Circuit Theory course in the undergraduate focused engineering program at Roger Williams University. The control group consisted of 24 students in the Fall 2014 offering of the course, while the two experimental groups consisted of 68 students from the 2015 offering and 63 students from the 2016 offering of the course.

The mean values of student ratings of the achievement of lab learning outcomes are displayed in Figure 2. The upper bar for each outcome corresponds to the ratings from the control group, the center bar represents results from the 2015 experimental group, while the lower bar represents the mean values from the 2016 experimental group. It can be observed that the mean value for every single outcome increases in the experimental groups when compared to the control group. In addition, the general trend is that the 2016 experimental group saw a slight increase when compared to the 2015 experimental group. Although it is easy to observe this trend, the question remains: are these changes significant? In an attempt to answer this question, two methods are used: the Cohen Size Effect and the null hypothesis t-test.

To measure the effect size between the control group results and the experimental group results, the Cohen size effect is computed. Table 1 summarizes the quantitative results of this study, presenting the average, standard deviation, and size effect for each group. Size effects larger than 0.8 are considered large, and are highlighted in green, while size effects between 0.2 and 0.8 are considered medium and are highlighted in yellow. There are no size effects below 0.2, which is considered small. A valuable takeaway from these data is that there is a positive effect to all outcomes as a result of using skills checks as a method of performance based assessment. Each effect size is, at the smallest, considered medium, indicating that the difference is likely to be noticeable to the naked eye. The facilitators of this study can concur with these results, as the improvement of student laboratory skills is evident in down-stream courses.

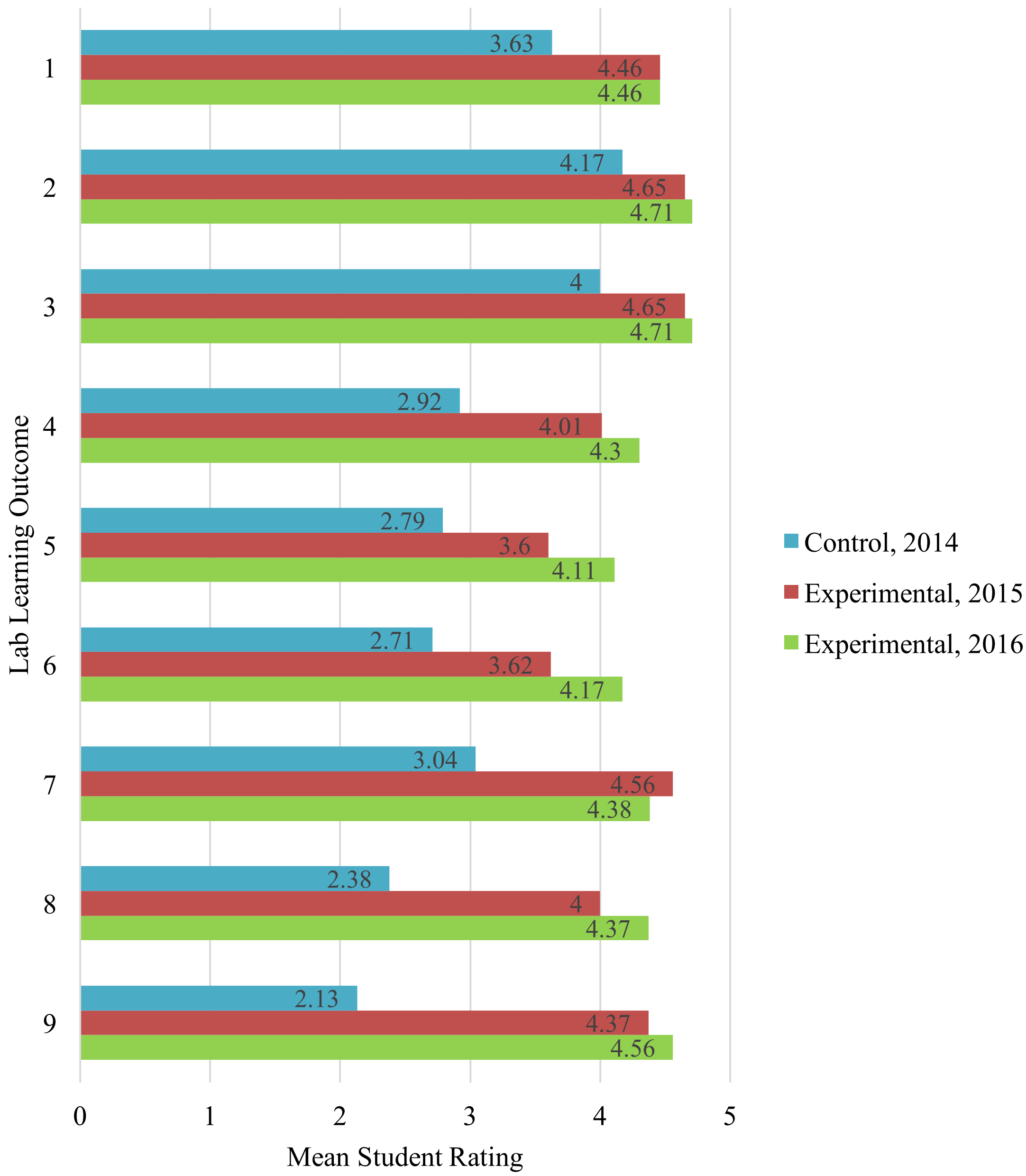

Figure 2 Mean values of student ratings of achievement of lab learning outcomes.

Table 1 Numerical results with Cohen Size Effect.

	Control, 2014		Experimental, 2015			Experimental, 2016		
Outcome	Average	Standard Deviation	Average	Standard Deviation	Cohen Size Effect	Average	Standard Deviation	Cohen Size Effect
1	3.63	1.48	4.46	0.72	0.72	4.46	0.64	0.73
2	4.17	1.12	4.65	0.62	0.53	4.71	0.46	0.64
3	4.00	1.31	4.65	0.62	0.63	4.71	0.52	0.72
4	2.92	1.27	4.01	0.89	1.00	4.30	0.89	1.26
5	2.79	1.30	3.60	0.99	0.70	4.11	0.97	1.15
6	2.71	1.40	3.62	0.99	0.75	4.17	0.96	1.22
7	3.04	1.53	4.56	0.76	1.26	4.38	0.85	1.08
8	2.38	1.68	4.00	0.85	1.22	4.37	0.77	1.52
9	2.13	1.94	4.37	0.86	1.50	4.56	0.56	1.70

Comparing the two experimental groups, the effect size is larger in the 2016 experimental group for all but one lab learning outcome. This lab learning outcome does, however, still display a large size effect when compared to the control group. Furthermore, in the 2015 experimental cohort, four outcomes saw a large size effect increase, while in the 2016 experimental cohort, six outcomes had a large size effect increase. Potential reasons for these improvements are further explored in the discussion.

In addition to the Cohen Size effect, hypothesis testing is also used. The null hypothesis is as follows: skills checks as a form of performance based assessment have no appreciable effect on student laboratory skills as outlined by the lab learning outcomes. In order to reject this null hypothesis, a single sided t-test must result in a p-value lower than the significance level, often set to be $\alpha = 0.05$. In this study, a significance level of $\alpha = 0.01$ is used, in an attempt to ensure that the result is not due to sampling error or random chance. As can be observed, the calculated p-value for each outcome with both experimental groups is much less than 0.01. with the largest value being 8.23E-09. This suggests that the null hypothesis should be rejected, and the original hypothesis that the employment of performance-based assessment by using skills checks improves student ability to complete specific tasks related to the use of test and measurement equipment and standard software used in engineering, be accepted.

Table 2 Control and experimental means with p-value calculated using a single-sided t-test with significance level α =0.01.

Outcome	Control	Experimental, 2015	p-value	Experimental, 2016	p-value
1	3.63	4.46	2.48E-14	4.46	2.28E-15
2	4.17	4.65	8.23E-09	4.71	4.37E-14
3	4.00	4.65	8.33E-13	4.71	2.66E-16
4	2.92	4.01	1.54E-15	4.30	1.24E-18
5	2.79	3.60	2.33E-09	4.11	3.41E-16
6	2.71	3.62	7.74E-11	4.17	2.56E-18
7	3.04	4.56	1.61E-25	4.38	6.81E-19
8	2.38	4.00	1.24E-24	4.37	1.12E-29
9	2.13	4.37	5.09E-32	4.56	2.29E-42

In addition to the quantitative analysis, the data can be plotted using a different strategy to help researchers observe the proportion of positive responses to negative or neutral responses. Such a method for displaying Likert scale data was proposed initially by Robbins et al[27] who suggested that data should be plotted in a diverging stacked bar chart. In this chart, the neutral answer is shown in yellow, and is centered around 0%, while responses indicating a positive response are shown as positive percentages in shades of green, and responses indicating negative responses are shown as negative percentages in shades of red. For sake of space, only the 2014 control group and the 2015 experimental group data are shown. Since the overall means increased from 2015 to 2016, it is not necessary to plot the 2016 results, if the 2015 data are sufficient in presenting the case.

Figure 3 displays the results of the Likert scale survey for the control group, while Figure 4 displays the same results for the experiment group. One immediate observation that can be made from these charts is that the 2015 experimental group had a far lower percentage of negative responses than the 2014 control group. This method of displaying data suggests that the increase in sample mean is not simply due to a higher percentage of students acquiescing and selecting 5: Strongly Agree, but instead suggests that far less students selected negative responses. (1: Strongly Disagree or 2: Disagree). Although these results may not add much to the discussion quantitatively, they do provide an attractive and easily understandable graphic for communicating the result. It should be clear that the higher degree of green seen on the graphic, the better the result!

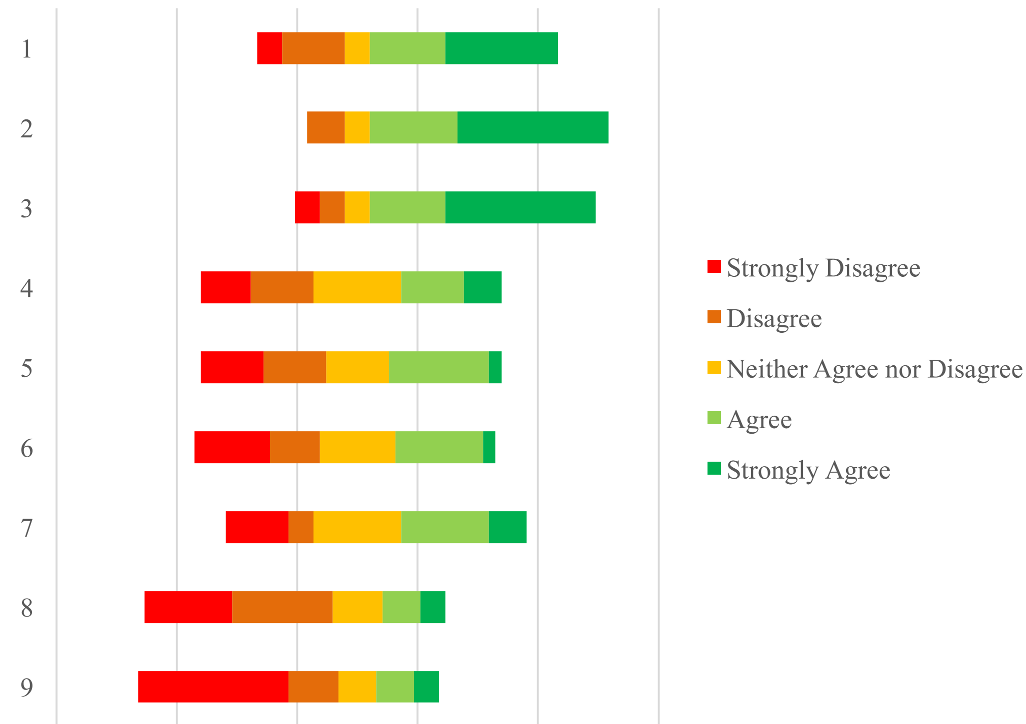

Figure 3 Diverging stacked bar chart displaying data from the 2014 control group.

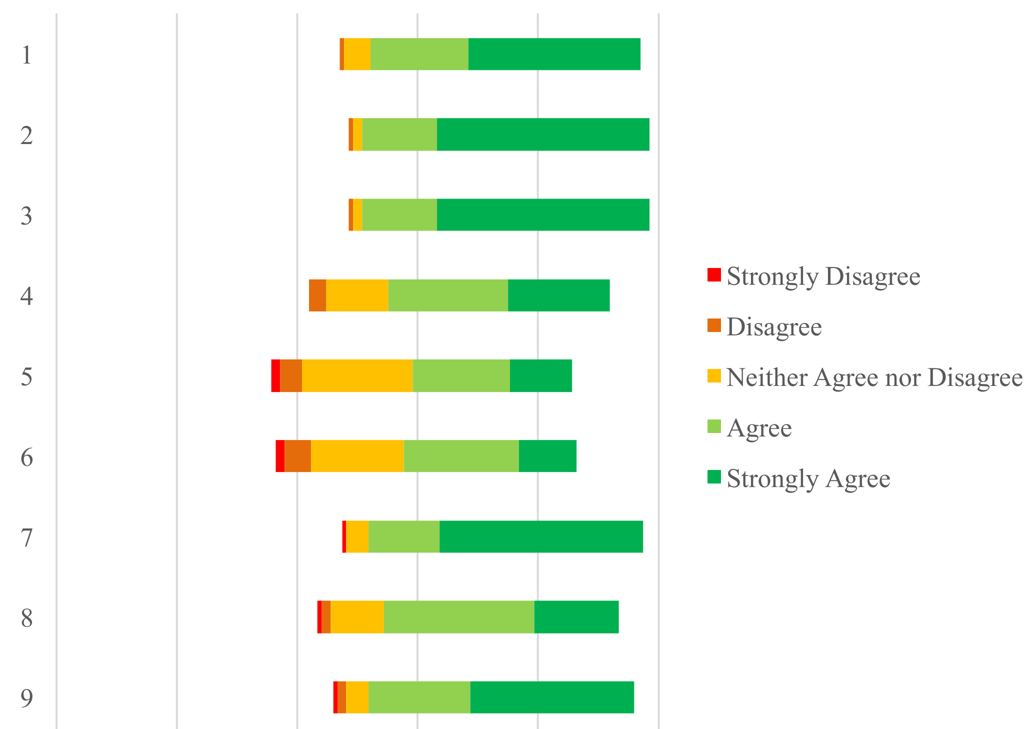

Figure 4 Diverging stacked bar chart displaying data from the 2015 experimental cohort.

Finally, students from the 2016 experimental group were asked to qualitatively evaluate the usefulness of skills checks in their laboratory education. These results are categorized into four sets, students who felt the skills checks were helpful, those who felt skills checks were somewhat helpful, those who felt they were hurtful, and those who abstained from providing an answer. The results of the qualitative survey are displayed in Table 3. From these results, it is possible to see that only 4.8% of respondents had a completely negative response to the use of skills checks. This amounts to 3 of 63 respondents. A total of 9.5% abstained from response (6 of 63), while the remaining 85.7% of respondents felt that the skills checks were at least somewhat helpful. Many of the students who felt that the skills checks were helpful stated so emphatically, which is encouraging for continuing this strategy in future course offerings.

Table 3 Results of qualitative survey.

Category	Percentage of Respondents
Helpful	69.8%
Somewhat helpful	15.9%
Hurtful	4.8%
No Answer	9.5%

Discussion

The results provided in the previous section compose significant evidence that the skills check as a method of performance based assessment is useful in encouraging student retention of laboratory skills. In this section, the authors will attempt to explain some of the results, and provide further evidence of the study's validity to remaining skeptics. Potential sources of error stem from differences in academic ability, as measured by the GPA of students entering the course, course performance, indicated by outgoing course GPA, and the effect of different instructors. In addition, the pros and cons of this method are discussed, as well as some lessons learned as a result of undertaking this study.

Incoming and outgoing GPA statistics are summarized in Table 4. Starting with academic ability, the incoming GPA for the control group was 3.04, while the incoming GPA for the 2015 experimental group was 3.06, and for 2016 the same metric was 3.04. If incoming GPA were a predictor in the resulting performance in laboratory environment, then logically the 2015 experimental cohort ought to have displayed the highest results, which they did not. Furthermore, the percent difference in incoming GPA among the three groups is about 0.65%, which can hardly be classified as significant.

Continuing in discussion of course performance, the outgoing course GPA is also displayed in Table 4, as well as the Δ between incoming and outgoing GPA. If course performance or difference between incoming and outgoing GPA were predictors of student achievement of lab learning outcomes, then the highest result would be the control group, and the lowest would be the 2016 cohort. This has already been shown, in the Results section, to be the opposite. Therefore, it is reasonable to conclude that GPA was not a large contributing factor in student rating of achievement of lab learning outcomes.

Table 4 Incoming and outgoing GPA statistics for control and experimental groups.

Semester	Incoming GPA	Outgoing GPA	Δ
Fall 2014	3.04	3.22	+0.18
Fall, 2015	3.06	3.15	+0.09
Fall, 2016	3.04	2.89	-0.15

The effect of different instructors may be more significant than the GPA data and should be discussed appropriately. The control group was composed of students working with three different instructors, and the 2015 experimental group saw students with those same three instructors. On the other hand, the 2016 experimental group were instructed by two of the original instructors, with the addition of two first-time circuits instructors, making up the instruction of 51% of the study participants in this cohort. It is reasonable to suggest that this change may have resulted in the increase from 2015 to 2016 that is visible in the data. However, the change in instruction cannot account for the differences observed between the 2014 control group and the 2015 experimental group. Such differences therefore must be largely due to the addition of skills checks into the laboratory experience.

A supplementary comment on the assessment of the efficacy of this method, as previously stated, is that the facilitators of the study could not justify any method of direct assessment of student ability as viable other than laboratory grades. The authors object to using grades as a method of assessing pedagogical techniques, as grades are subjective and at the discretion of the laboratory instructor. Furthermore, any more direct assessment of students' skills would require the use of something like skills checks for the control group, and since this research studies the effect of skills checks, this would compromise the analysis. Another form of direct assessment would have been to subject students to the skills checks sometime after the completion of the course and record scores at that point, but this was found to be inviable. If this study were repeated, this is one area that could be greatly improved.

There are several positive impacts made as a result of this approach to laboratory education and assessment. The first is that students perceive they are better at performing certain laboratory skills when they are subject to skills check when compared to having no performance-based assessment. This is likely the result of students spending increased time with test and measurement equipment and software in preparation for the graded assignment. Another attractive quality of this approach is that it allows for one on one instruction if the student is unable to complete the skills check correctly. This can be significantly beneficial in a laboratory experience that is often completed as a group, and goes part of the way toward eliminating strong group members carrying weaker members. One final benefit of this method of evaluation is that it provides instructors with timely feedback on the strengths and weaknesses of their laboratory instruction. Repeated errors among several students participating in performance-based assessment can illuminate skills in which students lack appropriate competence. This feedback can motivate review and emphasis on important topics that students have not yet mastered.

This approach is not without detractions however (very few are). Performing skills checks takes away from dedicated time to complete laboratory assignments, and isolates a student from their group that requires their presence to complete the lab. Another negative to this approach is that skills checks take instructor attention away from the current lab. If there is no second instructor or lab assistant, this results in a lack of help for students that have completed their skills checks and would like to work on the current laboratory assignments. These diminutions to laboratory experience necessitate sharing some lessons learned throughout the period of this study which attempt to alleviate some of the negatives.

One lesson learned that can increase the speed of performing skills checks is to have two or three experimental apparatuses set aside for use in skills checks so that one student does not have to wait for another to completely finish setup and tear down of the equipment before received instructor attention. Another valuable lesson is that instructors should be both competent and receive appropriate training in use of the test and measurement equipment and software deemed important in the skills checks and lab learning outcomes. This has the added benefit that lab instruction in general is improved as a result. An additional lesson that improved implementation of this approach is that a capable lab assistant can lessen the feeling of low instructor availability during skills checks. Two final lessons that greatly improved skills check results were to create instructional videos for each piece of equipment, so that students may review at home, and to allow students some practice time at the beginning of the lab period prior to starting the skills check.

To conclude the discussion, although this method is not without detractions, the benefits to achieving lab learning outcomes outweigh potential detriments in some cases. This approach may not be for everyone, but was effective at an undergraduate focused engineering program with relatively small class sizes. One very positive, yet anecdotal, effect is that downstream courses, such as Signals and Systems, Control Systems, and Mechatronics benefited directly from improved student retention of laboratory skills from Circuit Theory.

Conclusions

The experimental design and results provide significant evidence in favor of using skills checks as a form of performance-based assessment to improve student achievement of lab learning outcomes based around the ability to use test and measurement equipment and software common to engineering practice. Not only does the data suggest that the hypothesis is valid, the difference in outcome achievement between the control and experimental groups is sizable, to the point that most differences are observable to the naked eye. These results are favorable for the inclusion of similar approaches in other engineering laboratory courses or, at the very least, in similar Circuit Theory courses at other institutions.

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