Reflection on System Dynamics Principles Improves Student Performance in Haptic Paddle Labs

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Abstract*—*Contribution: **Significant effort has been placed on the development of laboratory exercises for mechanical engineering curricula. Often, however, the exercises are not structured to encourage students to see the labs as a scientific process, instead of a checklist to be completed. Facilitating reflective observation and abstract conceptualization during the concrete experience (CE) of the lab improves student performance.**

Background: **Extensive work has been put into the development of simple, low-cost educational tools to improve learning by supplementing curricula with hands-on experiences. Several devices, including haptic paddles, have been developed to combine dynamics and mechatronics content which culminate in rendering virtual environments. Despite demonstrated student interest in haptic devices and the foundational role of CE in learning, experimental comparisons of learning outcomes over a broad range of devices have had mixed results.**

Intended Outcomes: **Device design can only address the experience portions of the learning cycle—effort put into encouraging and mediating a reflection phase will improve student performance. To test this hypothesis, the performance was compared of groups receiving the standard haptic paddle lab curriculum or a curriculum intended to facilitate reflection.**

Findings: **Students receiving the reflective curriculum had statistically significant higher scores on lab report grades than those receiving the standard, non-reflective curriculum. The increased performance across multiple student GPA quartiles suggests that even modest curriculum changes designed to encourage reflection can improve student performance.**

***Index Terms*—Haptics, laboratory, mechanical engineering curriculum, mechatronics, reflection, undergraduate.**

I. INTRODUCTION

THE GOAL of any laboratory hardware implementation is to improve student learning by supplementing curriculum with hands-on activities—a foundational element of undergraduate engineering curricula. Low-cost haptic devices are valued for their ability to transmit kinematic and sensory information, especially for topics best explained through interactions [1], [2]. Many well-designed devices have been developed for dynamics and mechatronics curricula, where the goal is to connect students' lifetime of experiences using and interacting with dynamic systems with established engineering principles and models, in a reasonably controlled and simplified manner. Recently, haptic devices have been implemented in curricula in nanoscale science [3], biology [4], and broad STEM education [5]. For all implementations, students have consistently expressed interest and enthusiasm for these devices, both anecdotally [1], [6], [7], and when evaluated with Likert-scale surveys [8], [9]. A few controlled experiments undertaken to examine the impact of haptic paddles on student learning [2], [10] showed generally positive results of implementing haptic paddles. Bowen and O'Malley [10] examined the impact of adding the haptic paddle to laboratory curriculum, and quantified this impact through a 16-item rubric which scored students' grasp of concepts on a three-level scale, ranging from not correct to fully correct. Gorlewicz *et al.* [2] quantified both the impact of the lab exercises and the timing of student learning, using a 25-question quiz, administered in a randomized manner before the lab, after a pre-lab lecture, after the lab, and after completing the lab report; this showed that completing all of the lab experience steps significantly contributed to student learning. However, these studies did not assess the impact their curricular modifications had on students' course performance, instead focusing on separate, ungraded assessments. Other studies show limited positive or even negative effects on learning outcomes with haptic devices [1].

Kolb's Experiential Learning Cycle (KELC) [11], a framework for the learning cycle based on an experiential learning model, consists of four abilities: Concrete Experience (CE), centered on involvement in an activity; Reflective Observation (RO), where students reflect on and observe the CE; Abstract Conceptualization (AC), where RO turns into generalizable concepts, and Active Experimentation (AE), using theories and concepts to solve problems and make decisions. Examining the current laboratory exercises for the haptic paddle using this model, it becomes clear that significant effort has been focused on optimizing CE, hoping to propel students straight through to achieving AE. Such efforts neglect the other steps of KELC.

It is also important to place emphasis on the design of devices and the laboratory exercises themselves, since it has been shown that exercises that devolve into assembly and other low-level operational concerns contribute to poor student learning [12], [13]. Clearly, neglecting to capture all

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the KELC abilities as a part of the pedagogy of the laboratory environment limits the efficacy of any exercise. The authors' hypothesis is that the transfer of knowledge is best achieved through labs that not only provide concrete experience, but complete KELC by facilitating reflection and abstraction during the experience, instead of relying on it occurring later, such as while writing lab reports. Reflection, say Boyd and Fales [14], is the key iterative process by which experiences transform the learner's conceptual understanding. Carol [15] posits that thinking reflectively is the cornerstone of learning, motivating research on reflection on student learning, or a "reflection on reflection."

In this spirit, the authors hypothesize that a laboratory curriculum that encourages student reflection will improve students' performance when evaluated across Bloom's Taxonomy of Educational Objectives (BTEO) [16], a fundamental paradigm for developing evaluations and assessments. The first of the six levels of BTEO, Knowledge, consists solely of information retrieval, ranging from facts to generalizations and theories. The largest and second level, Comprehension, is focused on translating, interpreting, and extrapolating communication received by the learner. The third, Application, takes Comprehension a step further, and hinges on the ability to select and apply an abstraction without guidance, where this lack of guidance is the key separation from Comprehension. The fourth, Analysis, exists on a spectrum between Comprehension and Evaluation, and is characterized by the detection of elements of a concept, relationships between these elements, and their governing principles. The fifth, Synthesis, is a creative behavior which results in the creation of new knowledge structures. In many ways, a learner who has achieved this level of BTEO has the KELC ability of Abstract Conceptualization. The sixth, Evaluation, at the highest end of the Analysis spectrum, consists of value judgments, with criteria either provided to, or by, the learner. To test the hypothesis that facilitating reflection will improve learning, student performance across BTEO in a junior-level dynamics course was compared between students receiving the standard curriculum, and those receiving materials that encouraged reflection across these levels.

The standard curriculum, the course description and a sample problem are detailed in Section II. The reflective curriculum and assessment methods are presented in Section III. A statistical analysis of the results of the study is presented in Section IV. Lastly, results and their implications for future work are discussed in Section V.

II. OVERVIEW OF MODELING DYNAMIC SYSTEMS

The junior-level system dynamics course Modeling Dynamic Systems at Rice University is a major distribution requirement for mechanical engineering, and a technical elective for bioengineering majors. The course provides students with tools for—and hands-on experience with—identifying, characterizing, and tuning various types of dynamic systems, in theory and in practice. Annual enrollment is approximately 70 students.

A. Course Objectives

Together, the laboratory and lecture sections of the course have the objectives to:

1) Develop skills in lumped parameter modeling for mechanical, electrical, thermal, and fluid systems.
2) Develop skills in analyzing dynamic systems through the application of Laplace transforms, block diagrams, and transfer functions.
3) Develop skills in analyzing dynamic systems through the application of transient response analysis.
4) Provide knowledge and skills associated with using computer software (MATLAB, Simulink) in analyzing dynamic systems and control systems.
5) Provide knowledge and skills associated with using an experimental hardware platform (haptic paddle) and basic electrical circuits, interfaced with computer software, in analyzing dynamic systems.

To achieve these objectives, students have assignments in both the lecture and laboratory portion of the course.

B. Laboratory Overview

The laboratory portion of the course, which is where the experimental reflective strategies were implemented, is focused on providing hands-on experiences of the second order system content, as well as an introduction to topics in control theory, electrical engineering, and mechatronics. All supplementary lab curricular materials, including assignments and rubrics, are available online: http://mahilab.rice.edu/content/mech-343-lab-handouts-and-grading-rubrics.[1]

The lab exercises are centered around the Rice University haptic paddle [17], a low-cost (compared to commercial educational products) single degree of freedom (DOF) device, designed to render haptic environments and illustrate mechatronic concepts. Inherent to the paddle design are nonlinear, multi-domain dynamics, which serves as an introduction to basic control theory, mechatronic implementation hardware, and sensors. The design of a teaching tool affects not only the practicality of implementing the device, but also the learning outcomes of using the device [1]. The haptic paddle design therefore balances performance with operational concerns, with a focus on maximizing productive time on the device, rather than time spent in assembly or repair [12], [13]. Using LabVIEW, National Instruments (NI) myDAQ or myRIO, and an Advanced Motion Controls 12A8 servoamp for closed loop current control allows students to neglect inherent, higher-order motor dynamics during the analysis, with good correlation to observed behavior. This equipment, and its robust design, encourage students to explore the performance of the device as a physical dynamic system, allowing more time for reflection and learning.

III. EXPERIMENTAL CURRICULUM DESIGN

While the performance of the Rice haptic paddle is sufficient to support laboratory experiments, the mere existence

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[1] Information on the design, drawings, bill of materials, and manufacturing instructions is posted online: http://mahilab.rice.edu/content/hands-haptics-haptic-paddle.

of hands-on experiments does not guarantee student learning of key concepts. Gunstone [12] raised specific concerns that the acts of assembly and taking measurements becomes the focus of lab exercises, instead of making interpretations of the experiment. This follows the authors' intuition that students do not complete KELC, but instead complete a checklist of actions. Therefore, the experimental laboratory curriculum was modified with purposefully-designed opportunities for reflective observation and abstract conceptualization, absent in the standard curriculum, that took the form of pre- and post-lab discussions, as suggested by Abdulwahed and Nagy [13]. At the start of each reflective lab exercise, rather than proctors presenting students with a predefined set of steps, proctors guided discussions to motivate students, and to have them design the lab experiment. The post-lab discussion—an exit requirement for the reflective lab session—questioned students about the meanings of results, and asked open-ended questions to have them further probe the purpose of the experiment before exiting the lab.

This section presents the protocol used to evaluate the impact of reflective learning activities, provides details of the laboratory exercises that comprise Rice's junior-level system dynamics course, and describes specific activities designed to promote reflection and the tools used to evaluate performance.

A. Experimental Protocol

The authors hypothesized that the inclusion of reflective learning activities in laboratory exercises in a system dynamics course would improve student performance in labs, homework, and exams. Data collection took place across two of the yearly offerings of the course (MECH 343, Modeling Dynamic Systems), a junior-level course required for all mechanical engineering majors at Rice University. During each of the two semesters, students attended lectures, completed homework and exams, and performed laboratory exercises. Four lab sections are offered each semester, with students divided into teams of two or three to complete the six exercises and reports.

Each semester, two lab sections received materials using standard delivery practices, and two were conducted using reflective activities, the experimental condition. Students were assigned lab sections to ensure that experimental groups (standard vs. reflective) were balanced according to incoming GPA. Informed consent was given by 131 students in compliance with Rice's University Institutional Review Board.

B. Lab Curriculum Description

Both the standard control curriculum and the reflective curriculum had the same experiments and procedures, but the reflective curriculum also contained reflective discussions, post-lab questions, and demonstrations of commercial haptic hardware. Reflective materials were designed to facilitate KELC. Pre-lab discussions were designed to encourage RO during the CE, to encourage more AC and AE during the lab. Post-lab questions were an exit requirement (ungraded, unrecorded) of the lab to force more RO, thus preparing students for AC during the lab report process. While the pre-lab discussions were tailored to the content of the individual lab, post-lab discussions were consistent across labs. Specifically, students were asked "Why did the lab happen?" "What did you learn?" and were required to pose one question extending the experiment in a meaningful way. In the authors' experience, these questions were typically answered correctly on the first or second attempt, with the main modifications to the group answer coming not from proctor input, but rather from intra-group discussion, and from having to contemplate the answer to these questions extemporaneously.

Lab 1: In the first exercise, students are given instructions on safe practices, introduced to the electrical circuit elements they would be using during the semester, and given an overview of the goals of the lab section. Reflective materials encourage students to make connections between the lab and lecture sections. Students receiving the reflective curriculum are led to discuss why there is a lab component to the course, to maintain the gains seen in [10], where student learning was improved through the addition of cohesive, connected lab experiments.

Lab 2: The second lab introduces the haptic paddle, and is focused on techniques for linearization, an early topic in the lectures. Students assemble their paddles, linearize the output of the Hall effect sensor, determine the motor torque constant, and conduct system identification experiments to determine paddle inertia. Reflective materials for this experiment are focused on deriving methods to determine the system parameters. Students are asked what methods they would use to characterize systems they interact with on a regular basis (buttons, diving boards, ceiling fans), leading them to suggest that they interact with the system in some measured way (push the buttons to see how stiff it is, bounce on the diving board to determine its natural frequency, watch the time response of the ceiling fan to see if the appropriate number of "clicks" had been applied to turn it off) to determine something about the system. Students are led to view the lab experiments as having the same form as their prior, familiar experiences, aimed at the BTEO level of Analysis. Post-lab questions, such as "What role did noise play in your measurements?", forced students to grapple with content beyond the course's curricular goals but that nevertheless impacts the experiment.

Lab 3: The third lab introduces first and second order passive RLC circuits, and how to tune their responses. It provides students with hands-on experiences with circuits, as well as a chance to generalize their knowledge of familiar linear mechanical second order systems to electrical dynamics. The reflective materials focus on this often-missed connection. Students are asked to identify mechanical analogs for RC and RLC circuits in pre-lab discussions, aimed at Comprehension/Application (depending on the level of guidance provided to students by proctors), to better transfer familiarity from the mechanical domain to the electrical. These discussions also stress the value of the time constant, damping ratio, and natural frequency when describing any dynamic system, aimed at the BTEO level of Analysis. Post-lab questions ask students to connect the magnitude of the step responses in the experiment at hand (square waves increase in frequency from 10 Hz to 1kHz, and the capacitor cannot fully charge), and the new concept of a frequency response, aimed at the BTEO spectrum between Analysis and Synthesis.

Lab 4: The fourth lab in the sequence continues the fundamentals of electrical engineering content of the course by introducing op-amps. Pre-lab discussions are focused on connecting students' intuition about damping and friction as non-ideal effects in mechanical systems to the electrical domain, driving home the difference between idealized op-amp equations and practical ones. Questions about the ideal vs. practical integrator, aimed at the Analysis level of BTEO, require students to combine their knowledge of the equations for the integrators with their experience with electrical circuits. Additional post-lab questions ask students to describe the value of tunable parameters in their systems (i.e., potentiometers) to account for unaccounted resistances.

Lab 5: The fifth lab completes the system identification of the paddle system, with experiments using first and second order time responses to determine motor damping and total system inertia and damping while utilizing closed loop feedback control. In the pre-lab discussion, students are asked to design an experiment to determine the damping parameters of a ceiling fan, with the goal being to identify multiple sources of damping (fan blades and bearing/motor losses). This motivates the design of the experimental set up (shunt resistor across spinning motor). This activity, aimed at Comprehension and Analysis, is key in preparing students for post-lab questions targeting Evaluation. In addition to the "what" and "why", the post-lab questions require students to identify limitations in the experimental design, and suggest improvements. One deliberate limitation to the experimental design is the use of a small value (5Ω) resistor, which, if slightly incorrect, can greatly impact the results of their experiment. While some groups identify this shortcoming, often students require some leading questions pointing towards the equations governing the spin-down response, and the variability in resistances measured in prior labs.

Lab 6: The final lab is the culmination of the course, interacting with virtual environments and teleoperation with the haptic paddle. In the pre-lab discussion of virtual environments, students are asked how to approximate simple haptic environments, such as a virtual wall. Specifically, proctors would ask "What values of stiffness and damping would you use to approximate a wall?" with student responses varying from "high" to "low" for both stiffness and damping properties. Follow up questions led them to the correct conclusions that both values should be high, moving the targeted level of BTEO from Application to Comprehension. The pre-lab discussion also established connections between the labs, by directly asking students "why" and "how" the labs were connected. Additionally, students were shown connections from the lab course to active areas of research at Rice, to bookend the information presented at the beginning of the laboratory series.

C. Evaluation Tools

This section explores the assignments used in this study in terms of the levels of BTEO, from Knowledge to Analysis, evaluated in aggregate in the lab reports. These reports were a combination of individual grades on the pre-lab assignment, and a collective grade on the lab report. While the lab reports address some aspects of Knowledge, such as the general form of second order differential equations and their solutions, most of the reports examined the interconnected levels of Comprehension, Application, and Analysis. In prelab materials, students would be given abstractions, and instructions for how to use them (Comprehension). In the lab reports, students would be given opportunities for unguided selection and use of an abstraction to answer questions (Application) as well as requirements for identifying underlying relationships and principles (Analysis) in their discussion sections. Post-lab questions required students to make some Evaluation-level critiques of the experiment design and haptic paddle design, but were treated only as an exit requirement from the lab, and not part of the grading rubric.

Grading rubrics were tailored to each lab and used to evaluate student performance across multiple levels of BTEO. For the lab exercises, students worked in teams of two or three, and turned in a group report that included pre-lab exercises, graded separately for each individual, and worth approximately 10-15% of the report grade. These small teams were shifted weekly, decreasing the likelihood of the same individuals performing most of the work. Students were graded by the proctors of their lab sections, who were given instructions on standards and provided with sample responses in addition to the solutions. This separated grading scheme meant that the graders of the experimental group did not have knowledge of the control group performance, and vice versa. The homework assignments and exams were graded by proctors for the lecture course, and had no specific knowledge of this experiment.

D. Sample Exercise - Time Domain System Identification

This section provides a detailed description of the experiments and scoring of the fifth lab exercise for all students. (All curricular materials are available at the URL given in Section II-B.) Lab 5, "Time Domain System Identification" focused on characterizing haptic paddle components. This system identification experiment is designed to meet course objectives 1, 3, 4, and 5 by requiring modeling of both mechanical and electromechanical systems, analyzing the step responses of these systems, comparing experimental data to modeled behavior in MATLAB, as well as providing opportunity to interact with experimental hardware.

The lab exercise has two parts, first, to determine the damping constant of the motor via a 'spin down' test, and second, to generate a step response with the haptic paddle, providing a hands-on experience with first and second order system responses. To provide context for the system identification experiments, and to help distinguish individual input from the team lab score, the prelab assignment is more extensive than for other labs, and is worth 20 of the available 100 points for the assignment. This portion consists of drawing the free body diagram of the motor subsystem and complete haptic paddle system (8 points), generating the equation of motion (2 points), solving for the EOM as a function of time (2 points) and deriving system parameters for the electromechanical and mechanical systems (8 points). Operational aspects of the lab report are worth 15 points, requiring students to identify the goal of the experiment, explain the experimental procedure and equipment used, and draw correct conclusions from the experiments. The lab report separates results and explanations of these results into two sections, to provide opportunities for students to earn points on lower levels of BTEO (Knowledge, Comprehension) with direct questions answered with formulas and established equations, as well as higher levels (Analysis and Synthesis).

The first result required in the lab report is to plot the first order decay generated after spinning up the motor to a constant speed and shorting a power resistor across the motor leads (2 points). Combined with the prelab equations of motion, students are required to determine the time constant of the system, τ, (3 points), use this dimensionless parameter, along with the calculated inertia value (2 points) to determine the total damping constant of the electromechanical system (3 points), parse out the contribution of the motor (3 points) and lastly simulate the system in MATLAB (2 points), for a total of 15 points. The explanation of these results is worth 20 points, with students being asked some guiding questions. This explanation requires students to provide the equation of motion (4 points) and response as a function of time (4 points) to discuss the meaning and utility of the time constant τ (4 points), the causes of differences between theoretical expectations and experimental results (4 points), and to address the (dis)similarity of solutions to the first order differential equations (4 points).

To complete the second portion of the lab, students set virtual spring and damping rates on the haptic paddle, and generate an oscillating step response measured by the Hall effect position sensor that they calibrated in the second lab exercise. For their results section of the report, students are required to reproduce the plot of paddle handle angle over time (3 points), calculate the parameters ζ and ω_N which govern the oscillatory decay using the logarithmic decrement method (4 points), determine the complete system inertial, damping, and spring constants (4 points) and then determine the contribution of the transmission to the total damping of the system (4 points). They must explain why these results have a steady state error (5 points) and compare the various experimentally-determined damping coefficients (10 points). This final task proves to be challenging, as to explain the results students must fully understand the assumptions made during the motor damping experiment of part I, utilizing the higher BTEO levels of Analysis, Synthesis, and Evaluation.

IV. RESULTS

The proposed curriculum was assessed in its impact on homework, laboratory grades, and final exam grades, under the assumptions that positive changes in the laboratory curriculum can carry over into classroom performance. In addition to gross impacts, the assessments are also shown within each of four GPA quartiles to investigate the primary beneficiaries of the reflective materials.

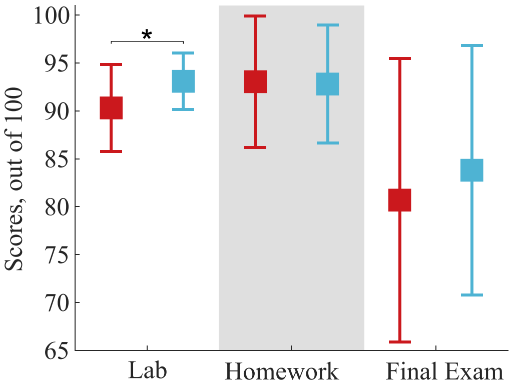


Fig. 1. Factorial ANOVA shows a statistically significant difference in lab averages between control (left of each pair) and experimental group (right), motivating the use of the proposed reflective curriculum. Error bars extend one standard deviation from the means.

A. Factorial Design

First, students' incoming GPA, homework average, lab average, and final exam score were analyzed with a 2×4×2 [Group (control, experimental); Total GPA quartile (1-4); and Year (1 and 2)] factorial ANOVA, summarized in Fig. 1. Prior to the ANOVA, one subject's scores were removed as outliers, since they fell outside of three interquartile ranges past hinges, resulting in a final sample size of 130 (63 control, 67 experimental). There is a main effect of whether the student was in the control or experimental group for the lab averages, F(1, 114) = 18.64, $p < .001$. No other variable had a significant effect or reliable interaction with experimental group. This result supports two conclusions. First, the experimental and control groups were well balanced entering the study, because there were no significant effects or interactions with students' GPA. Second, the experimental condition had an effect on students' lab average scores, but not on the rest of the course. Due to these conclusions, further investigation is restricted to the relationship between Group and Lab performance with a mixed design investigating individual labs.

B. Mixed Design

Next, the students' scores on each lab were analyzed with a 2 × 4 × 2 × 6 [Group (control, experimental); Total GPA quartile (1-4); Year (1 and 2); Lab Exercise (1-6)] mixed ANOVA with repeated measures on the last factor.

There are significant main effects of Lab Exercise, F(5, 570) = 26.89, $p < .001$, Group, F(1, 114)= 18.64, $p < .001$, and an interaction between them, F(5, 570)= 2.85, $p = .015$. There is also a significant main effect of GPA quartile, F(3, 114)=6.63, $p < .001$. This suggests that the students found some labs more challenging than others. A significant interaction between these factors suggests the reflective activities had a greater impact with some labs than others. The additional significant effect of GPA quartile motivates splitting the data to see how the experimental curriculum affects different student groups, shown in Fig. 2.

For the first quartile (highest GPA), there is a significant main effect of Lab Exercise, F(3.63, 105.25)= 7.36, $p < .001$. There was a marginally significant main effect of

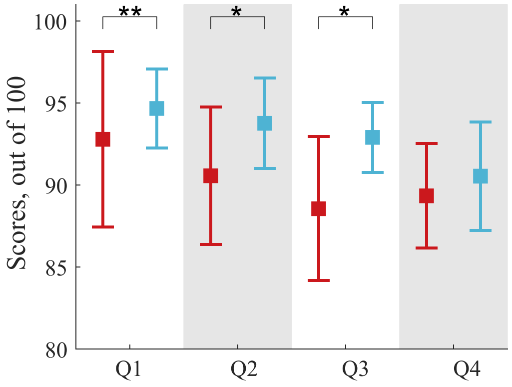


Fig. 2. Average lab scores separated by GPA quartile, with Q1-Q4 organized highest to lowest incoming GPA. Error bars extend to one standard deviation from the means, with control group scores on the left of each quartile and experimental groups on the right.

Group F(1, 29)= 3.78, p = .062. Also, there is a significant interaction between Group and Lab Exercise, F(3.63, 105.25) = 2.73, p = .038 with a Huynh-Feldt (HF) adjustment made to reduce the departure from sphericity.

For the second quartile, the experimental group has significantly higher lab grades than the control group, F(1, 30)= 5.85, p = .022. The overall scores on the labs are significantly different, F(5, 150)= 5.24, p < .001; however, the interaction between them is not significant.

The third quartile has the same results as the second, with the experimental group scoring significantly higher than the control group, F(1, 31)= 11.88, p = .002. The lab scores are significantly different as well, F(5, 155)= 7.92, p < .001, but there is no interaction between them.

For the fourth quartile (lowest GPA), the experimental group scores are not significantly different from the control, and there are no significant interactions between Group and Lab Exercise, although there is a significant main effect of Lab Exercise, F(5, 120)= 8.82, p < .001. The experimental curriculum failed to make a difference in the students struggling with the material, which can also be observed qualitatively.

The repeated measures were used to examine the students' scores on individual lab exercises, suggested by the interaction between Group and Lab Exercise found for the first quartile. Fig. 3 shows how students, within each GPA quartile, scored on individual lab assignments with significant and marginally significant main effects labeled with * and **, respectively. For the first GPA quartile, there were significant main effects of Group for Lab 3: F(1, 29)= 8.31, p = .007, and marginally significant main effects for Lab 1, F(1, 29)= 3.532, p = .070. For the second GPA quartile, only Lab 1 had significant main effects of Group, F(1, 30) = 6.75, p = .014. Interestingly, the third GPA quartile had significant main effects for Lab 1, F(1, 31)= 6.48, p = .016, Lab 4, (1, 31)= 5.21, p = .030, and Lab 5, F(1, 31)= 6.00, p = .020 with additional marginally significant main effect of Group for Lab 2, F(1, 31)= 3.19, p = .084. Lastly, for the fourth GPA quartile, there were marginally significant main effects of Group for Lab 1 F(1, 24) = 3.18, p = .087.

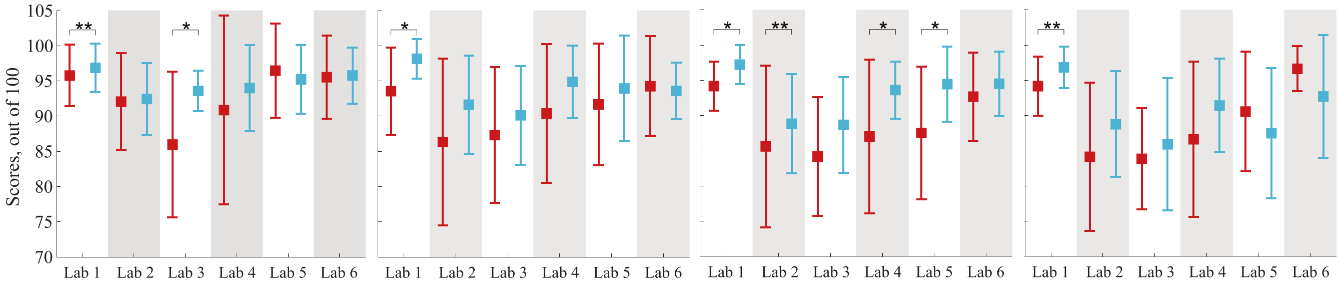
V. Discussion

The difference in student performance between the control and experimental curriculum conditions supports the proposed reflective curriculum. It is the authors' hypothesis that the prelab discussions, and the requirement for students to pose questions extending the materials in the lab protocol, facilitated the final stages of KELC and improved their performance. In addition to the significant differences between control and experimental groups for the middle quartiles, the experimental group had both higher lab averages and smaller standard deviations than the control for the top three quartiles, further supporting the use of reflective materials. However, Fig. 3 shows that, on a lab-by-lab basis, many of the differences between the experimental and standard curriculum are not statistically significant, which could be a result of the limited sample size. Also interesting was the significant main effect of Lab Exercises on scores. This difference which suggests that some of the labs were more difficult than others, in particular, Lab 3, which had a large drop in scores except for students receiving the reflective curriculum in the first quartile. This suggests that the reflective curriculum can address this increase in difficulty, and could be improved or further developed to impact the other quartiles.

The experimental curriculum did not have an effect on homework or final exam performance, which suggests a few interpretations. The homework and exam assessments were not designed as a part of this study, and it is possible that they are not accurate assessments of BTEO or KELC. Potentially, the lecture course assessments did not measure the practical, experimental knowledge students gained during the lab. If that is the case, it would likely be beneficial that students be evaluated on multiple, non-overlapping areas (theoretical and practical) of system dynamics. Regardless, this lack of transfer should be investigated in future studies that investigate the timing of the curriculum, such as Gorlewicz *et al.* [2], to determine if the lab materials did not complement the course well, or if the knowledge did not transfer. Increasing the reflective content of the lectures, improving the cohesion between the lab and lecture materials, and the timing of their delivery, could be methods for improving student performance. Additionally, improvements in traditional lecture-based coursework could be found in later courses that build upon these materials.

The experimental design also had some limitations. While the experimental and control groups were balanced to have roughly the same average GPA, students in control and experimental groups might have worked together outside of the course hours. Additional limitations to comparisons over multiple years were posed by the course having three lecturers over the two years of the experiment, each with unique lecture-associated assignments. While the training provided to control group proctors (e.g., providing sample graded lab reports and definitions of rubric terms) remained constant across the two years of this study, changing proctors could have contributed to some small inconsistencies in the course. Writing the lab report in small teams could mask individual performance, even with the individual portion and mixing groups.

In general, problems arising from changes in the lecture course and control group lab proctors were addressed through



(a) 1st Quartile (b) 2nd Quartile (c) 3rd Quartile (d) 4th Quartile

Fig. 3. Each of the six lab scores separated by overall GPA quartile (highest-lowest, (a)–(d), respectively), where * refers to statistically significant ($p < .05$), and ** refers to marginally significant ($p = .07$ (a), $p = .084$ (c), and $p = .087$ (d)). Error bars extend to one standard deviation from the means, with control group scores on the left of each quartile and experimental groups on the right.

the use of consistent rubrics for both the reflective and control materials. These rubrics addressed the effect of 'teaching to the test,' in that the rubrics and reflective materials were developed separately. Rubrics are the result of previous instructor grading schemes based on curricular goals; the reflective materials in general focused on establishing a deeper understanding of why the experiments were conducted, by having students engage in developing the experiment, to replicate the success of such activities in other STEM fields [18].

One shortcoming of the rubric was the aggregate scoring of performance across multiple levels of BTEO, which assumed that students would move sequentially through BTEO levels, that is, a low score would indicate only achieving low levels of BTEO. However, progression of learning through BTEO is not always supported by experimental studies [19], and future experiments should record separate scores for the different levels separately to examine interactions between reflective strategies on each educational objective level.

The results presented in Fig. 3 support a few interpretations. First, while not all increases were statistically significant, scores of students receiving the experimental curriculum had smaller standard deviations and generally higher means, raising the 'floor' of student scores. Next, the statistical significance of first quartile Lab 3 scores, along with the relatively low scores among all other quartiles suggests that either the material was more challenging, or perhaps there were external factors contributing to this decrease. Either way, this significant improvement suggests that the reflective materials can result in better transfer of the students' knowledge of mechanical systems to electrical circuits, a transition many students do not make. Fig. 3 shows the increases associated with the reflective material, which was statistically significant for the first quartile only. As when students are faced with this challenging abstraction task, the reflective material had a statistically significant or marginally significant effect on new material, such as the first lab. While the reflective materials were not as intense for this particular class, it is possible that the pre-lab lecture, and the basic framework of engaging students made an impact. Also, material that requires some combination of previous experiments, such as Lab 5, showed benefit among students in the third GPA quartile.

The open-source nature of haptic paddles and this reflective curriculum lends itself to implementation in other locations. Faculty wishing to implement reflective materials should first pursue the simple, but effective changes proposed here: exit questions, which require reflection of the lab experience and the pre-lab discussions, which provide much needed context and motivation. These simple changes resulted in a statistically significant increase in lab scores while only adding 15 minutes to the lab exercise. To assess these changes, researchers should develop rubrics which assess each level of BTEO separately, and assess higher level (Analysis and Evaluation) content in the post-lab exit questions.

Lastly, the relationship between student performance and learning bears discussion. This work relies on the assumption that performance is good proxy of learning, a fundamental question in education. On the spectrum of assessment tools, the authors posit that lab reports, while still limited as a means for assessing true learning, are a reasonable evaluation due to their requiring essay-form explanations of results and responses explaining the "why's" of the experiments.

VI. FUTURE WORK

The results of this study motivate further investigations into the relationship and transfer of knowledge between lab and lecture, to illuminate why the reflective lab curriculum did not impact the lecture assessments, and potentially motivate changes to both parts of the course.

Using the haptic paddle as a platform for modules covering multiple courses could improve both operational aspects (students already being familiar with the hardware), as well as new curricular goals. These new modules would provide opportunities to pursue higher-level educational objectives, such as the BTEO Synthesis level [16], with new student-developed laboratory experiments, assessed with methods having a greater emphasis on revisions to BTEO [19].

Further studies on reflective activities should include mechanisms for students to develop the reflective habits suggested by the curriculum, by informing students of the experimental design after the course. Additionally, the authors are interested in further investigations examining how students can be more involved with developing the lab experiments. While the authors hypothesize that the thought experiments during the pre-lab discussions contributed to the increase in student performance, developing lab handouts that give less information, and instead require students to develop the experiment, could leverage the same mechanism.

VII. CONCLUSION

Low-cost devices such as haptic paddles have the potential to improve learning outcomes in undergraduate education and to democratize the field of haptics. Previous implementations of haptic devices in undergraduate education have focused on traditional laboratory curriculum development and iterative design, to improve procedural aspects of laboratories with the haptic paddle. Here, the scores of students receiving the standard materials with those receiving reflective curriculum were compared. Reflective materials can encourage students to view the labs as a scientific process instead of a checklist of actions. Results showed statistically significant differences in many, but not all, lab scores, supporting the further development of reflective materials in undergraduate dynamics curriculum.

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