WIP: Effects of a prototyping course on capstone design performance

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Abstract
At the University of Illinois Chicago (UIC), our design spine includes a 300-level prototyping class to augment practical engineering skills. The prototyping class, entitled *Physical Prototyping for Design*, aims to increase familiarity and confidence working with various materials, power tools, and machining techniques. We hypothesized that participation in this course would enhance student ability in capstone design. Specifically, during the first semester of capstone design, students individually propose a technical solution for their team project based on design inputs. This affords us the opportunity to evaluate the efficacy and translational outcomes from the prototyping course on engineering skill and ability in capstone design. From 2022-2024, a total of 20 students completed the prototyping course. Seventeen of these students remained in BME and were enrolled in capstone design between 2022-2024, where they were placed among ten different teams. The design proposals from students who completed the prototyping course were scored against their team members who did not take the course. Scoring was performed based on written communication, graphical communication, and materials identification. Projects ranged from machine learning application (all software) to rehabilitation treadmill (electromechanical systems) and imaging phantoms (all hardware and CAD). On average, students from the prototyping course earned 70±13% of the available points from design proposals whereas their peers scored 68±11% (N=10 teams, $p=0.72$). Though, for projects that utilized most of the skills fostered in the prototyping course (e.g., the imaging phantom used CAD, 3D printing, and physical design features exclusively), the students that took the prototyping course scored substantially better than their peers. Overall, we report no significant effect of early prototyping exposure to design proposal ability in capstone. Future versions of the prototyping course will be revised to introduce and reinforce additional skillsets that may readily translate to capstone design.

Introduction

A common initiative in American undergraduate engineering programs is the introduction of a "design spine" that spans the curriculum [1-6]. The logic behind this curricular implementation is to allow students more time and opportunity to develop practical skills that will enhance their performance in capstone design, and ultimately, their abilities as engineers [4]. While design spines represent a popular trend in engineering programs, few reports evaluate the effectiveness of these curricular innovations on performance in capstone design. From these limited reports, University of Illinois Urbana-Champaign bioengineering implemented "just-in-time" workshops to foster maker skills in capstone [7]. They found that the workshops generally informed capstone performance as assessed by final reports and student surveys. In another example, United States Military Academy (West Point) studied the effects of an introductory mechanical engineering course on capstone performance [8]. They found mixed results, but report that the introductory course significantly improved conceptual analysis of students in capstone design.

At the University of Illinois Chicago (UIC), our design spine includes a compulsory 100-level class that emphasizes 3D printing and prototyping (including CAD work and circuit design), a compulsory 200-level team-based class, and a selective summer clinical immersion program to identify and validate needs for capstone design development [9-11]. Notably, our program previously lacked a formal prototyping class for developing physical fabrication and machine shop skills, which presented an obvious deficiency. To address this, in 2022, we introduced a new 300-level elective course, *Physical Prototyping for Design*, aimed at increasing student familiarity and confidence working with various materials, power tools, and machining techniques [12, 13]. Course learning outcomes are: 1) understanding of prototyping tools and techniques, 2) proficiency in use of hand and power tools, 3) understanding of materials characteristics, such as wood, soft plastics, fabric, and metal, and 4) knowledge of safety procedures and protocols for using prototyping equipment. Here we report on the effectiveness of this course in improving downstream outcomes in capstone design with the hypothesis that participation in this course enhances students' ability to propose feasible design solutions. We propose this hypothesis based on the assumption that experience and competence with basic making skills will inform one's ability to propose realistic and feasible design solutions. This hypothesis is supported by previous literature which finds engagement in maker spaces decreases anxiety and enhances motivation according to self-efficacy assessments [14].

Methods

During Fall 2022 and 2023 semesters, a total of 20 biomedical engineering (BME) students enrolled in the *Physical Prototyping for Design* course. Seventeen (17) of these students continued with the BME major and were later enrolled in capstone design between 2022-2024, where they were placed among ten (10) different teams. During the first semester of capstone design (Fall semester), students individually propose a technical solution for their team project based on previously identified design inputs. This assignment allowed us to differentially evaluate the efficacy and translational outcomes from the *Prototyping for Design* course on engineering skill and ability of individual students in capstone design. The design proposals from students who completed the prototyping course were scored against those of their team members who did not take the course to control for project and grader discrepancies. Grading of design proposals was performed by the authors and a trained teaching assistant across several rubric categories as shown in the Table. The *written description of the prototype* category concerns the ability for students to demonstrate how their proposed solution will function and to demonstrate appropriateness in design with regards to meeting design objectives and addressing design inputs. The *written description of fabrication* category concerns the ability for students to demonstrate appropriate means of fabrication. This is inherently related to the ability of the proposal to function. The *bill of materials* category concerns the summary of material choices and allows students to demonstrate appropriateness in their selections to meet design inputs. Importantly, relating to the description of fabrication, the selection of materials has pragmatic consequences for the design effort that may only become apparent when selections and commitments have been made. The *figures* category concerns the ability for students to visually and clearly communicate their designs and intentions, which may include CAD, circuitry, or process diagrams. The *Prototyping for Design* course provided experiences which are reflected in each of these rubric categories. Notably, total points shifted slightly between 2022 and 2023-2024 where the latter rubric was revised according to the inclusion of additional content in the assignment. In the circumstance that a team had more than one student from the *Physical Prototyping for Design* class, we averaged the scores from those students. Projects ranged from machine learning applications (all software) to rehabilitation treadmills (all electronics) and imaging phantoms (all hardware/CAD). This study was exempted according to IRB protocol STUDY2023-0423-MOD004.

Table. Rubric for assessment of design proposals. Scoring was performed based on written communication, graphical communication, and materials identification as shown for the academic years.

Category	Points 2022	Points 2023-2024
Written description of prototype – how it works, how it meets design objective, and how it meets design inputs	5	5
Written description of fabrication – tooling and techniques	3	2
Bill of materials	3	2
Figures	1	1

Initial Results and Discussion

On average, students from *Physical Prototyping for Design* did not perform statistically better than their peers on capstone design proposals, earning 70±13% (N=10 teams, p=0.72) of the available points versus 68±11% earned by their team members. However, for projects that most utilized the skills fostered in *Physical Prototyping for Design*, students who completed the course did score substantially higher than their team members, suggesting the possibility that early exposure to these skills might influence downstream performance. For example, one project involved designing an imaging phantom for MRI utilizing CAD and 3D printing skills, both of which were components included in *Physical Prototyping for Design*. The students on that team who had completed *Physical Prototyping for Design* scored an average of 87.5% compared to 47.2% scored by their counterparts. Another example involved the design of an *in vitro* bioreactor for liver tissues wherein former *Physical Prototyping for Design* students designed castable molds as part of their proposals – a fabrication technique directly covered in *Physical Prototyping for Design* – scoring 75% versus 55%. Due to the varied nature of design efforts, additional maker skills training may be useful to enhance value of the *Physical Prototyping for Design* course to a wider range of capstone projects. For example, the University of Illinois Urbana-Champaign introduced a variety of "just-in-time" modules (e.g., computer-aided design, python programming, Arduino programming) for exactly this purpose [7].

Several limitations also influence the outcome from this study. First, there was a small cohort and a variable time delay between early exposure to prototyping skills in *Physical Prototyping for Design* and application of those skills in capstone design (range 0-2 years). Second, we were unable to control for factors such as individual student academic ability and contributions from other sources (e.g., hobbyist influence or experience). Third, effects of the *Physical Prototyping for Design* course may be evidenced in other capstone design deliverables, including verification and validation testing. However, these standardized assignments are generated by student teams, and we did not identify individual contributions in these documents, therefore precluding individual assessment. Fourth, the only assessment presented in this report was grading of the design proposals. The IRB approval for this work only permitted the retrospective tracking of students between courses and differential assessment on standard course deliverables. In another study, student self-assessment and confidence with maker skills would also be useful to evaluate. Fifth, while the capstone design course was taught and graded by the authors over the years included in the current report, there remains the possibility of grading inconsistency.

Overall, we report no significant effect of early prototyping exposure on design proposal ability in capstone design. Importantly, student projects may not benefit from traditional prototyping and manufacturing techniques, especially in an age of easy and habituated use of 3D printing. It may also be the case that access to skilled machinists reduced the skills required of students to conduct the work themselves. Moving forward, we intend to adopt the *Prototyping for Design* course as a permanent addition to our design spine. Future iterations of the course will be revised to introduce and reinforce skill sets that may more readily translate to capstone design. Indeed, given the wide array of design projects in capstone design, additional skills not already in *Physical Prototyping for Design* may be useful (e.g., soldering, mechatronics, fasteners, adhesives, simulation software, programming). Going forward, we will also expand evaluation in capstone design to include the skills fostered in *Physical Prototyping for Design* as well as project selection preference. Additionally, future versions of capstone design could also include qualitative assessment from students and critical self-reflection of their performance as impacted by the *Physical Prototyping for Design* course.

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