2021 ASEE ANNUAL CONFERENCE
Virtual Meeting | July 26–29, 2021 | Pacific Daylight Time
Paper ID #34692

Using Rapid Prototyping to Realize Design: Mindset and Engineering Self-Efficacy

Dr. Andrea T. Kwaczala, Western New England University

Andrea Kwaczala is an assistant professor at Western New England University in the biomedical engineering department. She teaches Biomechanics, Biomedical Engineering Laboratory Courses, Senior Design and Prosthetic and Orthotic Design. She focuses on hands-on labs centered on student engagement and project based learning. She works in collaboration with Shriners Hospitals for Children where her research focuses in the design of assistive technologies to help people with mobility disabilities move and exercise so they can explore their world, independently.

Prof. Robert Gettens, Western New England University

Rob Gettens is a Professor and Chair of Biomedical Engineering at Western New England University.

Dr. Denine A Northrup, Western New England University

Denine Northrup, Ph.D. is a Professor and Chair of the Department of Psychology at Western New England University. Dr. Northrup's research interests surround factors that promote student success and resilience with a special interest in underrepresented populations in STEM fields.

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Abstract

The construction of low-fidelity prototypes is a critical phase of the engineering design process important for realizing design functionality, and to aid in the communication of engineering design ideas to others. The physical act of building, or constructing a prototype is a way to help young engineers develop the confidence they need to recognize themselves as engineers. This research elucidates differences based on gender and 1st-generation status when experiencing rapid prototyping. This work demonstrates the importance of constructionist activities in the engineering design classroom and awareness of its effect on different archetypes of undergraduate students. Females were significantly more likely to see these learning opportunities as an empowering moment, where construction of artifacts made them feel like design engineers compared to their male peers. Additionally, prior experience before college in tinkering, building, and making things were both higher in male students and those from 1st-generation students compared to females. There was a strong association between engineering self-efficacy and confidence in constructionist activities: rapid prototyping low-fidelity artifacts and developing CAD models based on individual design ideas. Not surprising, those with higher engineering self-efficacy had more confidence in their building skills. A major discovery from this work was a clear delineation that those with low engineering self-efficacy also had a lower perception of access to facilities like makerspaces, and rapid prototyping materials that help realize design ideas. The students and faculty agree that making activities are critical as part of the design process and the conclusions of this work demonstrate the need for more exposure to constructionist activities in the engineering design classroom and a stronger message for the availability of resources. Continuous building activities embedded throughout the engineering curriculum may help promote design skills and confidence in those with low engineering self-efficacy.

Introduction

The construction of low-fidelity prototypes is a critical phase of the engineering design process important for realizing design functionality, and to aid in the communication of engineering design ideas to others. The constructionist theory identifies that the act of creating an external artifact which can be shared and reflected upon will promote learning and lead to the generation of new ideas [1-2]. As engineering design instructors, it is often difficult to get students out of the conceptual design space and into the mindset of prototyping and building physical artifacts. To evaluate the student experiences, engineering self-efficacy could help to understand the intrinsic motivation as well as their academic performance [3-4], especially when evaluated in a making environment that utilizes the constructionist framework in the design classroom.

The physical act of building, or constructing a prototype is a way to help young engineers develop the confidence they need to recognize themselves as engineers. The constructionist framework also speaks to how a learner's reasoning is embedded in their emotional state and perceptions of the experience. However, the key to developing a constructionist mindset relies on providing an opportunity for students to take control of their own learning, and give opportunities to build meaningful products with potential to impact society [5].

Creating low-fidelity prototypes requires some technical skills, open access to low-cost resources, and a collaborative environment to construct. Hands-on learning such as what occurs in a rapid prototyping session is touted by engineering programs as a strength of their curriculum but is often not assessed for its efficacy in teaching transferable skills. More work is needed to determine the connection between high-impact practices in the design classroom with direct evidence of students' demonstrated learning [6]. This research aims to evaluate engineering self-efficacy in students who conducted rapid prototyping in design classrooms. The assessment of engineering self-efficacy can help elucidate concepts of confidence in technical skills, motivation, and mindset towards building activities.

There are several different ways to introduce rapid prototyping into an engineering design classroom. Depending on the type of engineering being taught (e.g. electrical, mechanical or biomedical) different styles of rapid prototyping are more informative than others. Some of the different methods of making physical prototypes include computer aided design (CAD) modeling, creation of low-fidelity rapid prototypes with inexpensive materials, story boarding, circuit boarding and bread boarding. There are more advanced rapid prototypes that can help with design realization such as appearance models for feasibility of design, advanced limited low-fidelity prototyping and system integration designs with proper tolerancing of mechanical parts and machining activities. This work focuses on rapid prototypes made through CAD and low-cost materials for limited functional prototypes. The idea is to demonstrate functional mechanisms and design appearance as students translate design ideas into physical models.

The Engineering Design Classrooms

Survey data was obtained from undergraduate students who had recently completed rapid prototyping as part of the engineering design class. Rapid prototyping occurs in all years of the engineering curriculum and data was collected in each cohort. The engineering design prompts were different for each classroom.

First Year Data Acquisition and Processing (ENGR 110) – Smart Project: This module involves the creation of a "smart product" invention in a team environment [7]. Student teams consist of both engineering and business students in groups of 3-5. The "smart" part of the project indicates that the students develop a product that incorporates the use of electronic sensors and/or effectors in the product design. Incorporation of sensors ties to the data acquisition learning objectives of the course. The project begins with "pain point" finding in order for teams to determine a meaningful project to pursue, continues through the design thinking process and culminates with the creation of a feasibility prototype, business plan and product pitch. A major step in the production of the final prototype is the creation of an initial "looks like" or low fidelity appearance model in the beginning of the prototyping phase.

Sophomore Biomedical Engineering Laboratory (BME 206) – Assistive Technology: This module was designed to allow students the chance to implement user-centered design to create assistive technologies. In the sophomore laboratory course, students were asked to consider mechanical advantage and energy efficiency in considering their design made to assist a wheelchair bound client from wheelchair into the seat of the car, 18" higher in elevation from seat surface [8, 9]. They work to assemble a proof-of-concept prototype to display design concepts in three ways, engineering sketches, CAD models of the design, and a rapid low-fidelity prototype over the course of three 4-hour lab blocks.

Prosthetic and Orthotic Design (BME 425) – Upper Extremity Prosthesis: In this module, students work independently to develop a functional mechanism of a body-powered transradial prosthesis capable of picking up a water bottle. It was implemented in an elective biomedical engineering design course, comprised of junior and senior biomedical engineers. The students underwent a 3-day prototyping workshop to develop a low-fidelity upper extremity prosthetic hand with the ability to grip, grasp or articulate using a five-digit design or prehensor hook [9. 10]. The device needed to be controlled by a body-powered harness to open/close the device using movement by the contralateral side tethered with a cable.

Senior Biomedical Engineering Capstone (BME 437) – Medical Device: In this 3-hour workshop, students had to develop a limited functional prototype of their capstone design project. Senior biomedical engineering students spent 10 weeks researching and developing engineering design ideas following the FDA's waterfall design process [11]. In this workshop, they worked in teams of 2 or 3 to develop limited functional prototypes to demonstrate proof-of-concept designs made from low-cost materials. This 3-hour workshop was intended to help stimulate creativity, and test feasibility of design ideas in order to help narrow down design choices during Design Decision Matrix evaluations.

These activities have been conducted for several years at Western New England University. Due to COVID-19, special precautions were made to ensure social distancing Undergraduate design students were often split into two cohorts to allow social distancing and were provided individual kits of materials and supplies. Courses met for at least one hour and twenty minutes, where the 1st year, sophomore lab and Senior design was part of a lab blocks that were reserved for up to 4 hours of available class time. The Prosthetic and Orthotic Design class met for 1 hour and 20 minutes and rapid prototyping activities were conducted three consecutive days to allow enough design time.

Assessing Engineering Self-Efficacy and Student Perceptions in the Design Classroom

The data collection tool was comprised of a student survey delivered by SurveyMonkey at the conclusion of rapid prototyping workshops that were conducted in each of the engineering design classrooms, previously described. Surveys were approved by the Institutional Review Board (IRB) at Western New England University prior to the start of the study. Numerical data were statistically compared using a Student's two-sample, two-sided t-test. The significance level was set at $\alpha=0.05$. Examples of open-ended student responses were reported in raw form at the end of this paper.

Students responded to questions to score their engineering self-efficacy on a 5-point Likert Scale, using a validated tool [12]. Additionally, they were surveyed on perceptions towards the importance of activities such as CAD modeling, rapid prototyping low-fidelity prototypes, and 3D printing models. They were asked to assess their technical abilities to complete design prompts, and their confidence in design activities in the classroom. Finally, students were asked to report on their perception of access to resources such as 3D printers, machine shop and access to materials to help facilitate rapid prototyping activities.

After survey completion, student data were grouped into two categories based on response to questions related to engineering self-efficacy. The highest responders on the engineering skills scales greater than 4 on a 5-point Likert Scale were grouped as high-engineering self-efficacy, or high-ESE, and compared to those responders that scored less than 4 on a 5-point Likert Scale as low-engineering self-efficacy, or low-ESE.

Student perceptions towards different design activities were also measured. To examine the reliability of the scales for engineering self-efficacy, rapid prototyping, CAD, and 3D printing, the set of questions associated with each scale were assessed using Cronbach's alpha test. A Cronbach's alpha greater that 0.70 was considered an adequate level of internal consistency for each measure within a scale. All group comparisons of the data are represented as mean ± standard deviation and analyzed using a Two-sample Student's t-test. When appropriate, questions were pooled within a specific scale (e.g. rapid prototyping were combined) and group means were compared.

Results

The data reported were tabulated from student surveys that were completed via SurveyMonkey. The surveys were deployed shortly after rapid prototyping workshops were concluded in engineering design classrooms. Sixty-four students participated in the survey; seven responses were omitted due to incomplete responses. Data were sorted by gender (male vs. female), 1st-generation status (a student whose parent(s) did not complete a four-year college or university degree) and finally by responses based on scoring on the engineering self-efficacy scale (threshold value of 4.0 out of 5 set as high-ESE).

Thirty-two females completed the survey and twenty-four males, one student identified as genderqueer or non-binary. This data point was not considered when comparing differences in gender due to the small sample size but was considered for analysis of 1st-generation and low- vs. high-engineering self-efficacy. Eighteen students reported being 1st-generation, thirty-nine were not. Twenty-one scored 4.0 or greater on measures of engineering self-efficacy, thirty-six scored below 4.0.

To examine the reliability of the scales related to rapid prototyping, CAD, 3D printing and access, Cronbach's alpha scores was calculated. A Cronbach's alpha greater that 0.70 was considered an adequate level of internal consistency: Engineering Self-Efficacy (0.78), Rapid Prototyping (0.86), CAD Modeling (0.85) & 3D Printing (0.90) were evaluated. All scales had a strong internal consistency.

Rapid Prototyping Perceptions Varied by Gender:

There were some important differences in perceived design skills between female and male engineering students (**Table 1**). Males reported 53% higher experience in building and making things prior to starting college ($p<0.05$). They also displayed 19% higher confidence in building machines, and 25% higher confidence interfacing with microprocessor and programing software compared to the female students (Student's t-test, $t(53)=3.1$, $p<0.05$).

A critical finding of this work was that females were 15.5% more likely to report that the rapid prototyping activities made them feel like a design engineer compared to the male engineering students (Student's t-test, $t(54)=-3.1$, $p<0.05$). Female students were more confident in their communication skills, both in written form (10% higher in females, $p<0.05$) and through visual communication (7.6% higher in females, Student's t-test, $t(54)=-2.3$, $p<0.05$, **Fig. 1**).

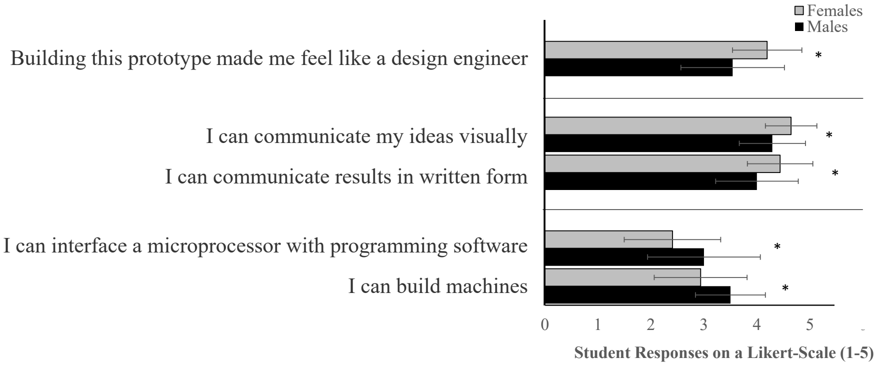

Figure 1. Gender differences in engineering self-efficacy and building skills and activities measured in undergraduate design engineers. Data is represented as mean ± standard deviation, n = 32 females, n = 24 males (Student's t-test, *$p<0.05$).

Worth reporting were also nearly significant differences between genders in engineering skills. Males again reported a higher ability to assemble things (8%, Student's t-test, $t(54)=1.85$, $p=0.07$) and better sense of exposure to rapid prototyping activities throughout the engineering curriculum (17% higher in males, Student's t-test, $t(53)=1.8$, $p=0.077$). Females demonstrated a higher value of rapid prototyping to realize where a design might fail, and it's importance in the design process (11% higher in females, Student's t-test $t(54)=-1.7$, $p=0.088$). Females were also more confident in their ability to get a good grade in their engineering courses compared to males (9%, Student's t-test, $t(54)=0.29$, $p=0.065$, **Table 1**).

Table 1. Gender differences in engineering self-efficacy and perceptions towards engineering design activities. Data is presented as mean +/- standard deviation of the groups Likert Scale (1-5), % differences between the two groups, compared using a Student's t-test.

Engineering Self-Efficacy	**Males n=24**	**Females n=32**	**% Diff**	**p-value**
Before college, I would rate my level of experience building and making things as (Rating Scale, 0 -100)	53±26	35±18	53%, m	0.003*
I can communicate results of experiments in written form (Likert Scale, 0-5)	4.0±0.8	4.4±0.6	9.9%, f	0.023*
Communicate my ideas through visual communication	4.3±0.6	4.6±0.5	7.6%, f	0.022*
I can earn a good grade in my engineering related courses	3.9±1.0	4.3±0.5	9.2%, f	0.065
Engineering Self-Efficacy: Building				
I can build machines	3.5±0.7	2.9±0.9	19.1%, m	0.011*
I can interface a microprocessor with programming software	3±1	2.4±0.9	24.7%, m	0.029*
I can assemble things	4.4±0.6	4.1±0.7	7.9%, m	0.07
Rapid Prototyping Experience				
Building this prototype made me feel like a design engineer	3.5±1.0	4.2±0.7	15.5%, f	0.005*
CAD: Recognize where the design might fail	3.7±0.9	4.2±0.9	11.4%, f	0.054
CAD: I find it very helpful as part of the design process	3.7±1.0	4.2±0.9	10.8%, f	0.088
I feel like I have done a lot rapid prototyping	3.3±1.0	2.8±1.0	17.3%, m	0.077
I have access to the machine shop to make physical prototypes out of materials like aluminum, wood, and materials that require machine shop tools to process	3.2±1.0	3.6±1.0	13.1%, f	0.083

*$p<0.05$ using a Two-Sample Student's t-test
m = male students scored higher
f = female students scored higher

Rapid Prototyping Perceptions Varied in First-Generation Students:

First-generation students who self-report as a student whose parent(s) did not complete a four-year college or university degree, represented 32% of the undergraduate demographic surveyed. They had some unique insights into the engineering design classroom (**Table 2**). They scored similarly to non-first-generation students in terms of engineering self-efficacy but reported a lower score by 11% in communicating results in written form (Student's t-test, $t(54)=2.2$, $p<0.05$). However, data also suggested they scored higher in their perceived ability to do a good job in almost all of their engineering coursework (9.5% higher in 1st-generation students, Student's t-test, $t(54)=-1.8$, $p=0.07$). 1st-generation students perceived 3D printing as a skill all engineers should have (9% higher than non-1st-generation, Student's t-test, $t(55)=1.7$, $p=0.10$). When exposed to rapid prototyping activities, first-generation students were more 10% more likely to report these activities as being important parts of the engineering design process and had 8% higher perception of its importance in helping to understand how someone would interact with the product (Student's t-test, $t(55)=2.1$, $p<0.05$).

There were important trends showing rapid prototyping activities helped 1st-generation students feel like design engineers reporting 10% higher when compared to non-first generation students (Student's t-test, $t(54)=-1.7$, $p=0.094$). First generation students had some access to resources issues, where they were 25%

more likely to respond that they did not complete a project due to lack of access to materials (Student's t-test, $t(54)=-1.8$, $p=0.079$, **Table 2**).

Table 2. Differences in engineering self-efficacy and perceptions towards design activities in 1st-generation students vs. non-1st-generation. Data is presented as mean +/- standard deviation of the groups Likert Scale (1-5) and % differences between the groups, compared using a Student's t-test.

Engineering Self Efficacy	**Non-1st n=39**	**1st Gen n=18**	**% Diff**	**p-value**
I can communicate results of experiments in written form	4.4±0.7	3.9±0.7	11.2%, non	0.029*
I can do a good job on almost all my engineering coursework	4.0±0.9	4.4±0.6	9.5%, 1st	0.07
3d printing is a critical skill all engineers should have	3.8±0.8	4.2±0.7	8.9%, 1st	0.1
Rapid Prototyping Experience				
I find it very helpful as part of the design process	4.4±0.7	4.8±0.4	9.8%, 1st	0.013*
Helps to understand how you would interact with the product	4.3±0.7	4.7±0.5	8.2$, 1st	0.045*
Building this prototype made me feel like a design engineer	3.7±0.9	4.2±0.9	10.3%, 1st	0.094
As a WNEU student I didn't complete a project in the past because I didn't have access to materials	1.4±0.7	1.9±1.2	24.8%, 1st	0.079

*p<0.05 using a Two-Sample Student's t-test
Non-1st = non-first-generation students
1st Gen= 1st-generation students

Low vs. High Engineering Self-Efficacy Affects Students Perceptions Towards Design Activities:

Student data was sorted into two cohorts, those with high engineering self-efficacy (high-ESE, average self-efficacy Likert Scale ≥ 4.0) or low engineering self-efficacy (low-ESE, < 4.0). Their confidence in rapid prototyping activities was strikingly different when sorted by ESE (**Table 3**). The students with high ESE felt more confident in being able to quickly determine feasible solutions and could assemble components quickly (Student's t-test, $t(54)=-2.1$, $p<0.05$). Student's with high-ESE had a 25% higher preference towards CAD modeling compared to rapid prototyping, but the preference was not statistically significant (Student's paired t-test, $t(20)=1.3$, $p=0.21$). Interestingly, students with Low-ESE strongly preferred rapid prototyping by 33% over CAD modeling when realizing design functionality (Student's paired t-test, $t(34)=2.7$, $p<0.05$, **Table 3**).

Table 3. Differences in perceived skills and preference towards design activities in students with low vs. high engineering self-efficacy. Data is presented as mean +/- standard deviation of the Likert Scale (1-5) and % differences between the two groups, compared using a Student's t-test.

Rapid Prototyping Experience: Low vs High Engineering Self-Efficacy	**Low ESE (<4.0) n=36**	**High ESE (≥4.0) n=21**	**% Diff**	**p-value**
I could quickly determine a feasible solution and start working towards a functional design	3.9±0.7	4.3±0.7	11.1%, H	0.037*
I felt like I could assemble components quickly and understood how they were supposed to work	3.9±0.7	4.3±0.8	12.3%, H	0.027*
I feel confident in my ability to build physical prototypes	4.1±0.8	4.5±0.6	10.0%, H	0.047*
I feel confident in my ability to use the design process to succeed in engineering design projects	4.2±0.5	4.7±0.5	10.4%, H	0.010*
Rapid prototyping helps me understand how component work and mesh together	4.4±0.6	4.8±0.4	10.6%, H	0.005*
I prefer rapid prototyping to CAD modeling (internal, paired t-test)	33%	-25%	--	L: 0.01* H: 0.20

*p<0.05 using a Two-Sample Student's t-test
ESE = Engineering Self-Efficacy
H = high-engineering self-efficacy group

When comparing student's perceptions among high- and low- engineering self-efficacy groups, there was no difference between perceived skill levels in CAD modeling (Student's t-test, t(54)=-1.0, p=0.33), but opposite to preference, confidence in rapid prototyping was 10% higher in the high ESE students (Student's t-test, t(54)=-2, p=0.33), yet the low-ESE students preferred rapid prototyping design activities. No major differences were apparent related to perceptions towards the usefulness of rapid prototyping in the design process between low- and high- ESE. However, CAD modeling was perceived as being more valuable in high-ESE students compared to low, and 3D printing was seen consistently as more valuable to high-ESE students (Each higher in CAD, all significant: *16%, *19%, *16%, *14%, *16%, *10%. Each higher in 3D printing, not all significant: 8%, 8%, 8%, 8%, *16%, 7%, Student's t-tests, *$p<0.05$, **Table. 4**).

Table 4. Differences in perceptions towards the value of rapid prototyping, CAD modeling, and 3D printing in the design process between students with low- vs. high-engineering self-efficacy. Data is presented as mean +/- standard deviation of the Likert Scale (1-5) and % differences between the two groups, compared using a Student's t-test.

When it comes to _________, rate your level of agreement	**Rapid Prototyping**				**CAD Modeling**				**3D Printing**			
	Low ESE (<4.0)	**High ESE (≥4.0)**	**% Diff**	**p-value**	**Low ESE (<4.0)**	**High ESE (≥4.0)**	**% Diff**	**p-value**	**Low ESE (<4.0)**	**High ESE (≥4.0)**	**% Diff**	**p-value**
Helps me to communicate my design ideas to others	4.4±0.7	4.4±0.8	-0.2%	0.97	4.0±0.9	4.6±0.6	16.3%	0.005*	4.1±0.7	4.4±0.8	8.0%	0.13
Helps me to realize design functionality	4.4±0.6	4.5±0.8	1.8%	0.66	3.9±0.9	4.6±0.7	18.8%	0.003*	4.1±0.7	4.5±0.8	8.2%	0.12
Helps me to recognize where the design might fail	4.4±0.6	4.6±0.7	5.9%	0.15	3.8±0.9	4.3±0.7	13.9%	0.04*	3.9±1.0	4.3±1.0	8.7%	0.2
Helps to visualize how components might mesh together	4.3±0.6	4.8±0.4	10.6%	0.004*	4.1±0.8	4.7±0.7	16.2%	0.003*	4.2±0.8	4.6±0.7	8.3%	0.12
I find it very helpful as part of the design process	4.5±0.6	4.5±0.8	-1.1%	0.78	4.3±0.7	4.7±0.7	9.5%	0.04*	3.8±0.9	4.3±0.9	15.6%	0.03*
Helps to understand how you would interact with the product	4.4±0.6	4.6±0.8	4.2%	0.33	-	-	-	-	4.3±0.8	4.6±0.6	6.9%	0.17

*$p<0.05$ using a Two-Sample Student's t-test
ESE = Engineering Self-Efficacy

Individual responses from questions within four separate scales were pooled: rapid prototyping, CAD modeling, 3D printing and access to resources, which showed general trends between low- and high-engineering self-efficacy. Student's with low engineering self-efficacy consistently scored these activities as lower in terms of their value in engineering design (**Table 4, Fig. 2**). An important finding of this work is the difference in perceived access to resources. Students were asked questions about their perceived access to 3D printers on campus, access to the machine shop to make their prototypes, and experiences when purchasing supplies and seeking reimbursement to complete design projects. Overall, students with high engineering self-efficacy rated their access to resources and materials as 15% higher compared to low-ESE students (Student's t-test, t(502)=-4.8, $p<0.05$). Low-ESE students were 35% more likely to report a negative experience related to reimbursement or an lack of awareness of how to obtain materials to support making activities (Student's t-test, t(54)=2.1, $p<0.05$, **Table 5, Fig. 2**).

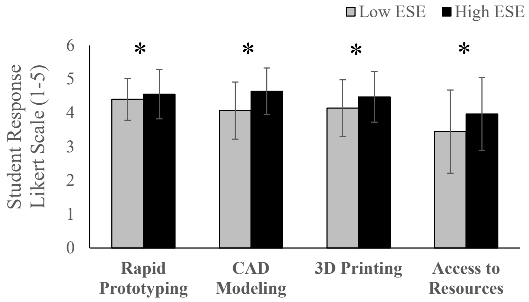

Figure 2. Differences in perceptions of value to the design process for rapid prototyping, CAD and 3D printing and access to resources from students with low- (gray, < 4.0) and high- (black, ≥ 4.0) engineering self-efficacy (ESE). Data is represented as mean ± standard deviation, Low ESE: n=36, High ESE: n=21 (Student's t-test comparing High- to Low-ESE, *$p<0.05$).

Table 5. Differences in student perceptions towards access to makerspaces and prototyping materials between students with low- and high-engineering self-efficacy. Data is presented as mean +/- standard deviation of the Likert Scale (1-5) and % differences between the two groups, compared using a Student's t-test.

Perceptions of Access to Materials and Technical Resources	Low ESE (<4.0)	High ESE (≥4.0)	% Diff	p-value
I have access to 3D printers on campus and can use them whenever I need them	3.1±1.1	4.1±1.1	32.4%, H	0.002*
I have access to the machine shop to make physical prototypes out of materials like aluminum, wood, and materials that require machine shop tools to process	3.1±0.9	3.9±0.9	28.1%, H	0.002*
I can buy materials for my engineering projects and get reimbursed	3.0±1.2	3.7±1.2	23.4%, H	0.043*
When I need a material, I know who I should talk to in order to get it ordered or purchased with COE funds right away	2.8±1.4	3.7±1.1	32.7%, H	0.013*
As a WNEU student I didn't complete a project in the past because I didn't have access to materials	1.8±1.0	1.2±1.6	30.1%, L	0.037*
I have wanted to purchase supplies for a class project in the past, but I didn't because I couldn't afford it and didn't know who to ask	2.4±1.4	0.6±0.9	34.5%, L	0.021*

*$p<0.05$ using a Two-Sample Student's t-test
ESE = Engineering Self-Efficacy
COE = College of Engineering
WNEU = Western New England University
H = high- engineering self-efficacy group
L = low-engineering self-efficacy group

Discussion

This work aimed to elucidate student perceptions of design activities such as rapid prototyping, CAD modeling and 3D printing when executed in the undergraduate engineering design classroom. These responses were then linked to engineering self-efficacy using a validated measurement [13]. Students were assessed in all classes within the undergraduate curriculum and responded positively to making design activities. Their response to engineering self-efficacy varied, and these differences helped to elucidate some important connections between different student archetypes, specifically those from underrepresented groups regarding learning preferences, access to resources and overall usefulness of making activities.

Differences in gender and 1st-generation demonstrate the need for a diverse design curriculum: There were clear differences in the perceptions towards makerspace activities that were unique to females and 1st generation students. Females and 1st-generation students both reported rapid prototyping as an activity that made them feel like a design engineer, an important criterion in promoting engineering self-efficacy. Interesting, these two groups of students had unique preferences in the engineering design classroom. For instance, females preferred CAD modeling over rapid prototyping, and were more likely to have lower engineering self-efficacy. Females demonstrated their confidence as visual communicators over male students, which may connect to the visual aid that CAD provides during designing. On the other hand, first generation students consistently scored rapid prototyping as the most useful design activity and used this to help realize design ideas (**Table 1, 2**). Similarly, 1st-generations reported a higher previous exposure to building activities, and a preference towards physical constructions. This may suggest students may like what they are good at. It would be important to determine if more exposure to tools like SolidWorks or other 3D computer aided design programs earlier in the curriculum; its consistent use could change student perceptions towards that skill and its usefulness during the design process.

These data suggest the multifaceted nature of the student personas in a diverse engineering classroom. It is important for design instructors and makerspace coaches to avoid pigeon-holing student groups too readily into any given archetype but may instead offer a variety of making activities so students can self-select the modality that is most beneficial for their individual design process. Using broader application of design activities and experiences could help promote engineering formation in underrepresented groups. The gender gap associated with engineering self-efficacy has been well documented and is a cause for concern as it relates to young engineers leaving the profession [14]. The recognition that rapid prototyping helps underrepresented groups feel like design engineers is a critical finding that could be implemented more intentionally to help support these students in the classroom. Future work is ongoing to further support underrepresented groups on campus through 1st year programming and Society of Women Engineers for a series of makerspace activities that are conducted in safe and supportive constructionist classrooms.

Perceived access to resources is connected to low engineering self-efficacy: It is critical to consider access to resources, facilities and makerspace labs when teaching to diverse communities of learners. It is important for all students to feel included and accepted within the makerspace community to promote its use and can be an effective tool to help build engineering self-efficacy [15]. Students with low engineering self-efficacy consistently rated their access to resources such as machine shops, 3D printers and makerspace materials as lower compared to those with high ESE (**Table 4**). They also had a higher occurrence of negative incidence associated with a makerspace activity which puts them at risk of being left out, feeling ostracized and not seeking resources in future design work.

Finding ways to actively communicate resource availability to all students within the engineering curriculum is critical in removing this barrier to entry to technical skill development. By using low-cost materials for prototyping, the researchers try to encourage early development and familiarity with making activities. Current work is underway within the Biomedical Engineering department at Western New England to provide low-cost materials within the engineering classroom that are readily accessible, well organized and in an area that does not require special access or permission to use supplies.

An open-access makerspace community is harder to manage at the college level and requires staffing and resources to stock, maintain, and supervise these types of facilities. For example, access to machine shops, 3D printers and prototyping equipment is available on most engineering campuses, however there is not open access to these resources and only serves a small cohort of students and student projects often requires submission of parts through administrative personnel [16]. Submission of engineered parts for someone else to make on your behalf takes away some of the benefits of making as described by the constructionist framework [1] and may prevent tinkering skill development. More work is needed to recognize strategies to promote the student training in making facilities, both within an individual college and across the engineering community. This could also lead to better access and opportunities for involvement and usage.

Individual design work helps improve learning for all students: Working individually on a design prompt gives students the chance to hone their skillset. It also allows students to feel closely connected to their design concepts and its evolution through the design implementation process. In the sophomore lab, students had very different approaches for solving the lift of a 160 lb. person by 18 inches using mechanical advantage and simple machines. Three extremely different approaches to the problem can be seen in the student design samples that all met the requirements of the design prompt (**Fig. 3-5**).

Similarly, the Prosthetic and Orthotic Design class was conducted as an individual design challenge using makerspace rapid prototyping kits [8]. This was useful for two reasons. First, helping students independently overcome design challenges was a critical phase in the design process. Students self-reported this process as a major milestone that gave them a chance to reflect on their improvements and progress and realize where designs might fail. This is a critical piece in the engineering self-efficacy development [13]. Second, it allowed the professor the opportunity to understand which students required more individual support and design coaching in the classroom. Those that were independently problem solving and constructing could be left to their own devices. Those that were stuck were offered more guidance and prompting to help move the activity along. If the activity were done in teams, those that struggled to get started might not get the opportunity to independently construct limited fidelity prototypes due to the nature of team dynamics and would miss this critical part of the design realization phase.

Conclusions: In future work, the researchers aim to develop tools to assess technical skill development. If there was a way to demonstrate growth or improvement in skill development during the undergraduate experience, it would serve two purposes. First, it could serve as a method to evaluate the technical work that occurs in the design classroom, more fairly and with clear transparency to the students. Second, it would allow students to see how their skills have developed over the course of their education. In general, differences among gender, 1st-generation and students with low- and high- engineering self-efficacy all suggest that a variety of these activities should be planned intentionally to promote exposure to and development of technical skillsets. Intentional incorporation of different design activities that all students are required to complete and work towards mastery can help to improve engineering self-efficacy. Finally, an awareness by the instructor on the student engagement during the design process can help to support all different types of learners.

These data reflect student perceptions in the undergraduate engineering design classroom. The researchers hypothesized that making activities such as rapid prototyping, CAD modeling and 3D printing would vary by gender, 1st-generation status and when divided based on low- and high-engineering self-efficacy. Physical construction of artifacts helps in engineering identity in underrepresented groups. There is a clear distinction between perceived access in low- vs. high-engineering self-efficacy. Providing students with access to materials and a variety of prototyping activities in the design classroom can help to create a more inclusive classroom. Providing experiences that help students feel like design engineers through a series of makerspace activities can help in the formation of engineering professionals and will also help with technical skill development that is needed to be successful in the field.

Student Design Samples from Rapid Prototyping Activities:

Sophomore engineering design classroom activity: Students built limited functional prototypes for a mobility assist device to help a wheelchair bound client to get into the car while considering mechanical advantage and energy efficiency. They worked individually to create engineering design sketches, transformed into a CAD model and then built a low-fidelity model that displayed movement during a rapid prototyping workshop.

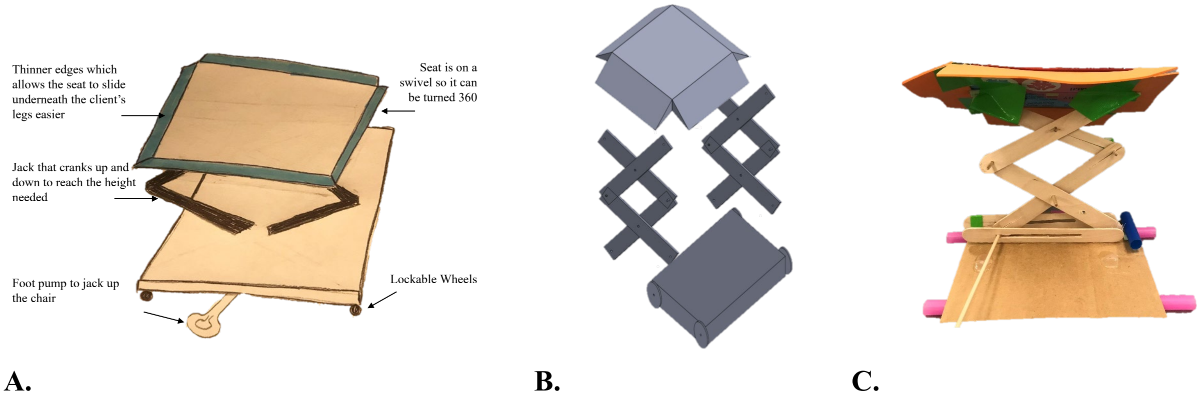

Figure 3. Assistive Technology Mobility Lift, Student Design Example: ***The Jack Lift Seat***.
A) Design started with a simple engineering sketch, B.) Converted into a SolidWorks model and then C.) a low-fidelity rapid prototype was created with cardboard, duct tape, straws, popsicle sticks and dowels.

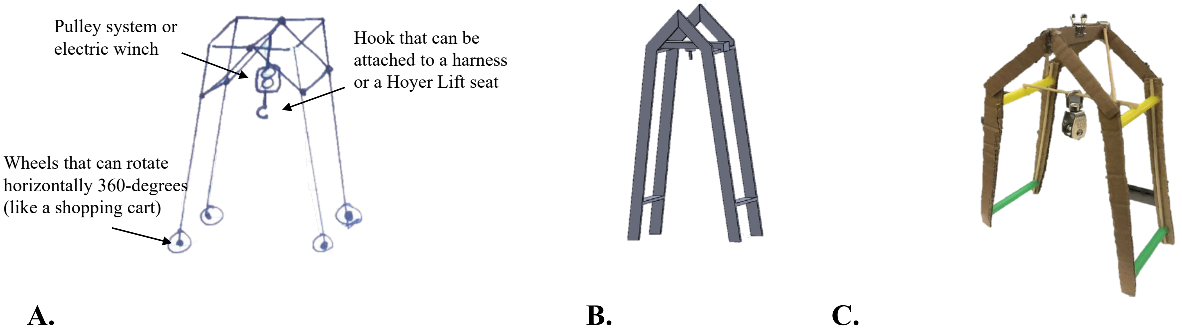

Figure 4. Assistive Technology Mobility Lift, Student Design Example: ***A-Frame Winch Lift***.
A.) A student example of an engineering design sketch, B.) SolidWorks Model of the prototype, C.) A rapid prototype made out of cardboard, dowels, straws, a pulley and binder clip.

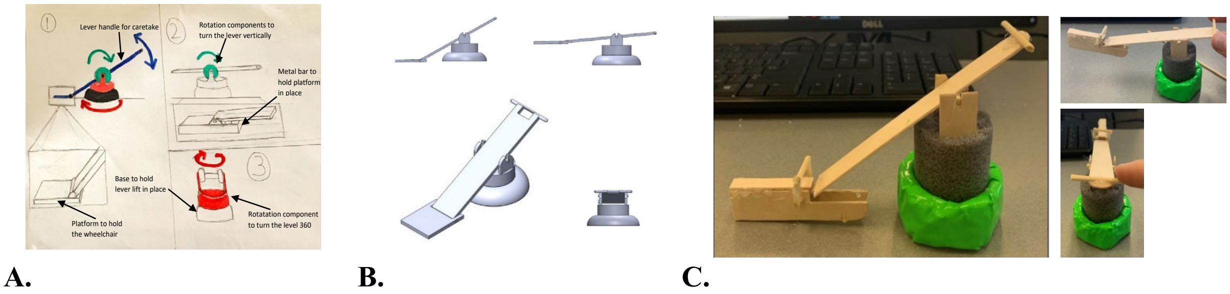

Figure 5. Assistive Technology Mobility Lift, Student Design Example: ***The Lever Lift***.
A.) Design started with a simple engineering sketch, B.) Converted into a SolidWorks model and then C.) a low-fidelity rapid prototype was created with foam, duct tape, popsicle sticks and dowels.

Student's Open Response to the Entrepreneurial Minded Learning Module

Sophomores in BME 206 Wheelchair Assistive Transfer Device - Perceptions of CAD vs rapid prototyping tasks:

- I enjoyed this exercise and thought it was an encouraging introduction to design engineering. I liked how it was ***broken down into steps to make the process less intimidating***, I find a lot of introductions in engineering expect some background and do not necessarily start with the simple basics. The exercise challenged ideas without leaving a discouraging impact and gave me more confidence in my skills.
- This activity ***definitely made me use more of an engineering mindset*** which is helpful because in many classes we don't get to act like engineers. I personally struggle in the design aspect as it challenges me to think outside of the box. I also struggle with SolidWorks especially since I have not used it since the Fall semester of Freshman year. This activity forced us to create a device intended for a specific client which allowed us to learn about mechanical advantage and energy efficiency. Overall, this activity was helpful and ***allowed us to be engineers***.
- I liked this activity because there was ***enough freedom to do what I wanted***, but not enough that I would get overwhelmed with all the possibilities.
- Overall, this lab was successful in experimenting with different design concepts and applying our ideas to real world scenarios. I personally like doing physical prototypes better than CAD modeling because it is a 3D model ***you can touch and move around***. Being more tactical learner versus a visual, it is much easier for me to assess a physical prototype. However, the CAD modeling was definitely helpful while understanding the mechanical properties of the Dynamic Exo which can't be done accurately with a physical prototype. ***This lab has strengthened my SolidWorks skills and I feel more confident using the program*** for future projects.
- This process was ***very exciting and fun to build***. I loved seeing my design come together in ways I haven't before. I was able to make most of my design in SolidWorks and I am very excited about that. The ***rapid prototyping process was difficult but needed***. I found that my cross brace needed to be revised and things needed to be changed about my design again, which was also needed at every step.
- I enjoyed this design activity and the way that it was presented to us. I enjoyed how we were sketching ideas the first day that we got the problem statement and then we jumped right into the SolidWorks in the next class. It was a design experiment that went quick, but I feel that they are more beneficial that way. ***It forces you to think on your toes and come up with effective designs quickly.*** If I was to continue developing this device, my next step would be to 3D print the SolidWorks parts and to start brainstorming about what kind of motor I could use to power the chair. I also feel like I learned a lot about mechanical advantage during this activity. It gave me a better understanding of how to apply force to a specific place and that the force performed needs to be proportional to the force applied to the device. ***This activity overall sharpened my design skills and helped me improve on communicating my designs*** to other students and my superiors as well.
- This activity was very ***helpful for me in visualizing my design and bringing it to life***. I think that the rapid prototyping process is very important for creating an effective product.

Juniors and Seniors in Prosthetic and Orthotic Design - Perceptions towards experiencing failure when rapid prototypes of a body-powered upper extremity devices:

- Failure was a significant part of this semester for me. **Nearly every project personal or otherwise started with a failure of some sort.** I've always been quick in moving on from failure, but most projects would be abandoned afterwards or finished in a state I wasn't happy with. This class **fostered a tolerance for failure and strength of will to push through it when possible.**
- Ohhhh BME 425.. I don't even know where to start with how much this class has changed me. **Through the challenges, failures, and lessons learned**, this was by far my favorite class this semester. This activity taught me the most about myself as a learner **because I failed for the first time.** I found myself feeling defeated as I watched everyone around me come up with ideas s. I was determined to come up with my own idea and not to copy bits and pieces of someone else's design. As soon as I left the class and had alone time to think, I finally came up with an idea. **I was making it way more complicated than it needed to be.**

- My experience in this course was very positive and that is from the lessons I was able to learn. The first major obstacle that I had to overcome was the Sally Project. I am a very artistic person, I loved arts and crafts as a kid and still do, so when I saw the large bags of supplies, I got super excited. However, **that class turned out to be my worst nightmare and I failed miserably.** From that day forward, I learned to look at my project work with an open mind and become more creative and **know that it is okay to fail.**
- This course put me in some situations that were uncomfortable for me at first, but **repetition eventually made them not a big deal**. I also feel like I accomplished the main goals set out in the beginning: **developing empathy, designing for a specific end user, and developing the necessary technical language** when working with assistive technologies. Every module gave me more and more confidence in my abilities to achieve the goals. Not to say that there were not any failures, because there were plenty! Before the course, I really hated to fail. I always wanted to succeed and perform to the best of my abilities. This course **taught me that failure is not always a bad thing. Instead, it is perhaps the best way to learn….** I was a lot prouder of my upper extremity device because it was functional and durable, and I could really see improvement in myself.

Acknowledgments

The authors are grateful for the professional development training program at WNEU used to build this learning module thanks to the financial support from the Kern Family Foundation, the KEEN Institutional Grant at Western New England University. This work would not be possible without the administrative help on pre- and post-surveys from Baylee Houldson with the College of Engineering. Thank you to the WNEU Alumni Association for the Women-in-Engineering grant that supported rapid prototyping workshops.

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