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Increasing gender diversity in engineering using soft robotics

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Abstract

Background: There is a well-known gender disparity in the engineering field. Three of the most important factors related to the participation of women in engineering are differences in perceived societal relevance, technical self-efficacy, and tinkering self-efficacy.

Purpose/Hypothesis: Soft robotics is a relatively new engineering application with the potential to address these three factors. We investigated whether participation in a soft robotics design experience would improve students'—especially girls'—perceptions of engineering in contrast to a traditional, rigid robotics experience.

Design/Method: Soft robotics curriculum materials were developed for high-school engineering classes using design-based research. Seven teachers delivered soft and rigid robotics lessons; then 293 students reported their perceptions of motivation, interest, and self-efficacy following the lessons and retrospectively. We examined the relationship between gender and lesson type and differences in perceptions of engineering over time.

Results: The soft and rigid robotics experiences promoted engineering interest and general, experimental, tinkering, and design self-efficacy. Girls' perceptions of tinkering self-efficacy particularly benefitted from the soft robotics lesson, mitigating gender differences. A robustness check compared the outcomes of different statistical models and verified the stability of the findings.

Conclusions: Soft robot design experiences emphasize materiality and iterative design, which contribute to enhanced tinkering self-efficacy. The use of soft robotics in education represents a promising opportunity to integrate authentic engineering experiences, broaden perceptions of engineering, and support the development of future engineers.

KEYWORDS
design-based learning, gender, motivation, self-efficacy, soft robotics

1 | INTRODUCTION

There is a growing need for diverse ways of thinking to solve the increasingly complex problems faced by society. Establishing heterogeneous teams based on a variety of characteristics—including gender, age, disciplinary background, and level of experience—is an important contributor to creativity (Amabile, 1998). Incorporating such diverse perspectives can work to democratize design by reducing assumptions and stereotypes (Crewe, 1997), meaning that design processes can be more equitable and designed products can be more effective in meeting users' needs.

Engineering diversity and inclusivity has been a research emphasis of the field (National Engineering Education Research Colloquies Steering Committee, 2006). We agree that it is past time to "accept the research claim that diversity is important to engineering education" (Pawley, 2017, p. 531). However, students draw upon a "complex network of potentially competing and complementary reasons" when choosing engineering (Cruz & Kellam, 2018, p. 565). A barrage of factors and theories has been studied to understand obstacles to female participation in engineering and ways to improve participation (Beddoes & Borrego, 2011). Approaches have included addressing self-efficacy, mentoring and role models, teaming, and identity theories among others.

Despite acceptance of the need for diversity and many attempts to foster equity, there remains a well-known gender disparity in engineering professions and education. Women comprise less than 15% of the engineering workforce with negligible change over the past decades (National Science Board, 2018). Considering earlier educational and career processes, women earn only 21.9% of engineering degrees (Roy, 2018), although evidence has suggested that women who matriculate in engineering are equally likely to complete their degree (Ohland et al., 2011). This suggests that the gender gap precedes college enrollment. Indeed, young women are less likely than young men to express interest or enroll in engineering-related courses in high school (Gottfried & Plasman, 2018; Munce & Fraser, 2013) and are less likely to maintain interest in those classes (Sadler et al., 2012). Gottfried and Plasman (2018) reported that while high-school participation in engineering was related to the likelihood of completing an engineering degree for all students, it had a stronger effect on girls' degree completion. Therefore, early approaches to build and support engineering interest should be ongoing.

The research reported here is situated in the development and implementation of a novel design experience for high-school engineering classes. We examined whether participation in the design of *soft robots* had an effect on students'—especially girls'—perceptions of engineering. Soft robots are constructed from highly compliant materials similar to those found in natural organisms (Rus & Tolley, 2015). Our work is aligned with three factors related to the low percentage of women in engineering: societal relevance, technical self-efficacy, and tinkering self-efficacy (Baker et al., 2007). Next, we describe each factor before presenting the development of the design experience. Based on implementation in 22 classes, we report that the new experience had comparable impacts to existing robotics instruction and led to positive changes related to young women's tinkering self-efficacy. Student perceptions of engineering are nuanced, and this experience demonstrates a promising way to broaden engineering interest in precollege settings.

2 | PSYCHOSOCIAL FACTORS

Our research proceeds from the claim of Baker et al. (2007) that three of the most important factors for enhancing the participation of women in engineering are the perceived societal relevance of engineering, technical self-efficacy, and tinkering self-efficacy. Each of these beliefs is influenced by a variety of information sources over time. We recognize that these are not the only psychological aspects affecting engagement in engineering nor will these immediately solve the problem. However, evidence surrounding these factors makes a compelling case for the need to address these aspects of engineering education.

2.1 | Societal relevance

Societal relevance refers to a perceived "positive relationship between engineering products and services and how they can improve individual lives and benefit society and the environment" (Baker et al., 2007, p. 213). A meta-analysis of interest research has shown that men have a stronger tendency toward object-related fields and women have a stronger tendency toward people-related fields (Su et al., 2009). Science, technology, engineering, and mathematics (STEM) fields are seen as less likely to fulfill goals focused on others; however, interventions in how these fields are framed can have a positive effect on interest (Diekman et al., 2011).

Even within engineering, this people orientation is tacitly demonstrated by decisions about engineering majors among female undergraduates. The proportion of degrees awarded to female students is the greatest for environmental, biomedical, biological/agricultural engineering, and chemical engineering (Roy, 2018) where students perceive such activities as benefitting society (Kirn, 2014). In different marketing messages related to engineering, the most compelling motives were those that centered on making a difference in the world by promoting happiness, health, and safety (National Academy of Engineering, 2008). For example, efforts have focused on engineering for sustainability and the greater good as ways to increase student interest.

Recently, Godwin et al. (2016) investigated students' beliefs as they transition to engineering programs and advanced "critical engineering agency" as a framework for thinking about why students choose engineering. In addition to early mathematics and physics identities, an agentic part of the framework incorporated "self-beliefs about [students'] own agency to change their world through everyday actions and their broader goal … by choosing a career in engineering" (Godwin et al., 2016, p. 317). For all students, disciplinary identity beliefs and agency beliefs were significantly related to engineering career goals. However, for women, the effect of agency belief was a much stronger predictor of engineering choice than for men; it was also a stronger predictor than women's extant identities related to physics or mathematics. The importance of seeing societal benefits was affirmed in a qualitative investigation of the critical engineering agency framework where women spontaneously expressed these beliefs (Godwin & Potvin, 2015). Hence, recognition of the societal relevance of engineering concepts is of critical importance to improve and maintain girls' motivation for engineering.

2.2 | Technical self-efficacy

Baker et al. (2007) defined technical self-efficacy as "belief in competence to learn, regulate, master, and apply technical academic subject matter" (p. 213). These self-efficacy beliefs are antecedent to behavior and affect whether we will try to cope with a situation (Bandura, 1977). In this research, we operationalized technical self-efficacy as self-beliefs related to engineering content knowledge and problem solving generally and contrast it with beliefs pertaining to skills applied within engineering specifically, such as tinkering self-efficacy.

Self-efficacy beliefs are among the strongest predictors of engineering GPA for men and women (Mamaril et al., 2016; Vogt et al., 2007). Engineering self-efficacy beliefs are also consistently related to student intentions to persist in engineering (A. Jackson, 2018b; Mamaril et al., 2016). There is mixed evidence for gender differences in engineering technical self-efficacy. In some studies, women have reported lower self-efficacy than men in engineering (L. A. Jackson et al., 1993; Vogt et al., 2007). However, other studies have not reported a gender difference (Concannon & Barrow, 2009, 2012). Brainard and Carlin (1998) noted with concern that women who left engineering often had lower self-efficacy beliefs than men despite there being no differences in actual performance.

Engineering self-efficacy may be formed differentially for men and women, and these differences are amplified when there are few experiences to draw on. Competencies are often fostered through experience; however, in a traditionally gendered area such as engineering, girls likely have fewer experiences to increase confidence (Betz, 2006; Zeldin et al., 2008). When making comparisons with others, women are also prone to underestimating their abilities (Hutchison-Green et al., 2008). Considering these differences in the formation and levels of technical self-efficacy for boys and girls, it is necessary for engineering programs to provide experiences and feedback that build technical self-efficacy, especially for girls.

2.3 | Tinkering self-efficacy

Tinkering self-efficacy is a belief about "competence and comfort with manual activities" (Baker et al., 2007, p. 213), although others have broadened the definition of tinkering to include playful problem solving or the activities of making and deconstructing (Dong et al., 2019). Tinkering self-efficacy is associated with fluency when prototyping—for example, using a range of materials, tools, and approaches and finding a successful idea faster—and has a positive impact on design performance (Menold et al., 2018; Showkat & Grimm, 2018). In student interviews, previous tinkering experiences were a noted factor in understanding what engineering is and the choice to pursue it (Cruz & Kellam, 2018; Nelson et al., 2016).

Tinkering is process-focused and can be seen as a hands-on engineering skill instrumental for participation in engineering and distinct from the technical knowledge obtained from academic experiences (Baker et al., 2008; Mamaril et al., 2016). However, like technical experience, past tinkering is impacted by stereotyped gender roles and the types of experiences provided in adolescence (Betz, 2006). Early childhood stereotypes orient men toward tinkering activities, and these types of experiences subsequently inform choices to pursue engineering (N. Dasgupta &

Stout, 2014; Pereira & Miller, 2012). Despite equal academic preparation, men have reported higher tinkering self-efficacy and confidence in designing new things than women (Buckley et al., 2019; Mamaril et al., 2016; Schreuders et al., 2009). Taken together, this evidence suggests that engineering experiences also need to support hands-on, iterative exploration and familiarity with a range of building materials and tools to broaden female participation.

Overall, prior research suggests that gendered participation in engineering is a difficult problem and that ongoing attention to both personal issues and effective instructional design is key to increasing the diversity and inclusivity of engineering (Buckley et al., 2019; Knight et al., 2003). In summary, an experience that can couple engineering learning with evident societal benefits; provide technical content to foster confidence in problem solving; and facilitate tinkering through hands-on, iterative experiences would be expected to influence engineering perceptions.

3 | CURRICULUM CONTEXT

Soft robotics offers an intriguing solution to increase girls' interest in engineering because it addresses societal relevance, technical content, and tinkering processes of engineering. We position soft robotics, which is relatively new, as a complement to traditional robotics experiences, which are prevalent in educational settings. We have applied design-based research to seek feedback and make improvements to the soft robotics experiences in previous implementation phases. In so doing, our aim was to introduce students to a novel engineering experience that broadened their perception of engineering, and our efforts led to this culminating phase of the project.

3.1 | Rigid and soft robotics

There is widespread use of robotics in schools for their educational affordances (Benitti, 2012). A variety of robotics systems—for example, Arduino, Vex, or LEGO Mindstorms—has been incorporated in both formal and informal learning environments. The range of educational outcomes of robotics participation includes professional skills like collaboration, communication, design thinking, and problem solving as well as disciplinary knowledge and technical skills (e.g., electronics and programming; Benitti, 2012; Kopcha et al., 2017; McGrath et al., 2008). There is some evidence that robotics experiences bolster tinkering self-efficacy (Barker et al., 2012; Stubbs & Yanco, 2009). However, perceptions of traditional robots differ by gender due to the gendered nature of the materials in their construction (Hartmann et al., 2007; Showkat & Grimm, 2018). For instance, as an elective experience, participation in robotics tends to attract young people who are already interested in technical fields (Center for Youth and Communities, 2011; Witherspoon et al., 2016). In an analysis of FIRST Robotics participation, male and female participants reported taking on differing roles within projects with males more likely to be involved with central tasks (e.g., design, assembly, and programming) and females taking on peripheral tasks (e.g., marketing and fundraising and making presentations). Subsequently, boys and girls reported differing impacts: For boys, interest in science, technology, and STEM-related careers grew with girls seeing improvement in teamwork and communications skills (Center for Youth and Communities, 2011).

Familiarity and assumptions regarding traditional robotics systems, hereafter rigid robotics, may limit the benefits of these experiences for girls. Said another way, there is little evidence that rigid robotics programs have addressed the gender disparity in career interest or confidence in the technical aspects of engineering. Because soft robotics is a burgeoning field in engineering and represents a substantial shift in conceptions about robotics, female participation in the technical aspects of soft robotics may increase, and a corresponding increase in their interest and self-confidence related to engineering may occur.

Soft robots are constructed from flexible and compliant materials, thereby embedding safety during human interaction (Alici, 2018; Trimmer, 2013). This material property opens a host of societally relevant applications that are difficult to achieve in rigid robotics designs (Lipson, 2014), including prosthetics and medically assistive devices (e.g., for physiotherapy), wearable devices and sensors (lightweight, sensory clothing), and agricultural use (handling delicate objects). While rigid robots have immense potential for societal impact, the materially soft robots may draw a more intuitive connection to potential societal benefits of human–robot interactions due to their inherent safety and biological inspiration.

The technical principles of soft robotics are also shifted to align with areas of greater female interest mentioned earlier (environmental, biomedical, biological, and chemical engineering) by the bioinspired designs and polymer synthesis often used in construction (Kim et al., 2013). This means that soft robots are not only a natural fit to leverage societally relevant applications in these domains but can also lead to an increase in technical participation based on these interests.

Finally, the building blocks of soft robots differ. The compliant materials have a different feel and appearance than rigid robots and can broaden conceptions of engineering machines and devices; the different fabrication process also leads to holistic iteration on designs rather than tinkering with a small part of the design (Wang et al., 2015). While this might emerge in a rigid robotics design process, it is imposed by the material selection and might change the tinkering and design processes used in a soft robot experience. In many approaches, the robots are also made from scratch (i.e., starting out with liquid materials that solidify into stretchable, rubbery materials), which is quite different from building with rigid wooden and metal pieces (Ilievski et al., 2011).

3.2 | Lesson development

Our curriculum materials were adapted from existing materials on rigid robotics construction in a ninth grade course, Foundations of Technology. To isolate the effect of robot type, instructional materials and design tasks were adapted as little as possible. The design-based lesson included learning objectives related to design and modeling from the *Standards for Technological Literacy* (International Technology Education Association, 2007) and *Next Generation Science Standards* (NGSS Lead States, 2013). The lesson was planned to take approximately 8 h (1 week of 90-min classes or 2 weeks of 50-min classes), but in practice, we found most teachers spent 8–12 h with the project. In lessons for both rigid and soft robotics, students were introduced to the design challenge to create a gripper capable of performing a pick-and-place operation. For rigid robotics, the operation was to pick and place blocks; for soft robotics, students moved artificial produce goods. In the rigid robotics lesson, the system was controlled by hydraulic syringes attached to the gripper; in the soft robotics lesson, the system was pneumatically actuated by a hand pump (see examples in Figure 1). Students were given preliminary instructions on the underlying scientific principles (hydraulics for the rigid robots and pneumatics for the soft robots) before pairs of students received materials and were given time to build and test their ideas. Students then worked to design the device and document their progress using design notebooks. The project culminated in a presentation and demonstration of their work.

Both lessons were created with pedagogically sound practices for teaching design. Students worked in pairs throughout the project, creating an opportunity for peer modeling and encouragement. Students were familiar with the

FIGURE 1 Student fabrication examples from the rigid (top row) and soft (bottom row) robotics lessons. Cutout rigid components (top left) and example rigid robots (top middle and right). Molding silicone (bottom left), cured and demolded material (bottom middle), and inflated soft robot (bottom right) [Color figure can be viewed at wileyonlinelibrary.com]

design process and scaffolded through redesign cycles as part of their experience. Teacher scaffolding attempted to support inquiry and intentionality in redesigning instead of trial and error (Crismond & Adams, 2012). Materials available to students in the design process were chosen to support the exploration of ideas in construction. When ideas did not work, teachers encouraged reflection and redesign in an attempt to foster greater understanding of the underlying principles (Kapur & Bielaczyc, 2012; Lottero-Perdue & Parry, 2017). Both the lessons also incorporated class discussions as a means to share pitfalls and insights and support student success.

The fabrication process for soft robots also required adaptation from traditional engineering laboratories to fit classroom objectives, fabrication constraints, and student understanding, which have been described elsewhere (A. Jackson, Mentzer, et al., 2017). In our approach, students used a reconfigurable mold to cast a two-part silicone rubber. They then adhered a fabric layer to seal the inner air chamber and control actuation. While the materials and specific process constrain student design work, the modular mold was created to support the freedom of student design and focus attention on the optimization of design variables (Zhang et al., 2017). As shown in Figure 1 (lower left), the finger length had multiple discrete options, while air chamber configuration was almost infinitely variable as was the gripper thickness within the limits of the cavity. Each configuration impacted finger curvature in response to input pressure. While rigid and soft robotic systems can be used together, our soft robot fabrication process was wholly soft to isolate the effects of this material change on student perceptions. The new lesson and process were tested in outreach and classroom settings before widespread implementation whereupon the lesson and process were improved even further.

3.3 | Our past inquiry

Using design-based research, analysis in years one to three of our project has demonstrated feasibility and led to improvements to the soft robotics curriculum for classroom settings. The molds and initial instructional plans were refined through small-scale, local implementation before being expanded to multi-district training and implementation for the research evaluation (A. Jackson, Zhang, et al., 2017; Zhang et al., 2017). Teacher recommendations were integrated into the lesson plan, and the lesson has been well received by these participating teachers. Since our first professional development with teachers, we have provided training for implementation with 17 teachers in two states, reaching approximately 1250 students prior to the fourth year analyzed here.

However, during the first three project years, research findings have illustrated discord between quantitative analysis—which indicated that no significant changes were measurable in student perceptions—and the qualitative feedback received from teacher and student project participants—which indicated differences between rigid and soft robotics lessons. Quantitative changes in student responses from the beginning to the end of the of the soft robotics lesson showed changeability but not synchronized improvements in student self-efficacy, motivation, or interest compared to a rigid robotics experience (A. Jackson et al., 2018, 2019). On the other hand, qualitative observations of the experience and participant feedback were positive. A think-aloud verbal protocol analysis of four design dyads revealed that soft robotics can affect perceptions of engineering and the design process (A. Jackson, 2018a). We observed that the cycles of soft robot design catalyzed reflection among student team members beyond encouragement to redesign from the teacher, and students viewed the soft robotics experience as a more authentic engineering task than the activities they had participated in previously. Through interviews and participation on our project advisory board, teachers also indicated excitement about soft robotics.

Conflicts in the findings of mixed methods can illustrate the contextual aspects of an issue and naturally lead to interrogation of the data along with follow-up inquiry (DiLoreto & Gaines, 2016). Several aspects of the experience led us to continue with data collection: the newness of the experience and the lesson's conceptual alignment with the psychosocial factors for changing engineering perception. Ongoing analysis and improvement are also congruent with the design-based approach (Anderson & Shattuck, 2012). Therefore, we revised the curriculum materials, refreshed the teachers through professional development, and repeated data collection. In addition to these preparations, we followed recommendations to evaluate the rigor of our measurement approach and revise the procedures as discussed next (Moffatt et al., 2006).

4 | METHODS

Previous inquiry and discrepant findings built a foundation for the revisions to our approach and current analysis. Over a year-long implementation period, participating teachers delivered rigid and soft robotics lessons to their students and facilitated data collection via an electronic survey. Evaluation of the soft robotics lesson experience maintained a focus on whether the implementation of soft robot design experiences improved engineering motivation, interest, and self-efficacy when compared with traditional rigid robot design experiences. The educational context, teachers and classes, and measured variables in the primary analysis were consistent with our previous approaches. However, based on our reflection, we modified the research survey to have a retrospective structure. To further verify our findings, we conducted a robustness check to examine the stability of results under several alternative models.

4.1 | Students and teachers

The implementation studied in this report included seven engineering teachers who participated in the research. Each teacher had at least 10 years of experience and had previously taught the ninth-grade course. The teachers had also been trained on the soft and rigid robotics lessons and delivered them in classes in the previous year. Section assignments for the lesson type were randomized by the researchers with more soft robotics assignments in cases where the teacher delivered an odd number of classes. For the data analyzed here, the two robotics lessons were delivered to 22 classes throughout the school year (15 for soft robotics; 7 for rigid robotics) with about 24 students on average per class.

We received 361 total student responses in all. Of the participants who responded, 94 (26.93%) were female and 285 (82.13%) identified as an underrepresented minority race other than White. A majority of the students (63.32%) chose to take the class for themselves; others may have been placed in the class by a parent or school counselor. The elective nature of the course was determined by the district and, therefore, represented an important control variable for our model (see Section 4.3; Darby, 2006).

4.2 | Retrospective approach

To resolve the differences in the reported perceptions of the experience we had seen in earlier years of the project, we modified the research procedures to capture student perspectives after the curriculum. We used a retrospective pretest, also called a "then-test," administered at the end of the robotics lessons to induce reflection about the beginning levels of each psychological factor (Howard & Dailey, 1979). First, in the survey, students were asked to report their current perceptions for each of the outcome measures "after finishing the robotics lessons." Next, they were asked to report their perceptions before the robotics lessons for the same items, "considering yourself before the robotics lessons (about two weeks ago)." Each participant's present-day responses were shown while answering the retrospective questions. We used the difference between present and retrospective response levels to calculate the gain score for each model, providing a means to evaluate whether the soft robotics lesson had an impact on student perceptions when compared to the traditional rigid robotics lesson.

By *simultaneously* asking students to account for their beginning and concluding self-perceptions, the different structure of the retrospective test accounts for response-shift bias that might exist from participation in the soft robotics curriculum (Howard & Dailey, 1979). Such a bias results from students overestimating their initial beliefs and understanding, which are calibrated from participation in an experience (Coulter, 2012). We accept that the initial self-perceptions reported in the retrospective format (the "then" responses) are colored by the students' experiences in the curriculum and their present state of each psychological factor and may not match a traditional pretest. However, these relative reports of self-perception are "a better indicator of change" (Drennan & Hyde, 2008, p. 707) and all the more meaningful when evaluating the soft robot design experience for positive effects and perceptual change.

4.3 | Variables and models

The end-of-lesson questionnaire was composed of four existing instruments presented in a randomized order and questions on student demographics. Instruments were chosen for their alignment with the psychological perceptions at the thrust of this research—perceived societal relevance, technical self-efficacy, and tinkering self-efficacy. Six outcome measures were scored from subscales of the existing instruments, repeated for the present day and retrospectively; other questions were asked only once. The Situational Motivation Scale (SIMS; Guay et al., 2000) and STEM Career Interest Survey (STEM-CIS; Kier et al., 2013) were related to students' perceptions of societal relevance; the General

Engineering Self-Efficacy Scale (Mamaril et al., 2016) was related to technical self-efficacy; the multidimensional Engineering Skills Self-Efficacy Scale (Mamaril et al., 2016), comprised of three subscales, was related to tinkering self-efficacy. For each outcome, we calculated a gain score as described in the Retrospective Approach and used the following model template:

$$\begin{aligned} \mathit{Outcome\ Gain}_i = {} & \beta_0 + \beta_1(\mathit{enrollment\ choice})_i + \beta_2(\mathit{minority\ status})_i + \beta_3(\mathit{perception\ covariate}\ 1)_i + \beta_4(\mathit{perception\ covariate}\ 2)_i \\ & + \beta_5(\mathit{gender})_i + \beta_6(\mathit{lesson\ type})_i + \beta_7(\mathit{gender} * \mathit{lesson\ type})_i + \varepsilon_i. \end{aligned}$$

The equation predicts outcome gains for students, *i*, based on their demographics and initial feelings about the course as well the lesson type they experienced—rigid or soft robotics—and the interaction between the students' gender and lesson experience. A description of each variable is given next with the variables italicized.

4.3.1 | Outcome measures

The first outcome related to perceptions of societal relevance, *motivation* for engineering, was measured by the SIMS. The instrument was developed by Guay et al. (2000) based on self-determination theory using four subscales to represent facets of motivation: intrinsic motivation, identified regulation, eternal regulation, and amotivation. For example, questions ask students to rate whether they are engaged in an activity "Because I think that this activity is interesting" (intrinsic motivation) or "Because it is something that I have to do" (external regulation). Following a procedure commonly used in self-determination research, subscale scores were weighted based on their relative position on the continuum of self-determination (+2, +1, −1, and −2 for the subscales in order) and summed into a composite score—a self-determination index (Stolk & Martello, 2015; Vallerand, 1997). The greater an individual's self-determination index, the greater his or her sense of internal motivation for the activity.

Next, the Engineering subscale of the STEM-CIS instrument (Kier et al., 2013) was used to measure students' *interest* in engineering careers, also related to perceived societal relevance of the field. The 11 engineering-related items are answered on a 5-point Likert scale to demonstrate aspects of social cognitive career theory (e.g., "I plan to use engineering in my future career"). In past secondary education research, the items have exhibited reliability (A. Jackson et al., 2019). We used the average score reported by the students to indicate their interest in engineering.

Self-efficacy outcomes in our study can be separated into technical self-efficacy or tinkering self-efficacy aspects in line with the psychosocial factors described previously. The measure of technical self-efficacy was the General Engineering Self-Efficacy Scale from Mamaril et al. (2016). This scale adapts existing instruments to a concise measure of student *general engineering self-efficacy* and reliably predicts engineering outcomes. The items include questions on completing coursework, learning, and achieving satisfactory grades in engineering, all related to the technical self-efficacy outcome of interest in this research (e.g., "I can do a good job on almost all my engineering coursework"). The original scale includes five items. However, based on the recommendation of past work, we removed one item to improve the fit of the scale for administration in secondary education (A. Jackson, 2018b).

In addition to the General Engineering Self-Efficacy Scale, Mamaril et al. (2016) presented three subscales within the Engineering Skills Self-Efficacy Scale related to *experimentation*, *tinkering*, and *design*. Each skill has four items and a verified factor structure for use in secondary education (A. Jackson, 2018b). The Experimental Skills Self-Efficacy Subscale includes items such as "I can perform experiments independently." The Tinkering Skills Self-Efficacy Subscale includes "I can work with machines" and "I can assemble things" among others. Finally, the Design Skills Self-Efficacy Subscale includes items such as "I can identify a design need." While the match of the Tinkering Skills Self-Efficacy items to the tinkering psychosocial factor is evident, experimentation and design self-efficacy also relate to students' comfort with the processes of engineering. In this way, each of the engineering skills is conceptually related to confidence in how engineering is enacted.

4.3.2 | Control variables and demographic information

Several additional details were obtained from students or matched by researchers and incorporated into the primary statistical analysis. These included control variables and the groups of primary interest in the study. Because of the interplay among self-determination, interest, and self-efficacy perceptions in general (Bong, 2001; Lent et al., 1994) and in engineering specifically (e.g., Carberry et al., 2010), we included the initial reported levels of each of the other two constructs as *perception covariates* in the statistical model. For example, when predicting self-determination gains, we included overall self-efficacy and interest as predictors to account for beginning levels reported by the students.

Because the course setting of the study was an elective, we asked students about their *enrollment choice* for the course to account for positive predispositions toward the content. Furthermore, we asked students to report their race and then created a dichotomous grouping for *underrepresented minority status*. This grouping was included as a control variable in the analysis.

Our main focus was on gender differences and the effect of the lessons on student outcomes. Students were asked to report their *gender*. The *lesson type*, rigid or soft robotics, that students experienced was obtained based on their course enrollment. Finally, the *gender–lesson type interaction* was also included in the model to examine whether the new experience had a differential impact for girls.

The effect of *teacher* was also considered; however, the inclusion of a second-level variable in the model did not account for substantive variation in student scores based on the intraclass correlation coefficient. To ease interpretation and reduce model assumptions, this structure was omitted from the primary analysis.

4.4 | Primary analysis

Responses for the primary analysis were screened for missing data and engagement on each outcome variable and demographic characteristic. Data were also inspected for outliers with 19 cases identified as univariate outliers based on extreme changes relative to their gender or lesson type groups (Tabachnick & Fidell, 2007). The collection of missing and removed responses was also examined for underlying mechanisms of missingness. No systematic relationship was observed between missing responses and other data; therefore, we inferred that the data were missing at random. Furthermore, outliers were dispersed between gender and lesson types and included both increases and decreases in engineering perceptions. Considering the randomness of the missing data and randomized presentation order of the survey, we chose to use available cases for each outcome variable. The sample size varied slightly among the factors; however, the available case approach maximized the power of each linear regression model.

4.5 | Robustness check

In our analysis, each of the six psychological outcomes was modeled separately. This can raise concerns due to the number of possible outcomes from the selected measurement instruments—for example, whether to model overall and subscale composite values—and the subsequent multiple tests to be performed. Feise (2002) summarized the main benefit of adjustment for multiple comparisons as "weeding out false positives" (p. 2) and recommended that researchers consider the consequences of both Type I errors, incorrectly asserting results, and Type II errors, missing potential results. We considered the obstacles to the discovery of potentially effective approaches to be more severe; therefore, we limited the number of outcomes analyzed and made no further adjustments to the primary statistical analysis.

We also supplemented our primary analysis with a robustness check to compare several alternative statistical models and samples in our work and evaluate the impact of such decisions (Duncan et al., 2014; Lu & White, 2014). A comparison of variables of interest among the models—critical core coefficients (Lu & White, 2014)—can provide evidence for stability in the direction and magnitude of the statistical results, ensure that departures from the model assumptions were not problematic, and strengthen confidence in the analysis. Alternative regression models included (a) analysis using complete cases (this is more liberal in removing cases than the available case approach of the primary analysis), (b) controlling for teachers in a mixed-effects model, (c) using a penalized quasilikelihood specification to account for deviations from normality and the unbalanced design (also a mixed-effects model; Bolker et al., 2009), and (d) removing additional control variables in the model.

5 | RESULTS

The analysis of available cases included 257, 266, and 267 responses for self-determination, interest, and self-efficacy instruments, respectively. The collection of responses included 293 separate students with complete responses on at

TABLE 1 Demographics for rigid robotics and soft robotics lesson types

Student characteristic	Rigid robotics ($n = 86$) n (%)	Soft robotics ($n = 207$) n (%)	% of total
Demographics			
Female	25 (29.07)	58 (28.02)	28.33
Male	61 (70.93)	149 (71.98)	71.67
Minority status	75 (87.21)	166 (80.19)	82.25
Course election	52 (60.47)	132 (63.77)	62.80

TABLE 2 Descriptive and psychometric statistics for calculated outcome gains

			Overall psychometric properties			
Engineering perception gains	Rigid robotics M (SD)	Soft robotics M (SD)	n	ω_h	Potential range[a]	Measured range
Self-determination Index	0.60 (3.58)	0.58 (3.73)	257	0.88	−36 to 36	−7.25 to 10.75
Interest	0.25 (0.77)	0.28 (0.65)	266	0.85	−4 to 4	−1.64 to 2.18
Self-efficacy						
General	0.56 (1.16)	0.65 (1.06)	267	0.80	−5 to 5	−2.25 to 3.75
Experimental	0.60 (1.33)	0.60 (1.14)	267	0.84	−5 to 5	−2.17 to 4.50
Tinkering	0.46 (1.16)	0.66 (1.19)	267	0.81	−5 to 5	−2.33 to 3.75
Design	0.48 (1.22)	0.65 (1.15)	267	0.84	−5 to 5	−2.25 to 4.00

[a] The potential range is calculated based on item scales although extreme values are unlikely to be reported in reality due to the calculation of gain scores.

least one of the outcome variables and the demographic information. Of the group, 229 students (78.16%) had complete responses on all of the subscales. The proportion of female students, minority students, and those who chose to take the class matched observations prior to screening (Table 1).

Reviewing mean differences between the two robotics conditions is suggestive of the potential utility of the program, although effects are small (Table 2). The mean gains for general, tinkering, and design self-efficacy are higher for soft robotics participants overall than for the rigid robotics participants. These findings are merely suggestive for at least two reasons: The imbalance of students by lesson type and gender has the potential to affect these estimates and the large variation in gains may be controlled by additional variables as in our subsequent analysis. However, based on ω_h reliability values above 0.80, we conclude the reliability of these scales in our context. Internal consistency was measured by ω_h, which relaxes assumptions about the structure of measurement scales and is more appropriate than coefficient α in most cases (Zinbarg et al., 2005).

Our main analysis followed with attention directed at the core coefficients of gender, lesson type, and the interaction effect of these terms (Table 3). Because the outcome gains were centered, the significant intercepts for engineering interest and general, experimental, tinkering, and design self-efficacy indicate a positive change in participation in both hands-on design experiences. Other control variables such as enrollment choice or students' minority status also predicted student perception gains in line with extant work. The negative coefficients on the control variables for initial perception levels is curious—this could be due to a ceiling effect of the instruments where those reporting initially high values have little room to improve; however, there was little contextual value when these variables were included only to control for the main effects of interest (Lu & White, 2014).

Among self-determination, interest, and self-efficacy outcomes, a notable finding is the prediction of tinkering self-efficacy gains. For most outcomes, girls had lower gains than boys, but these were not significant (and this gender difference matches previous literature). For tinkering self-efficacy, there was a significant difference between boys and girls, with girls reporting lower gains ($\beta = -0.56$, $p < 0.05$). However, interpreting this finding in the context of the lesson type indicates that girls benefitted from the soft robotics lesson to a greater degree than the rigid robotics lesson—the interaction effect of gender and lesson was significant ($\beta = 0.63$, $p < 0.05$). Indeed, this leveled the reported mean gains for boys and girls in tinkering self-efficacy gains (Figure 2). There is still much variation to be explained in the models; however, the increase is roughly 10% of the range of gains reported by participants.

TABLE 3 Primary regression analysis coefficients and standard errors

	Self-determination gain	Interest gain	General self-efficacy gain	Experimental self-efficacy gain	Tinkering self-efficacy gain	Design self-efficacy gain
Intercept	1.42 (0.91)	0.80 (0.18)***	1.90 (0.32)***	2.11 (0.36)***	1.71 (0.35)***	1.83 (0.34)***
Enrollment choice	0.29 (0.35)	0.04 (0.09)	0.29 (0.14)*	0.41 (0.16)*	0.32 (0.15)*	0.21 (0.15)
Minority status	0.05 (0.40)	−0.10 (0.09)	−0.28 (0.15)	−0.55 (0.17)***	−0.40 (0.16)*	−0.35 (0.16)*
Self-determination "then"[a]		−0.01 (0.01)	0.00 (0.01)	0.00 (0.01)	0.01 (0.01)	0.02 (0.01)
Interest "then"[a]	−0.16 (0.22)		−0.33 (0.07)***	−0.31 (0.08)***	−0.27 (0.08)***	−0.32 (0.08)***
Self-efficacy "then"[a]	−0.15 (0.17)	−0.11 (0.03)***				
Female	−0.24 (0.65)	−0.04 (0.15)	−0.45 (0.23)	−0.48 (0.26)	−0.56 (0.26)*	−0.46 (0.25)
Soft robotics	0.03 (0.43)	0.00 (0.10)	−0.05 (0.16)	−0.32 (0.18)	−0.16 (0.17)	−0.14 (0.17)
Female × soft robotics	−0.30 (0.77)	−0.02 (0.17)	0.04 (0.28)	0.35 (0.31)	0.63 (0.31)*	0.52 (0.29)
R^2	0.02	0.07	0.13	0.12	0.09	0.10

[a] As noted in Section 4.3, the perception gain scores were predicted by initial levels of the other two engineering perceptions only.

Note: $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

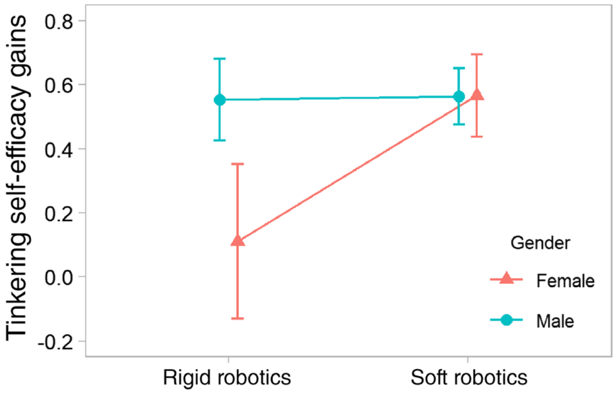

FIGURE 2 Interaction effect of gender and lesson type on tinkering self-efficacy gains. Tinkering self-efficacy was measured on a 6-point Likert scale with student gain as the difference over time [Color figure can be viewed at wileyonlinelibrary.com]

The robustness check was carried out by using alternative statistical models and samples with the range of resulting coefficients and standard errors reported in the online Supporting Information. Among the coefficients, there was some expected fluctuation due to the removal of control variables in one alternative model. Still, alternative models showed a consistent direction and magnitude for effects and stable standard errors. With the exception of the "no controls" model, the significance of the simple effect of gender and the interaction between gender and lesson type were confirmed to predict tinkering self-efficacy. All of this suggests the stability of the findings, that both experiences benefitted interest and self-efficacy generally and that the soft robotics experience was especially beneficial for girls' tinkering self-efficacy.

6 | DISCUSSION

This research aimed to discern possible benefits in student engineering perceptions following participation in a soft robot design experience in contrast to a traditional robot design experience. While there are theoretical rationales for the new soft robotics experience to impact student perceptions of societal relevance, technical self-efficacy, and tinkering self-efficacy, our quantitative findings indicated a generally comparable change for participants in the soft robotics and rigid robotics experiences. We also found gender differences similar to past literature among these engineering perceptions. An exception was that engagement with the soft robotics experience led to an increase in tinkering self-efficacy for girls, which relieved the gender differences in that element of engineering perception.

6.1 | Benefits of soft robotics for tinkering self-efficacy

Tinkering self-efficacy has been identified as an important area for engineering education innovations working to reduce gender disparities (Buckley et al., 2019). Engineering tinkering suggests curiosity and engagement with hands-on materials and can bolster students' engineering identity (Cruz & Kellam, 2018). Two attributes of the soft robot design experience may be related to the superior benefit of the experience: materially different robots and holistic redesign cycles.

First, soft robot construction in this design experience involved substantive shifts in material selection and structure of machines. Tinkering self-efficacy is related to comfort with manual aspects of engineering, engineering machines, assembly or disassembly, manipulating devices, and similar tasks. In contrast to traditional robot materials, which are already stereotyped by students (Hartmann et al., 2007), the soft robots were built from scratch using unfamiliar materials. Using these nonstereotyped materials may have welcomed equitable participation from boys and girls in the fabrication process. By producing a soft, squishy robot, the new robotics experience also affected perceptions of what constitutes a machine, thereby broadening student perceptions of engineering and who can be an engineer. The process and product differences may have encouraged girls to engage in ways they were comfortable while still recognizing the participation as engineering tinkering and working with machines.

Second, the pattern of iteration in the soft robotics experience necessitated holistic analysis and redesign. The materials used for soft robots were unlike traditional wood and metal materials that could be rearranged to adjust an idea. Instead, students mixed the two-part silicone to begin a chemical reaction, which meant the design attempt was fixed. After each attempt, the process naturally included opportunities for reflection and analysis before redesigning. The soft robotics experience may facilitate a desirable return to the design process when ideas do not work (Lottero-Perdue & Parry, 2017) and may reduce fixation or commitment to an idea through the expectation that there will be multiple attempts. Furthermore, these imposed cycles of design may play a role in helping students manage iteration throughout the design process (Crismond & Adams, 2012; C. Dasgupta, 2019). Finally, the redesign phases lead to multiple distinct attempts that may build up mastery experiences, an important source of self-efficacy (Bandura, 1977). For those who have not had previous engineering tinkering experiences—such as female students based on role stereotypes and past records of robotics participation (Betz, 2006; Center for Youth and Communities, 2011)—the repetitive design experience used here may have provided access to the process and reinforced perceptions of competency. Intentional iteration through soft robot fabrication seems to have affected the perception of the processes of engineering as signaled by the change in tinkering self-efficacy.

6.2 | Motivation, interest, and technical self-efficacy

In other aspects of student perception, the newly developed soft robotics experience performed as well as the traditional robotics experience. Both experiences provided a benefit to student technical self-efficacy. Student interest also increased although we did not observe a difference in self-determination (both related to societal relevance). This evidence suggests the benefit of early engineering experiences for student perceptions and is congruent with Gottfried and Plasman (2018) who showed long-term benefits to early participation in engineering. However, it differs from past work showing the limited effects of robotics experiences on student perceptions (e.g., Hartmann et al., 2007). It is possible that the embedded nature of this experience in a classroom as opposed to an extracurricular activity was an important characteristic here.

Research on past motivational interventions may also clarify the limited effect we observed on self-determination (in either lesson type). Past research has observed motivational changes in course-long interventions (Stolk & Martello, 2015; Vaillant et al., 2015), and Stolk et al. (2014) indicated the importance of matching the time scale of change to the underlying construct being measured. This leaves the question of whether engineering soft robots can have the desired impact in the short term. It is possible that motivation, for example, self-determination as measured here, is a more enduring perception and requires more than 2 weeks to change. Longer and earlier experiences have been recommended due to the difficulty of addressing gender gaps in engineering (Knight et al., 2003). On the other hand, in even 6 weeks when working with younger children, Capobianco et al. (2009) found that young girls can begin to adopt engineering mindsets. Whether motivation or self-efficacy beliefs come first is also unresolved although both perceptions are necessary for identity development and are mutually reinforcing (Godwin et al., 2016; Lent et al., 1994). It is possible that the increases in self-efficacy we observed may have a lagged effect in developing student motivation and choices to pursue engineering.

6.3 | Implications for instruction

As in earlier rounds of the development process, this lesson implementation gives insight to refine and improve instruction. Future soft robotics experiences would do well to focus on tinkering pedagogies, which might amplify the positive effects on tinkering self-efficacy observed here. Such strategies include affirming the value of iteration and learning from past attempts, helping students test ideas early, and drawing connections to underlying concepts throughout the experience (Vossoughi & Bevan, 2014). Soft robotics is a ripe context for learning from failure based on the materials and the consecutive iterations involved (A. Jackson, 2018a). These affordances of soft robotics may also be applied to more typical design experiences to support student learning and confidence for tinkering.

For engineering curriculum generally, this research advances the need to engage students in diverse experiences. By bringing new aspects of engineering into the forefront, students see a range of ideas and materials and can deconstruct stereotypes and misconceptions. This research also shows a nascent model whereby cutting-edge engineering research can be adapted to become authentic precollege engineering coursework. There are certainly challenges that need to be addressed for each adaptation through multiple revisions for feasibility and success. However, our example may lead to curriculum inspiration and future research-to-practice partnerships.

6.4 | Implications for research

As we evaluated the soft robotics lesson, we found differences in tinkering self-efficacy gains by gender. We have discussed several ways that the material changes and redesign cycles in soft robotics relate to tinkering, yet this take-away also leads to two alternative suggestions related to research for broadening participation. First, there may be impacts beyond what we traditionally identify as a research outcome that demonstrate changes in girls' and boys' ways of thinking about engineering. As tinkering self-efficacy involves process-related skills, the difference seen in this research may indicate broader changes in the thinking patterns of students. A more holistic picture of what transpires while designing would be needed to analyze such thinking processes. Second, this report aggregated student perceptions to quantitative metrics, whereas alternative approaches might highlight individual trajectories in a qualitative approach. In our case, the divergent feedback of quantitative and qualitative findings from earlier phases of design-based research spurred further development, leading to the current research. We affirm the value of coupling quantitative and qualitative research as both offer important perspectives for the evaluation process.

Another implication follows for research attempting to broaden perceptions of engineering: Due to those changing perceptions, it may be necessary to use alternative evaluation approaches that examine perceptions from the same frame of reference. Students' misconceptions about engineering represent a significant obstacle to developing interest or pursuing engineering until those beliefs are corrected (Betz, 2006; Cruz & Kellam, 2018). As previously described, our research applied a retrospective approach for collecting student responses. By obtaining simultaneous reports of perception, the educational intervention may have had the opportunity to take hold in student minds and calibrate beliefs. A retrospective approach may also be seen to offer balance between quantitative and interpretive paradigms as described here because of its foundation of student perception. No matter the measured impacts of a specific study, peripheral benefits to individual students, shifting frames of reference, and the buildup of positive experiences over time suggest that our collective efforts to encourage gender participation are a net positive.

6.5 | Limitations

The development of interest and self-efficacy beliefs is related to a multitude of factors and is even more complicated when set in a classroom research environment. As much as we tried to control a single aspect of the engineering learning experience—shifting the materials for robotics fabrication from rigid to soft components—there were additional changes that took place as a result. We recognize that shifting from rigid to soft robotics activated shifts from ambiguous to societally relevant in context, clean to messy in fabrication, and arbitrary to systematic in iteration. Any of these aspects may have been the actual cause of the changed perceptions we observed; on the other hand, each ensuing change reveals an opportunity to isolate and investigate in future research. Furthermore, soft robotics may work as a natural segue to these changes. This work identified and internally verified through the robustness check the overall benefits of soft robotics experiences on engineering perceptions and their promise for future development.

7 | CONCLUSIONS

To broaden participation, changes to our field need to target the engineering and not students or messaging alone (Riley, 2008). We have investigated a curriculum experience wherein the substance of engineering was changed from traditional rigid robots to novel soft robots. We anticipated benefits to girls' perceptions of the societal relevance of engineering (through the safe, interactive nature of soft robotics), technical self-efficacy (through the background domains of soft robotics), and tinkering self-efficacy (through the "level playing field" afforded by the introduction of novel materials synthesis and material system design). The soft robotics experience particularly impacted girls' tinkering self-efficacy, and embedding the robotics experience raised student perceptions of engineering generally.

The soft robotics lesson presents a flexible context in terms of the standards that it might address and the potential benefit to student perceptions. The soft robotics lesson was adapted to meet the same learning objectives and engineering standards as traditional robotics in deliberate redesign cycles. In the future, soft robotics lessons could also be modified to address a range of STEM learning outcomes due to the broad disciplinary base that informs soft robot design; in so doing, the lessons might tilt toward engineering fields that demonstrate greater female participation. The learning experience could also be extended to further incubate engineering motivations. Coupled with evidence of improving tinkering self-efficacy perceptions, the new lesson represents a promising opportunity to integrate authentic engineering content into secondary engineering education and support the development of future engineers.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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