Rethinking Human-Robot Interaction Through Soft Robotic Learning Approach

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Abstract

Material science, mechanical design, embedded sensing, and control design merge in the sphere of soft robotics to create flexible, adaptive systems capable of and suitable for facilitating safe and intuitive human-robot interaction (HRI). The primary research question guiding this initiative is: How can interactive soft robots help with students' interdisciplinary learning? This workshop investigates how active engagement in soft robotics via injection molding, programmable sensors, and HRI experiments can foster the integration of knowledge from across engineering, computing, design, and human centric domains.

The workshop curriculum is structured into three interconnected modules that build conceptual understanding and practical skills. The first module, Soft Actuator Fabrication via Injection Molding, immerses students in material-based design thinking. Students learn to mold and cure elastomeric components using silicone and thermoplastic polymers. In the second module: Programmable Sensing and Embedded Intelligence, sensor integration and microcontroller-based programming are introduced. Participants embed and program flexible strain gauges, capacitive sensors, or fiber-optic sensors into the molded structures to enable real-time feedback on pressure, stretch, and curvature. In the third learning module, technical developments from HRI and design integration are connected with human centric applications. Students holistically evaluate safe interactions between humans and soft robotic devices through collaborative projects such as wearable grippers, tactile gloves, or assistive rehabilitation tools. A survey is used to examine how such a workshop enhances interdisciplinary learning and impacts awareness of varied disciplines. Students are encouraged to reflect on questions such as "What skills from different disciplines did I integrate today?" and "How did materials, programming, and human feedback influence my design decisions?" These prompts help measure shifts in students' awareness of how disciplinary knowledge can build upon each other.

In an initial pilot offering of the workshop, evaluation focuses on learning outcomes across three areas. Interdisciplinary competence is measured through mid- and post-workshop surveys assessing students' confidence in cross-domain integration. Preliminary data suggests that engaging with soft robotics encourages students to think across disciplinary boundaries by combining analytical rigor with creative design thinking.

Introduction

Robotics has become one of the leading developments in modern engineering, with a significant impact across industries such as healthcare, manufacturing, and exploration, and this growth is reflected in the rapid expansion of educational robotics in K–16 science, technology, engineering, and math (STEM) programs. Recent meta-analyses and curriculum studies show that robotics-rich experiences can meaningfully improve students' learning performance, attitudes, and problem-solving skills when thoughtfully integrated into courses and programs [18], [19]. As the demand for robotics grows, engineering education programs are under increasing pressure to offer curricula that are not only technically rigorous but also aligned with current practice, often through project-based and active-learning formats that place students in realistic design and implementation roles [11], [12], [18], [20]. Despite increased demand and pressure, several strands of robotics remain underrepresented in formal coursework—either because they are relatively new, require specialized or expensive hardware, or have not yet become mainstream in research and industry. Reviews of educational robotics and soft-robotics-in-education literature repeatedly note that most offerings still rely on rigid platforms and focus on classic topics like kinematics, control, and mobile robots, leaving many emerging subdomains only lightly addressed, if at all [1], [3], [7]. As a result, students' exposure to some of the most promising frontiers of robotics is often limited, even though these areas may shape the next generation of engineering practice [1], [18], [19].

Soft robotics is a particularly important example of such an underrepresented area. It is a relatively new field that focuses on robots made from compliant, deformable materials—such as silicone rubbers and elastomers—that can safely interact with people and delicate objects, often in close contact or unstructured environments [1], [2], [9]. Educational and technical studies highlight how soft robotic systems naturally emphasize core engineering concepts such as material selection, mechanics of compliant structures, actuation principles, and fabrication processes, making them powerful contexts for teaching both theory and practice [1], [2], [5]. Soft robots are particularly relevant to applications in prosthetics, assistive and rehabilitative devices, and biomedical technologies because they can be designed with food-safe or biocompatible materials and can conform to complex shapes, [2], [9], [10]. At the same time, their compliant and damage-tolerant nature has been explored in domains such as underwater exploration and other extreme environments, where traditional rigid robots pose safety or adaptability limitations [1], [9].These characteristics make soft robotics attractive for engineering programs seeking to connect fundamental principles to real-world applications, as it offers many learning opportunities.

As such, the field of soft robotics is particularly well suited to a project-based hands on engineering curriculum. Studies of robotics and soft-robotics courses consistently show that project-based and design-oriented activities deepen students' conceptual understanding, support the development of computational thinking, and strengthen their confidence in tackling open-ended engineering problems [11]–[13], [15], [18], [20]. Soft robotics projects inherently require multidisciplinary collaboration: mechanical engineering students may lead computer-aided design (CAD), mold creation, and basic structural or finite element analysis (FEA); electrical and computer engineering students can focus on sensing, actuation, control, and embedded electronics; and computer science or computer engineering students can implement microcontroller code and data processing pipelines [2], [6], [14], [16]. Evidence from courses and workshops that combine these roles shows that students not only learn domain-specific skills (e.g., modeling, fabrication, sensing, controlling, programming), but also gain experience in teamwork, communication, and self-regulation—competencies that are repeatedly identified as critical outcomes in engineering education research [10]–[12], [17]–[19].

The soft robotics workshop described in this paper builds directly on these trends by offering an undergraduate, faculty-structured, student-led experience centered on designing and assembling a robotic arm with a soft humanoid hand for dexterous manipulation. Similar to other emerging soft-robotics learning environments—including interdisciplinary courses, virtual labs, undergraduate-led research programs, and student-designed modules—this workshop is structured to give students authentic ownership over the full lifecycle of a system, from material choices and CAD design to casting, assembly, electronics integration, and functional testing [2]–[6], [8]. Over a 15-week semester, students with diverse backgrounds commit several hours each week to hands-on exploration, guided mentorship, and iterative refinement, mirroring project-based robotics and STEM courses that have been shown to produce measurable gains in learning outcomes, attitudes, and teamwork skills [10]–[13], [18]–[20]. By asking students to reflect on material selection, CAD modeling decisions, fabrication challenges, and system performance, the workshop not only reinforces fundamental engineering principles but also generates rich evidence of how a focused soft robotics experience can broaden students' understanding of robotics and motivate institutions to place greater emphasis on soft robotics within their engineering curricula [1]–[5].

Method

1. Learning structure

This workshop is offered as part of a university-wide initiative to supplement undergraduate learning with extracurricular research. Students voluntarily commit to a project - in this case, one related to soft robotics and human-robot interaction - on a semester-by-semester basis. The workshop is essentially student-led, with veteran members assuming team lead roles and the leading professor acting as the project advisor. By having this structure outlined, the results of the workshop can be effectively attributed. The workshop has a mix of students ranging from first to fourth year. The workshop lasts for one semester, which is 12 weeks.

The top-level organization of this workshop encompasses the joint efforts of the soft robotics and human robot interaction teams. In order to enhance learning by discipline, the soft robotics and human robot interaction teams are each then split into subteams, each headed by their own leads who are responsible for overseeing task delegation and progress. Across each subteam, suitable weekly meeting times and durations are determined through an initial availability survey to accommodate members. Through this structure, students are enabled to make contributions to the creation of the robot that best suits their individual skillsets.

As previously mentioned, the soft robotics and human robot interaction teams function as separate entities within this workshop, as their work, while sharing several fundamental engineering principles, requires different specializations. However, they remain in close communication in order to ensure a successful integration of the soft robotic manipulator onto the robotic arm. This allows students to explore various disciplines while still participating in the same greater project. The subteams are formally declared after gauging student interests at an initial all-team introductory meeting; however, students may still navigate around early on in the semester should they wish to.

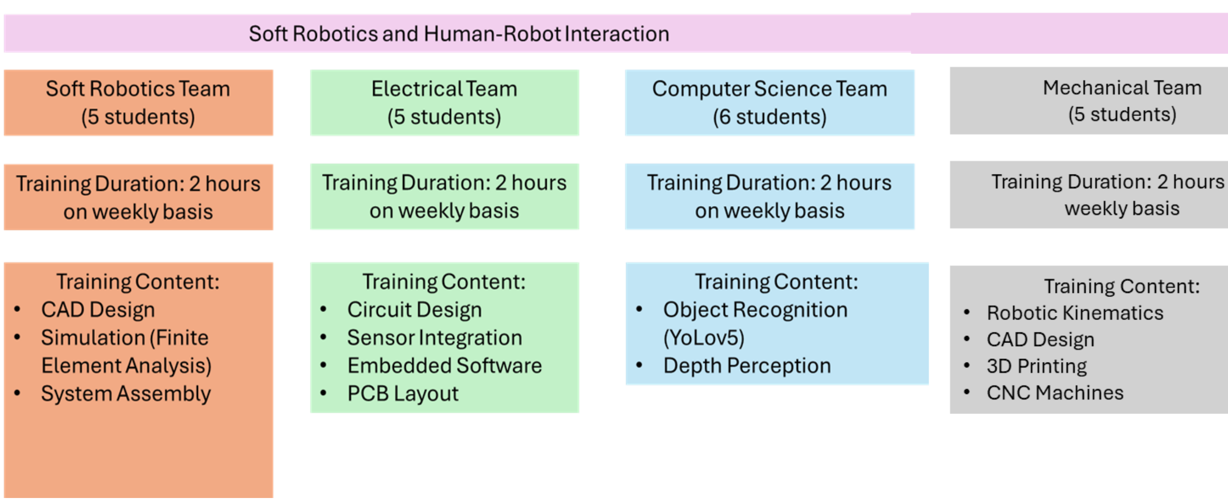
As the workshop itself is headed by students, team meeting structures are fluid and can be altered as necessary to best accommodate the needs of student members. As such, while a general schedule – involving regular meetings, check-ins, and project-wide end-of-semester reports – must be present, various subteam organizations can be observed. This also allows students to become familiar with team organization and project management.

Due to the differences in progression between the mechanical and electrical systems of the robot, the soft robotics and human robot interaction team are divided into the electrical engineering and computer science subteam, and the mechanical subteam. The students developing the electrical components must work very closely with the students who are writing code for the systems. Thus, this team organization optimizes progression in each major aspect of the robotic systems such that the subteams can reconvene at a later point when necessary for full integration and testing of the robot.

The electrical engineering subteams focus on control systems, sensor integration, embedded software, and printed circuit board (PCB) layout. Students are first introduced by team leads, which leads to an outline of the overall control system as well as the components chosen given the system requirements and team budget. Once students have a firm understanding of the end goal, they are polled on their interest in topics relevant to the project and are given preliminary tasks related to each subject. Through weekly check-ins, students report their progress and get their questions answered by their team leads. Once these tasks are completed, tasks shift towards testing sensors, writing software, and designing custom control boards to control the human-robot interaction arm and soft grippers.

The mechanical subteam of the human robot interaction team focuses on mechanical engineering principles such as statics and kinematics, CAD design, FEA simulation, and fabrication, for which foundational skills are first taught to students by team leads The progression of the robotic arm development generally follows that respective order, with a cyclic process governing the latter few domains.

(a) Team Structure



(b) Instruction mode

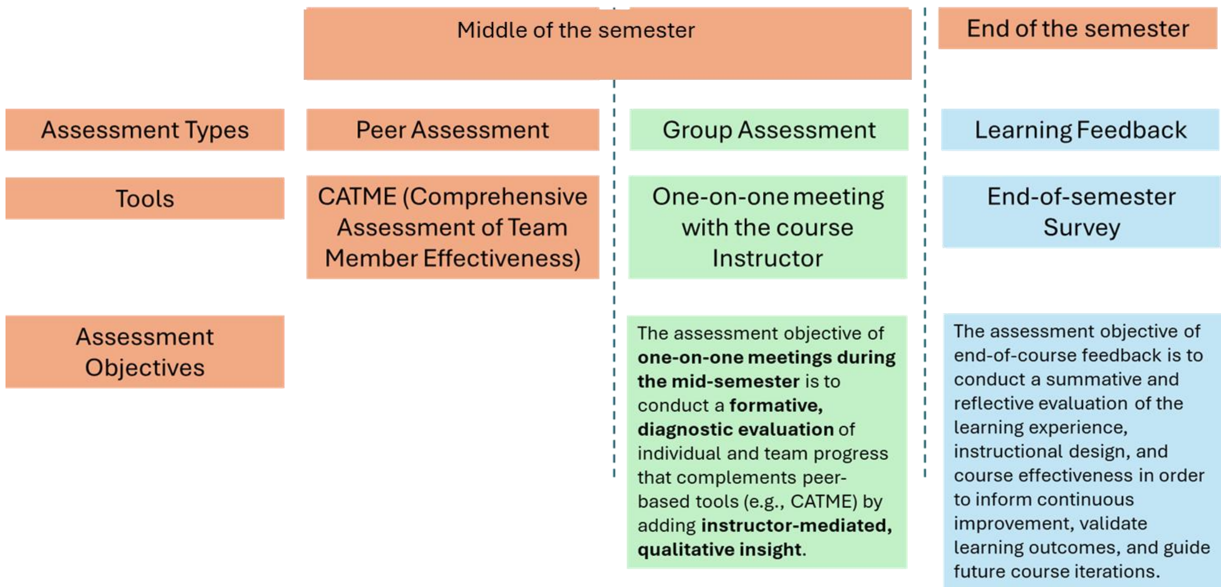
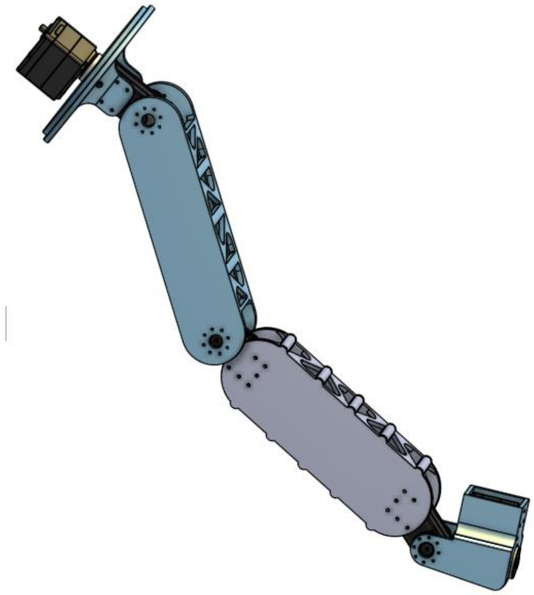


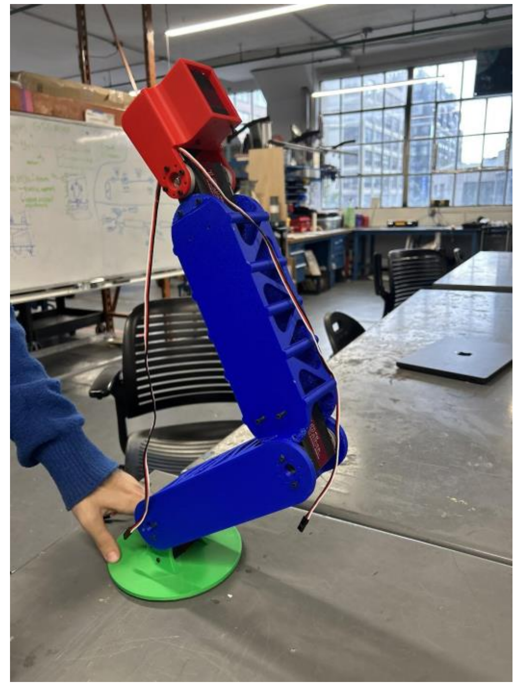
Figure 1: (a) Team structure of current robotic learning course, (b) Instruction model for learning process

The first few subteam meetings are dedicated as necessary to design robotic arm joints around mechanical and budgeting constraints. Lower-level part design is delegated among members to equally distribute the opportunity to develop CAD skills, and to foster cooperation between members as they design and review parts for one another to ensure successful assembly. Using the assembly developed in CAD, a finalized design meeting is devoted to setting up a simulated environment with proposed conditions to study the potential behavior of the robotic arm so that design changes can be made if needed. Once modeling and simulations are deemed satisfactory, parts are delegated across members to be 3D printed for prototyping, and all members collaborate to assemble the robotic arm. This allows everyone to practice usage of important fabrication machines, software, and tools.

(a) Human-Robot Interaction Arm



(b) Initial Prototype



(c) Integration with the soft gripper

(d) Soft robotic hand prototype

(e) Soft robotics molding process

(f) Humanoid robot assembly

Figure 2: CAD models and physical prototype

As mentioned above, once development has progressed sufficiently, more frequent communication is made with the electrical engineering and computer science subteam, as well as the subteams from the soft robotics team. Integration design of the robotic arm and the soft gripper is done in collaboration between representatives of each team. Functionality is then tested by integrating all systems of the robot together.

2. How is the survey being developed and conducted?

To understand how students learned and collaborated during the Soft Robotics workshop, two surveys were shared with all students in the program. The first tool was the CATME teamwork survey, which students completed around the beginning of the semester. This timing allowed for a study of how teams were functioning while projects were still unfolding—how students divided responsibilities, communicated, supported each other, and handled challenges in real time.

Students were gauged on their perspectives on their peers across five categories (Figure 3). The responses provided a window into group dynamics as well as whether peer learning and mentoring were actually taking place within each sub-team. Additionally, they quantified how students were performing in the soft robotics workshop according to their closest observers. The values taken in this survey are represented by the average of all of the ratings given to each participant in each category from 0 to 5.0, with a grade of 5.0 corresponding to the highest level of the quality respective to the category. Students scored their peers on: a) team contribution b) teammate interaction c) team time management d) expectation of quality e) possession of relevant knowledge and skills. These qualities were chosen as they not only reflect necessary abilities for the success of collaborative projects of any kind - not just limited to this workshop - but they also indirectly imply the progress of this workshop's projects partway through the semester. In this study, the metric of student success according to the CATME (Comprehensive Assessment of Team Member Effectiveness) survey has been taken as an average score above 4.0 out of 5.0 across all of the categories. Based on these guidelines, the results from the CATME survey have been tabulated and presented in a pie chart format to display the proportion of students that have been considered to have exceptional performances in the given categories (Figure 3).

The second survey, consisting of the attached self-learning questionnaire, was distributed at the end of the semester and shifted the focus to individual growth. Since the first survey was given after a significant portion of the semester had elapsed, it is likely that the subteams had settled into the routines that produced those results, so no meaningful differences were expected barring potential unexpected outlying events. Therefore, instead of rating teammates, students reflected on themselves – how much they felt they learned about soft robotics, whether they became more comfortable with material selection, CAD modeling, and fabrication, and how their confidence and engineering problem-solving skills developed. By giving both surveys to the full cohort and spacing them across the semester, learning was able to be analyzed from two angles: how students shaped one another's experiences, and how the workshop shaped students' personal understanding of engineering.

Results

1. CATME survey

The peer-evaluation data collected from the Soft Robotics workshop provides meaningful insight into students' conceptual understanding, technical skill development, and engineering mindset formation. Overall, the results indicate that the workshop successfully fostered students' abilities to communicate and collaborate while navigating gaps in disciplines and experience levels

Across teams, students demonstrated consistently strong performance in areas associated with technical contribution, engagement, and reliability, suggesting that participants were not merely following prescribed procedures but actively contributing to the engineering process. This trend aligns with the structure of the workshop, which emphasized iterative prototyping, design justification, and collaborative problem-solving—hallmarks of authentic engineering practice. The relatively narrow spread in peer evaluation scores further suggests that students developed a shared baseline competency in soft robotics concepts, rather than learning being isolated to a small subset of highly experienced participants.

The majority of students surveyed are shown to have excelled across all five recorded success metrics (Figure 3) with average scores of above 4.0 out of 5.0, with those not making the cut still scoring above 3.0, demonstrating developing abilities. The strongest qualities are the display of relevant knowledge, skills, and ability, as well as team interaction, with both results seeing 74.1% of students scoring above 4.0. The quality with the lowest proportion of students scoring above 4.0 is the ability to keep the team on track, which still achieved a 59.3% success rate.

Written reflections embedded within the peer-evaluation process indicate that students gained a clearer understanding of soft robotics design logic. In particular, students showed increased awareness of trade-offs in material selection (e.g., compliance versus durability), geometric constraints in CAD design for soft components, and practical considerations during fabrication and assembly. These reflections reveal an emerging ability to connect theoretical principles—such as deformation, load distribution, and actuation behavior—to real design decisions made during the workshop.

Importantly, the data suggests that the workshop supported learning beyond technical execution. Peer feedback reflects improved communication and coordination within teams, indicating that the workshop environment fostered collaborative engineering behaviors commonly expected in professional and research settings. Students were able to learn unfamiliar skills from teammates, as well as develop designs and solve problems after consolidating different perspectives.

From an educational perspective, these findings suggest that the soft robotics workshop contributes meaningfully to strengthening soft robotics education within engineering curricula. By blending conceptual instruction with CAD modeling, physical fabrication, and reflective peer evaluation, the workshop bridges theory and practice. The results indicate that such workshops can serve as effective entry points for introducing soft robotics concepts at scale, particularly in institutions seeking to expand hands-on, interdisciplinary robotics education without relying solely on advanced prior knowledge.

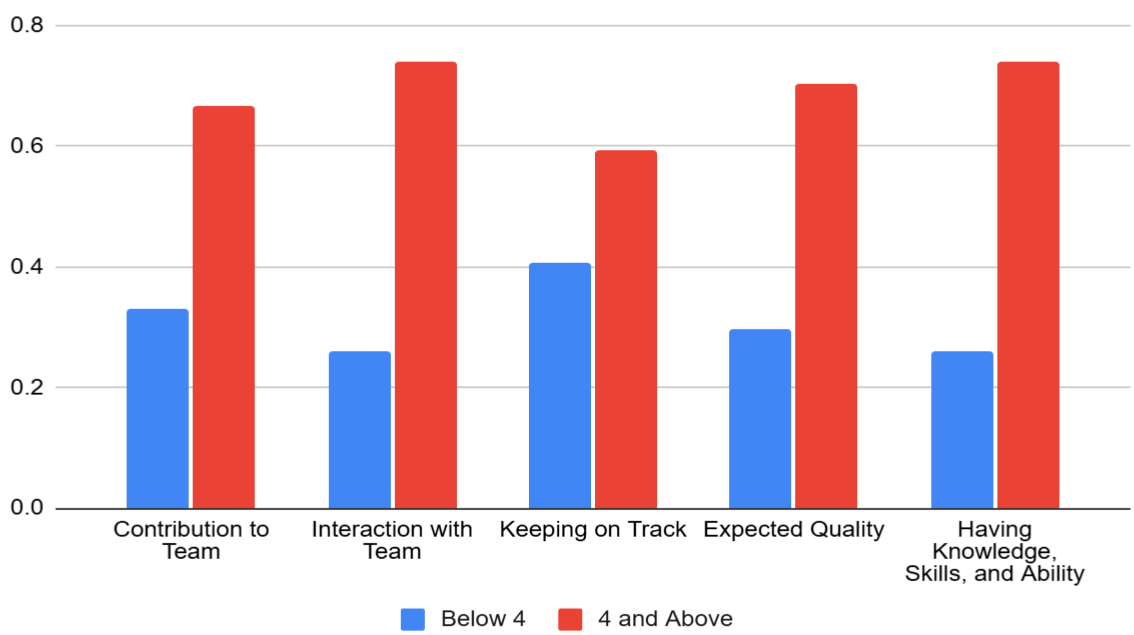


Figure 3: Peer Evaluation Analysis via CATME survey

2. Course Feedback Learning survey

The results from the course feedback learning survey display an analysis of the roles that each student holds in the workshop as well as the future career plans that students resonate with the closest (Figure 4). The learning survey had 16 total student respondents, in which some students belonged to multiple engineering backgrounds. Six of the respondents took on a design and fabrication role. Four of the student respondents held a role with electronics and sensing engineering. Five of the student respondents held a controls systems role.

Students were asked about their thoughts about different career paths related to robotics. The survey revealed that 8 students believed that they were likely to pursue a career in robotics research, while 3 students felt neutral and one felt unlikely. Eleven students believed they would likely pursue graduate school, while 1 student believed it was unlikely. Similarly, 11 students believed they would likely pursue industry roles in robotics, while 1 student felt neutral. Nine students believed they would be involved in interdisciplinary work with robotics, while 3 students believed this was unlikely. Overall, the results indicated that a majority of the students felt relatively satisfied with a career option related to robotics, whether it may be graduate school or an engineering career in the robotics industry. Based on the results, it can be seen that the soft robotics workshop was effective in influencing undergraduate students in either considering or pursuing a career in robotics.

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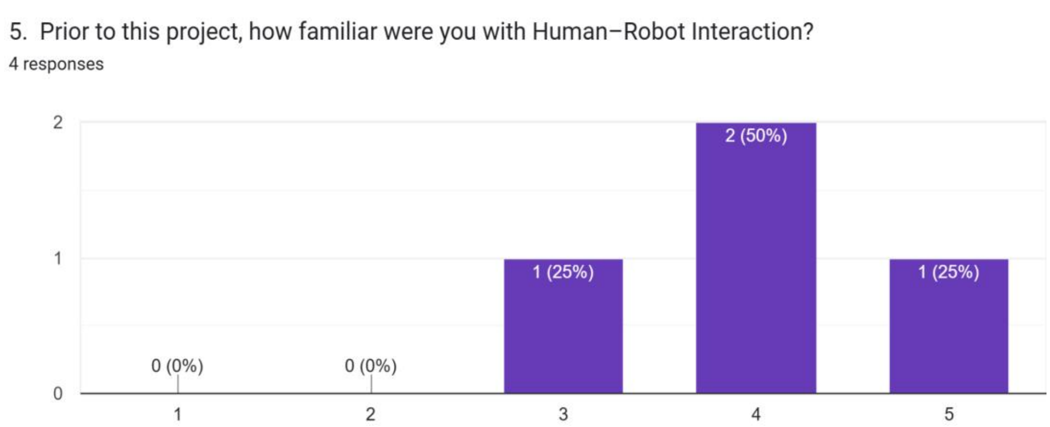
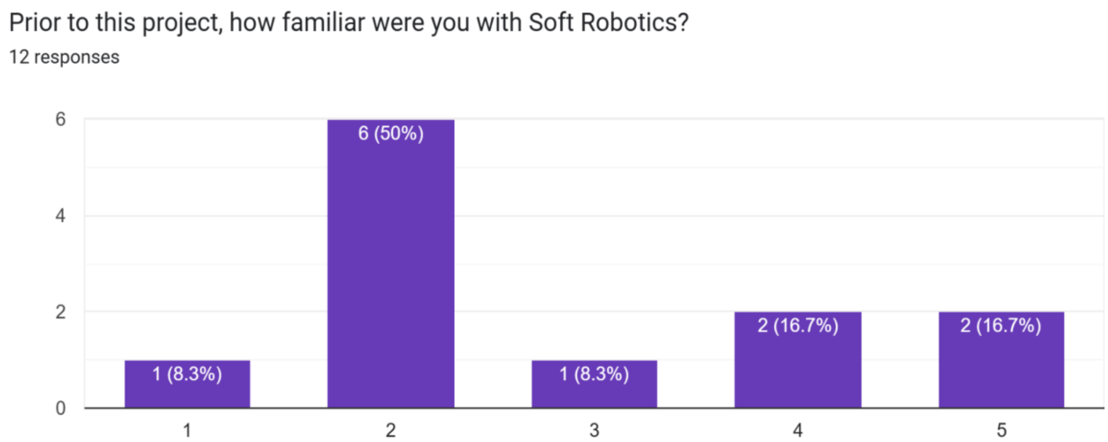
In summary, the peer-evaluation results and associated reflections provide evidence that the soft robotics workshop enhances students' understanding of both soft robotics as a discipline and foundational engineering principles. The workshop model shows strong potential for broader adoption as a scalable, experiential approach to soft robotics education in engineering programs.

(a) Previous Engineering Background





(b) Engineering Background & Role

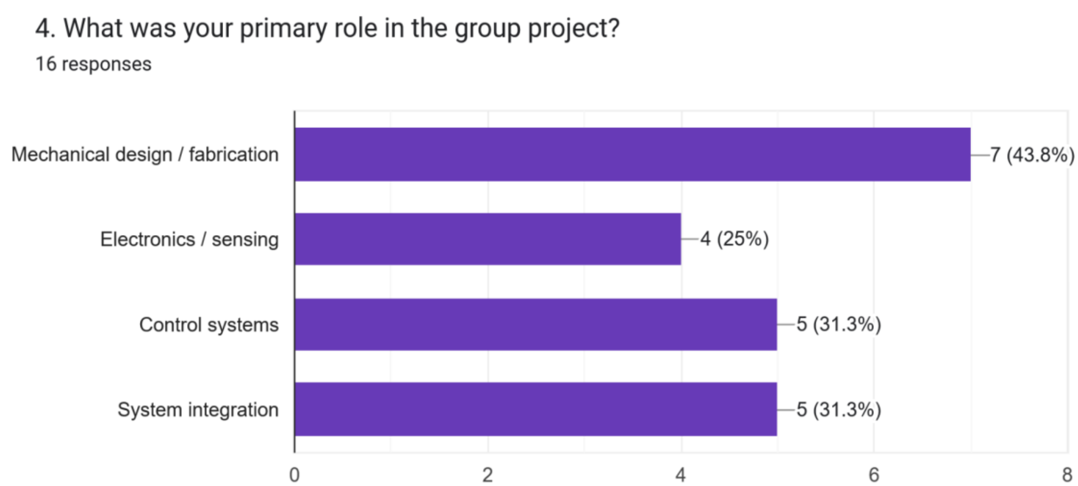


Figure 4: Course Learning Survey Results

Discussion

The results highlight the educational significance of using soft robotics as a hands-on learning platform to strengthen core engineering understanding. Student reflections and peer evaluations indicate that engaging directly with compliant materials, CAD-driven design, and physical assembly encouraged learning and decision-making past procedural task completion. Soft robotics requires students to consider practical conditions such as deformation, material behavior, fabrication constraints, and system integration, which are often overlooked in traditional coursework. The reflections suggest that students began to understand how design choices influence performance and reliability, which are critical in engineering design. The consistency in positive feedback across all members suggests that the workshop structure was effective in supporting learners with varied levels of prior experience, reinforcing the idea that soft robotics can serve as an inclusive entry point into advanced robotics study.

Additionally, the findings suggest that reflective and peer-based assessment can play a valuable role in evaluating learning outcomes in project-based engineering environments. The results provided insight not only into what students built, but how they collaborated with their peers to develop that shared objective, offering a richer picture of learning than technical performance alone. This is particularly important in design-focused courses, where teamwork is crucial in the prototyping process. Effective team management is inseparable with progressing in a project. From an institutional perspective, these outcomes point to the potential of soft robotics workshops to complement traditional curricula by fostering creativity, collaboration, and reflective thinking while still reinforcing fundamental technical principles.

Despite the strengths outlined by the workshop feedback, several limitations should be considered when interpreting the results. The reliance on peer evaluation introduces subjectivity, as student ratings may be influenced by interpersonal dynamics or differing expectations of contribution. Another source of uncertainty introduced by the use of quantification in analyzing success metrics is inconsistency on what values students may attribute to different levels of contributions or communication. The autonomous nature of the workshop that has resulted in unique subteam operations, as well as the difference in disciplines and tasks, may have also affected the extent to which students consider each surveyed quality relevant for the success of their team. Not to mention, the survey assessed students on the performances of their peers across the entire soft robotics workshop. This neglected to consider uncertain judgements made from the potentially insufficient level of interaction students in different subteams may have had with each other due to the stage of progression in the overall project at the point of survey. Additionally, the data reflects a single workshop within a specific program context, which limits the extent to which the findings can be applied to other institutional or instructional settings. While the reflections indicate improved conceptual understanding, they do not directly capture long-term retention or the ability to transfer these skills to future coursework or professional practice. The workshop also prioritizes foundational exposure over advanced analytical modeling, meaning that deeper technical mastery lies outside its immediate scope. Taken together, these limitations suggest that while the results are encouraging, they should be viewed as preliminary evidence supporting the educational value of soft robotics workshops rather than as a comprehensive measure of learning outcomes.

The findings from this workshop point toward a compelling case for elevating soft robotics within undergraduate engineering programs. By immersing students in the fabrication, sensing, and human–robot interaction dimensions of soft robotic systems, the workshop provided a learning experience that melded theory with hands-on design. Students were not only exposed to the scientific and mechanical principles that underpin soft robotics, but they were also challenged to apply them through tangible decision-making—selecting materials, prototyping geometries, debugging sensor systems, and integrating compliant mechanisms with rigid robotic architecture. Evidence from survey responses and peer evaluations suggests that students emerged with a more grounded understanding of how engineering fundamentals manifest in physical systems, which conventional coursework may struggle to convey.

The interdisciplinary structure of the workshop illuminates how innovation frequently emerges not from a single field but from the intersections among them. Peer feedback further highlights that students benefited from this collaborative environment by learning to communicate, delegate, and problem-solve as part of a team.

Importantly, the soft robotics workshop appeared to lower the barrier to engagement for students who may not consider themselves experts in robotics. Because fabrication methods are accessible and actuation systems are forgiving, students could quickly prototype, test, and revise their designs without requiring costly hardware or advanced coursework. Reflection data suggests that students gained confidence—not only in their technical abilities but also in their capacity to navigate ambiguous, open-ended problems. This confidence-building effect strengthens the case that soft robotics can help broaden participation and support students at varying levels of preparation.

Taken together, the results point toward a broader educational implication: as engineering increasingly intersects with health, bio-inspiration, and human-centered applications, soft robotics may function as a bridge between core knowledge and emerging opportunities. The workshop findings show that, even in a single semester, students can gain skills, perspective, and motivation that position them for future work in robotics, design, and innovation fields. These outcomes underscore the value of experiential soft robotics models and support their continued integration into engineering programs seeking agility, relevance, and inclusive student growth.

The current workshop demonstrates strong potential, as it opens several promising directions for future development. One opportunity is to broaden the educational scope by embedding soft robotics into multiple courses across a curriculum rather than limiting it to a single-semester experience. For example, introductory design courses might focus on mold making and material characterization, intermediate engineering electives could emphasize actuation physics and embedded sensing, and upper-level courses could explore closed-loop control, soft simulation modeling, or advanced human–robot interaction. A scaffolded pathway of this nature would allow students to revisit core concepts with increasing sophistication and help instructors measure longer-term skill progression.

Another direction lies in expanding collaboration with clinical, industrial, or community partners. Because soft robotics aligns naturally with rehabilitation, accessibility, and wearables, students could co-develop devices for real-world users such as physical therapy patients or individuals with limited mobility. Such collaborations would introduce authentic "customer discovery" dynamics—user needs analysis, regulatory awareness, testing with constraints—and could provide data beyond what classroom exercises allow. Partnerships with manufacturing facilities, machine shops, or medical simulation centers could also give students access to more advanced materials and fabrication tools.

Future work would also benefit from more structured and diverse assessment methods. Peer evaluations and reflections offer valuable insight but could be complemented with pre- and post-concept inventories, rubric-based design scoring, and artifact-based performance tests. For example, actuator displacement versus pressure curves or force tracking accuracy could quantify technical learning. Team audio logs, code repositories, or design revision histories could document process learning and project management growth. Collecting such data over multiple semesters would enable longitudinal analysis—revealing not just what students learn, but how learning trajectories shift as the workshop evolves.

Scaling capacity is an important consideration in education and research. As student interest grows, instructors may need mechanisms to support more participants without losing the workshop's high-engagement model. Viable strategies include training returning students as peer mentors, designing modular project tracks that link into a shared outcome, or running parallel teams exploring different actuation or sensing modalities. Tools to aid in lowering the entry barrier for students and institutions alike in adopting similar programs include a repository of open-source molds, curricula, and CAD.

Future research should explore whether soft robotics can influence student identity, belonging, and STEM persistence. Project based soft robotics could play a role in encouraging engineering students to view themselves as capable engineers, refine technical skills, broaden the field of soft robotics, and assist individuals historically underrepresented in robotics enter the research world. Through continued refinement, data collection, and dissemination, the workshop model described in this paper has the potential to bolster robotics education and the communities it serves.

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