# An Engineering Outreach Activity: How to Develop a Tendon-Based Soft Robotic Finger?

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***Abstract*—*Contribution:*** **This article presents an engineering outreach activity that aims to teach K-12 students how to develop a tendon-based soft robotic finger. The primary objectives of this STEM activity are to introduce students to the fundamentals of soft robotics, its interdisciplinary nature, and to offer them a hands-on and engaging learning experience using the project-based- learning approach.**

***Background:*** **Soft robotics, an interdisciplinary field combining chemistry, materials science, and robotics, has the potential to revolutionize the design and development of robots. However, introducing the fundamental concepts of soft robotics to K-12 students can be challenging since traditional robotic activities often require complex programming, technical expertise and expensive equipment and software.**

***Intended Outcomes:*** **Increasing the students' understanding of soft robotics principles, materials, and polymer processing. Positively impacting students' perception of engineering as a potential career path by enhancing their attitudes toward STEM.**

***Application Design:*** **Students could develop manually actuated soft robotic fingers within a 45-min workshop by utilizing 3-D printed molds, rapidly curing elastomeric materials, and the basic mold casting method. The outreach activity is intentionally designed to simplify the technology used by eliminating the need for complex programming, and to focus on utilizing novel materials and basic concepts to construct actuating soft robots, providing an effective and engaging STEM activity for K-12 students.**

***Findings:*** **The success/effectiveness of the activity was evaluated in three ways: 1) through direct inspection on the performance of the student-fabricated soft finger during the workshop; 2) through the pre- and post-tests to evaluate the learning outcomes; and 3) by conducting a STEM outreach survey to gather student feedback on the quality of the outreach activity and their attitudes toward STEM. During the workshop activities, the students were able to effectively follow the instructions, construct a tendon-based soft robotic finger, and manually actuate the finger using the tendon. According to the results of pre- and post-tests, the students increased their understanding regarding the principles of soft robotics, materials and polymer processing. Furthermore, the STEM outreach survey of IEEE powered "TryEngineering Portal" revealed that the developed outreach activity enhanced the achievement of pedagogical and quality outcome goals and measures, as well as program targets and objectives.**

***Index Terms*—Engineering outreach, soft robotic finger, STEM education, tendon-based actuation.**

## I. Introduction

EMERGING technologies have put nations proficient in STEM on the highway of innovation-based competitiveness. Thus, STEM industries have been growing much faster than the others, but STEM proficiency in education has been declining for decades creating a deepening shortfall of STEM-skilled people becoming a growing concern both in the U.S. [1] and in Europe [2]. Additionally, fewer students choosing STEM fields are likely to result in a looming shortage of skilled STEM leaders and educators in the future [3].

One of the possible factors for not choosing STEM fields was reported [4] to lie in school science itself, as it does not always offer children active participation through a hands-on experience and the connection between different subjects which allows the students to see the relevance and the use of STEM in everyday life [5]. An alternative solution to the issue is outreach activities as structured informal learning environments [6], [7] provided by parties outside school, such as companies and higher-education institutes [4], [8]. Additionally, most students prefer workshops over lectures and projects, and hands-on activities, in which students actively get involved, are reported to be the preferred teaching method stimulating autonomous motivation [9]. Hands-on outreach activities, especially early in the students' education, were reported to create a foundation for nurturing positive attitudes about STEM [10], to be promising add-ons for future science courses and willingness to engage in STEM-related fields in future career developments by providing autonomous motivation [9], [11], [12], [13] also to be helpful to achieve better results later at the university [14]

Robotic activities within the field of STEM often involve complex programming, requiring technical expertise, as well as expensive equipment and software. These features of robot-based activities can pose a challenge for students who

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are in the early stages of learning about robotics. Alternatively, an interdisciplinary approach of soft robotics, combining fields, such as chemistry, materials science, and robotics, can be used to create simple yet effective robots for STEM activities. Thus, we designed a soft robotics outreach activity that uses tendon-based actuation which has rarely been exemplified among other soft robotic activities [15], [16], [17], [18], [19], [20], [21], [22], [23], [24].

Our main educational goal we would like to achieve through this outreach activity is to inspire *K-12 students'* interest in STEM by teaching them how to develop a tendon-based soft robotic finger. Additionally, we aim to guide *STEM educators, teachers, and parents* on 3-D printing techniques and *encourage scientists and researchers* to create more outreach activities for K-12 students. The intended outcomes include increasing students' understanding of soft robotics principles and positively impacting their attitudes toward STEM and engineering as a potential career path.

Our primary target audience for this outreach activity is K-12 students, where we aim to inspire their interest in STEM education through teaching them how to develop a tendon-based soft robotic finger. Additionally, we also focus on engaging secondary audiences, including STEM educators, teachers, and parents, by providing guidance on 3-D printing techniques for fabricating the finger molds and demonstrative hand. Moreover, we extend our efforts to reach scientists, researchers, and academicians, inspiring and encouraging them to develop more outreach activities aimed at K-12 students.

This article presents the instructional outreach activity on the development of a soft-robotic finger. This article is structured as follows. After introduction in Sections I and II describes the materials and instruments used. Section III includes the relevant fabrication processes. Section IV discusses the pilot study (a small-scale preliminary study conducted before the main outreach activity). Section V represents an example of the outreach activity and discusses the results, Section VI includes the student feedback and finally Section VII draws conclusions.

### A. Pedagogical Principle

Project-based learning [25], [26] is an instructional learning approach which starts with a designated task or set of tasks, which guides students on the process of creating a final product, such as a design, model, or device. The culmination of the project could be the showcasing the resulting outcome [25], [27]. We adopted this learning method because the real-world relevance, hands-on learning and interdisciplinary nature of the approach well-suits the STEM-oriented soft robotics outreach activity. Additionally, project-based learning allows for authentic assessment of student learning by the evaluation of the tangible product and its performance developed within the outreach activity. This provides a clear and meaningful assessment of their understanding of the concepts and skills involved in building the soft-robotic finger in our case [28], [29].

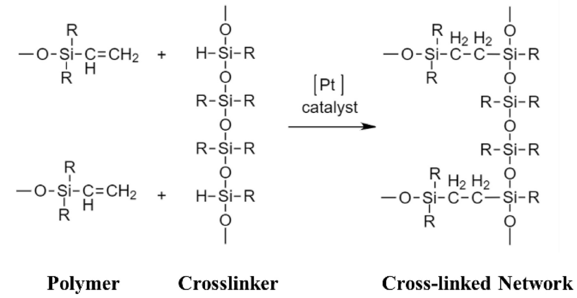



Fig. 1. Scheme of a curing (crosslinking) reaction for the silicone network formation in the presence of a Pt catalyst.

### B. Silicone Elastomers

Silicone elastomers are a range of rubbery elastic materials that are widely used due to their various favorable properties, such as flexibility, biocompatibility, durable dielectric insulation, and stress-absorbing properties over a wide range of temperatures between −100 °C to 250 °C [30]. Commercial formulations come in a wide variety of grades that meet the commercial demands of the application. They mostly have robust curing and low viscosity for easy processing.

Their polymer backbone with alternating units of silicone and oxygen (-Si-O-) distinguishes silicone elastomers from common polymers with traditional carbon-based backbone, providing high flexibility and softness with high-thermal stability. Commercially available silicone elastomers are mostly crosslinked using hydrosilylation (usually Pt-catalyzed addition) as illustrated in Fig. 1.

When the polymer and crosslinker are mixed together, a process known as "curing" occurs. Pt catalyst speeds up the reaction between the polymer and crosslinker to promote the formation of covalent bonds between the polymer chains, which leads to the formation of a 3-D network of crosslinked polymer chains. The crosslinking process results in an increase in the stiffness (solidify or harden), strength, durability, and resistance of the material.

Commercially available elastomer kits mostly consist of two premixes named "A" and "B," where one of them is the crosslinker (curing agent) and the other is the polymer (or base). Each of the premixes is unreactive and stable until they are homogenously mixed into each other. The most common mixing ratios, as supplied by the supplier, between the curing agent and the polymer is 1:1 or 1:10 for the formation of mechanically reliable elastomers. Room temperature curing or heat curing at elevated temperatures is possible depending on the commercial formulation. The other two important properties are the "pot life," which is defined as the time allowed for processing the premixes, and the "curing time" which is the duration for the completion of the crosslinking reaction.

The silicone elastomer was carefully chosen for the workshop because of the following advantages.

1) *Easy to Use:* Mixed with 1A:1B by volume.
2) Affordable (∼45 €/L) and cost-effective (∼0.45 € per finger).

3) *Fast Curing:* 6 min pot life and 30 min curing time.
4) Room temperature curing, no oven needed.
5) No need for vacuum degassing since no gas generated.
6) Soft and flexible, yet strong and tear-resistant
7) Compatible with the mold resin, no mold-release agent required.
8) Nontoxic and safe for use in ventilated environments.

### C. Material Processing Techniques

Among several material processing techniques used for the fabrication of soft robotic components, 3-D printing and mold casting are the most commonly employed [31]. 3-D printing [32] is widely used because it is accessible and affordable for both industrial and personal use. Additionally, 3-D printing services allow users to upload, sell, share, and order printed objects [33], [34]. The rise of FabLabs [35], which provide access to advanced technologies, such as 3-D printers, to inspire people to develop new products and prototypes, and Makerspaces [36], which provide collaborative and creative learning environments, is also evidence of the growing demand for 3-D printing technologies, particularly in STEM education.

Mold-casting technique is another popular method for the development of soft robotic actuators using soft silicon or elastomers. This process involves creating a mold to cast the soft robotic actuator. The mold is created by first designing the desired shape of the actuator using computer-aided software, which is then used to create a 3-D printed mold. Once the mold is complete, the liquid silicone or elastomeric material is poured into the mold and left to cure. The resulting soft robotic actuator can then be removed from the mold and used in various soft robotic applications. Mold-casting techniques offer many benefits for developing soft robotic components for STEM activities due to its low cost, room or low temperature, scalability, customizability, reproducibility, and ease of use [16], [20], [21].

### D. Tendon-Based Soft Robots

Soft robotics is a growing field involving soft components using highly flexible and stretchable materials instead of traditional rigid and hard counterparts [37]. The field is an interdisciplinary field of study where researchers from a number of subject areas (such as computer science, chemistry, robotics, material science, textile, nanotechnology, engineering, and automation control systems) contribute to its development [38]. Soft robots have already been used in many industrial applications, such as medicine, wearable electronics, locomotion, rehabilitation, prosthetics, and assisted industrial manipulation. Soft robots can be used in physical human-robot interactions because they mostly rely on mimicking the motion abilities of soft bodies existing in nature, such as invertebrates, plants, or human muscles and organs.

Among other actuation mechanisms [39], tendon-based actuation is widely used in soft robotic hands and grippers [40], [41]. The mechanism is based on controlling the motion of the soft material by retracting a tendon (cable/wire) that is embedded in the structure and bending the soft finger for grasping [42] as depicted in Fig. 2. The easy mechanical design of the tendon–based actuation well-fits this workshop for children and is used to develop manually driven soft fingers. Alternatively, manual control can be extended to a servo motor controlled with an Arduino, as available in other workshops [43].

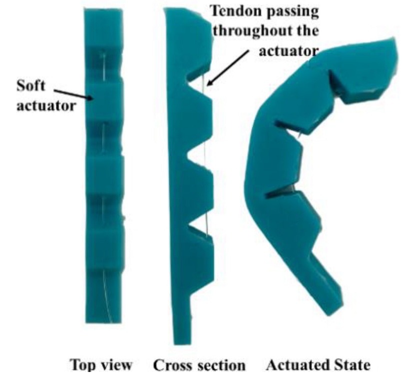



Fig. 2. Working principle of a tendon-based soft finger.

Fig. 3. Picture of all the materials used (left) and the soft fingers integrated on the demonstrative 3-D printed hand (right).

## II. Materials and Instruments

Mold Star 16 Fast rubbers were purchased from www.formx.eu. It is an easy-to-use silicon with two liquid components (indicated on package as A and B) that cures and hardens upon mixing.

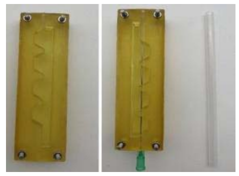
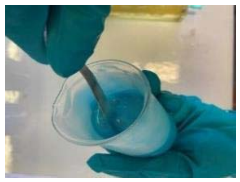
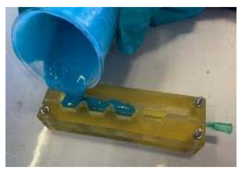
The materials used for the workshop (Fig. 3).

1) Plastic syringes without needles.
2) A disposable mixing cup (paper or plastic).
3) A wooden or plastic spoon for stirring.
4) 4 pcs M3 size (12-cm long) screws and 4 pcs nuts.
5) Vinyl gloves.
6) One thin craft stick or rod fitting in the horizontal hole along the mold. Any type, such as wooden or bamboo sticks or rods, could be used with dimensions longer than 11 cm and thinner than about 2 mm. We have used 12-cm long syringe needles, excess 1.5 cm is cut with a nipper to make it fit the length of the mold. Cutting off the dangerous and sharp end of the needle protects children against possible injury.
7) 15-cm long 0.5-mm thick-transparent fishing line.

## III. Fabrication Process

The fabrication of the fingers is designed to be followed by the K-12 students during the outreach activities. Using

TABLE I
SOFT ROBOTIC FINGER DEVELOPMENT STEPS

| # | Description of the step | Pictures |
|---|---|---|
| **1** | Start with assembling the mold. Put the two parts of the mold on top of each other (flat piece bottom, hollow piece top), place the screws from the bottom to the top, and tighten two molds together using the nuts on the top. Pass the needle through the small hole in the top part of the mold until the end. Your mold is ready. |  |
| **2** | Wear your vinyl gloves. Using separate syringes, get equal amounts of components A and B (5 ml of each) and mix them in a disposable cup with a spoon or stick. Give it a very good mix for 2 to 3 minutes. |  |
| **3** | Slowly pour the mixture into your mold, let the mixture flow into the mold, and scrape off the excess silicon if any. Let your mixture sit in the mold for half an hour to harden. |  |
| **4** | At least half an hour later, it is time to disassemble your mold. First, take the needle out of the mold by strongly pulling it out. Then loosen and remove the nuts and the screws. Firmly push the hardened silicone out of the mold and pull the finger out. |  |
| **5** | Pass the wire through the finger and give it a knot on the top. Your flexible and soft finger is ready. Pull the wire from the bottom to bend the finger. Optionally, you can build more fingers and assemble them into a 3D-printed hand*. |  |

* See supporting document for the SLA 3D printing of the molds for fingers and the 3D printing of the demonstrative hand. CAD files for the molds for fingers and the demonstrative hand are shared open source [44].

provided molds, they could develop soft fingers by following the step-by-step fabrication instructions indicated in Table I.

## IV. PILOT STUDY

A pilot study was conducted to evaluate the effectiveness of the outreach activity designed to promote interest in soft robotics among K-12 students. The study was conducted during a three-day workshop at the "I Love Science Festival" in Brussels, Belgium from 14-16 October 2022, which saw over 150 students in attendance. The workshop was attended by groups of eight to ten students from primary and secondary schools in Brussels, accompanied by their teachers on the first day. Being minors, the consents were collected by their teachers. Special care is paid to not to reveal any personal data, photgraphs or names. The workshop consisted of three morning and three afternoon sessions, each lasting 45 min, supervised by a researcher who provided guidance to the students. On the second and third days of the festival, which were open to the general public, including policymakers, teachers, and families with their children, the researcher provided guidance to smaller groups or individuals.

Fig. 4. Photograph of a group of K-12 students attending the pilot study workshop during the "I Love Science Festival."

After the introduction, an instructional manual (as shown in Table I) was distributed to the students. They followed the instructions and applied the procedure step by step. Before each session, a brief prelecture (suiting the group age) as an introduction about soft robots was given, videos of the soft robotic grippers from industrial applications were shown and hard robots versus soft robots were shortly compared and discussed with the involvement of the students. During the discussion, their attention was specifically drawn toward material development (durability, sustainability, and environmental concerns), the possibilities of the manufacturing process and smart soft robotic designs [45]. Following the completion of each workshop session, the students were requested to provide feedback on the activity through an electronic platform hosted by Innoviris. A binary scale in which the students could either choose "attractive" (positive feedback), or "not attractive" (negative feedback) was used (chosen by the festival). In the pilot study, the main outcome was to make sure the activity is attractive and joyful to them.

The success rate for the activity was evaluated via direct inspection and testing of the student-fabricated soft robotic finger by our research team. Success was defined by completion of the task: if the fabricated finger could bend upon the pulling of the tendon, and could relax back to the initial position, it was deemed successful.

Within the three-day-pilot workshop, 152 soft fingers were fabricated by mostly K-12 students (Fig. 4). We recorded about 10% adult attendees, in addition to 10% kindergarten children. 50% of the attendees were primary (elementary) and 30% were high-school students. Only kindergarten children needed the assistance from their parents during the tightening and untightening of the screws.

Within the given workshop time of 45 min, all attendees smoothly followed the instructions, achieved to build a tendon-based soft robotic finger and succeeded to manually actuate the finger via the tendon as a direct learning evidence. 138 votes for positive feedback and enjoying the workshop were collected out of 152 attendees (∼92%).

The supervising researcher noted that especially students found the practical aspect of the workshop engaging, enjoyed experimenting with the bendable robotic finger, and liked the idea of taking the finger with them. A few parents who own a 3-D printer expressed their interest in obtaining the technical drawings of the molds and the demonstrative hand, leading our research team to establish an engineering outreach publication with disclosed sources with the aim of disseminating the knowledge and resources. Based on the positive outcomes of the pilot study, it was concluded that the workshop could be successfully replicated at other events, with feedback gathered from the participants for further evaluation. As a result, the outreach activity was arranged at the Vrije Universiteit Brussels (VUB) Science Show.

## V. Outreach Activity

The second workshop was conducted at the "Science Show" [43] hosted by the VUB on 6 February 2023 and 7 February 2023, catering to 14 to 15 year-old and 16-year-old students, respectively. The workshop consisted of four repeated 1-h sessions spread across two days, with a maximum capacity of 20 students per session. A total of 80 students attended the workshop with 21 of them being female students, accounting for 26% of all attendees.

The authors developed a multidisciplinary test with ten relevant questions, each offering five choices with one correct option (Fig. 6). The questions were aligned with the workshop's learning objectives and derived from concepts taught in relevant educational resources. To ensure validity and reliability, the test underwent a review process by subject matter experts and educators from VUB, who provided feedback for refining the questions and ensuring alignment with the learning objectives.

Prior to the workshop, the test was administered (as pretest) to the students to assess their existing knowledge level.

Then, a-10-min introduction session consisting of material science, polymer processing and soft robotics were presented by a scientist-engineer. During the presentation, we covered a range of topics related to soft robotics, including an introduction to engineering, the differences between hard and soft robots, and their respective materials, functionality, and applications. We also discussed various ways in which engineers use soft robots to solve everyday problems, as well as the limitations and room for improvement in this field. Additionally, we provided a brief overview of the main components of robots and their functionality, with a focus on actuation methods and visual examples from soft robots. Finally, we delved into the properties of polymers and the various techniques used for polymer processing, such as mold-casting and crosslinking, and discussed sustainability and recyclability of polymers.

Fig. 5. Pictures of students manufacturing soft robotic fingers in the workshop of VUB Science Show.

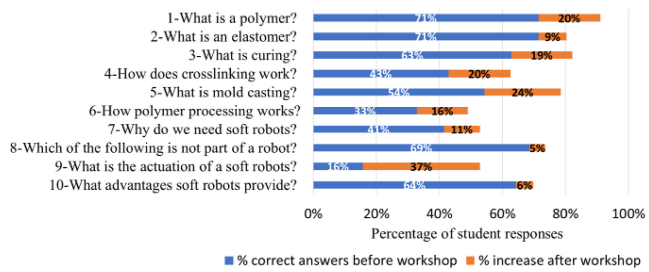



Fig. 6. Graph showing the percentage of correct student responses to the questions asked during the pre-and post-test before and after the workshop.

After the introductory presentation, the students were given an instructional manual (Table I) to guide them step-by-step through the fabrication process. They diligently followed the instructions and worked in groups of four to create the fingers, and provided mutual support and assistance to each other (see Fig. 5). In addition to the peer support, two experienced engineers supervised the students and provided assistance when needed, ensuring a safe and productive learning environment.

## VI. Student Feedbacks

Following the workshop, a post-test consisting of the same 10 questions was conducted. The pre- and post-test results, conducted before and after the workshop, were analyzed using an unpaired t-test to examine the difference between participants' initial knowledge levels and their levels at the end of the activity.

After each session in the second workshop, we have collected anonymous student feedbacks by using STEM outreach survey questions [46] from IEEE powered *TryEngineering Portal* [47]. Each feedback was evaluated and statistical conclusions were assessed—as indirect evidence of learning-accordingly.

The results of the pre-and post-test demonstrate a significant improvement in students' knowledge about polymers, polymer processing and soft robotics after attending the workshop (Fig. 6).

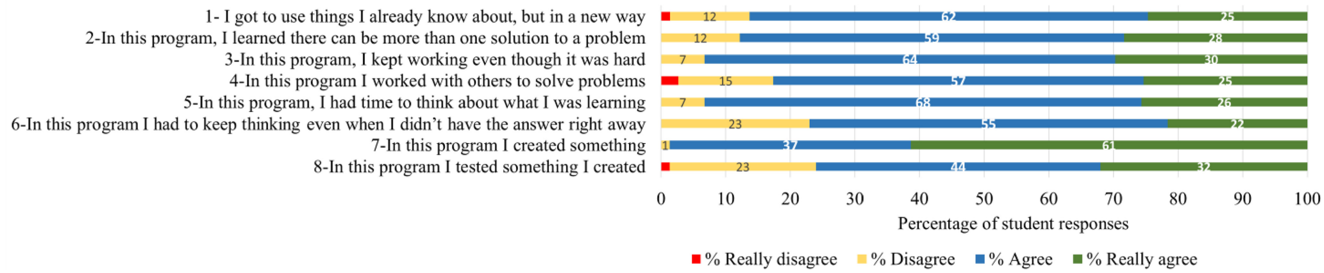



Fig. 7. Graph showing the percentage distribution of student responses to questions on the pedagogical and quality outcome goals and measures.

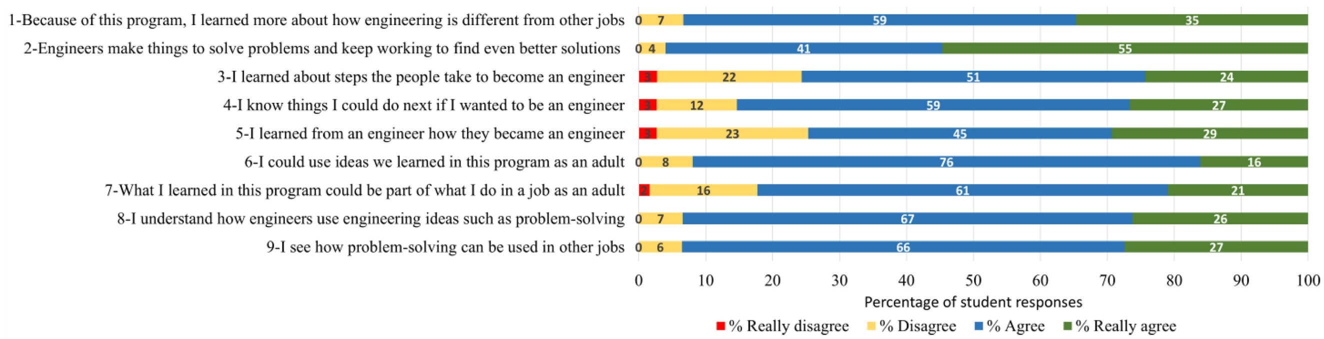



Fig. 8. Percentage distribution of student responses on the program targets and measures.

TABLE II
T-TEST RESULTS

| df | t-value | p-value |
|---|---|---|
| 131 | 4.51 | <0.0005 |

After attending the workshop, the percentage of correct answers increased for all questions, with an average increase of 17%. The results suggest that the workshop was effective in increasing participants' knowledge and understanding of the topics covered, particularly in areas where they may have had less prior knowledge or experience (Table II).

Based on the t-test results of the pre- and post-test, the obtained p-value is <0.0005, indicating a high level of statistical significance. Therefore, we can confidently reject the null hypothesis, which suggests that both results are the same. With a significance level greater than 99.95%, it is evident that the post-test results significantly outperform the pretest results.

As shown in Fig. 7, the student responses to the survey questions suggest that the program was successful in providing students with opportunities to create something and work with others to solve problems. A majority of students agreed or strongly agreed that the outreach activity facilitated hands-on, collaborative and challenging learning experiences. Notably, a high percentage of students (strongly) agreed that they had time to think about what they were learning and that they learned there can be more than one solution to a problem, which suggests that the program fostered critical thinking and reflection. Overall, the results suggest that the program was successful in engaging students in creative problem-solving and promoting a growth mindset.

As summarized in Fig. 8, the self-reported survey results of the students, there are indications that the program was found helpful in familiarizing students with the field of engineering and its applications to various other professions. A majority of students agreed or strongly agreed that the program provided them with insights into the problem-solving processes and the steps taken to become an engineer. In addition, a high percentage of students agreed or strongly agreed that the program helped them recognize the broader applicability of problem-solving skills.

It was observed from the results that a notable number of students expressed awareness of the path to becoming an engineer (see Fig. 9). While the data is based on self-reported responses from the students, it provides valuable insights into their perceptions and understanding of the engineering profession. Overall, the results suggest that the program was successful in promoting students' understanding of engineering and problem-solving skills, and encouraging them to consider a career in engineering. The responses to the questions suggest that the students have a positive view of engineering and can see themselves pursuing a career in this field. The majority of the students agreed or strongly agreed that solving challenges in the real world would be interesting, that engineering seems fun, and that they could become an engineer if they wanted to. The responses also showed that the students value the impact of engineering and the importance of the work that engineers do. A significant percentage of students (strongly) agreed that engineers have much impact on the world, suggesting the presence of sufficient awareness about the scope of engineering and its impact on society. Additionally, a significant percentage of students agreed that they could see themselves being an engineer in the future. This suggests that the program has had a positive impact

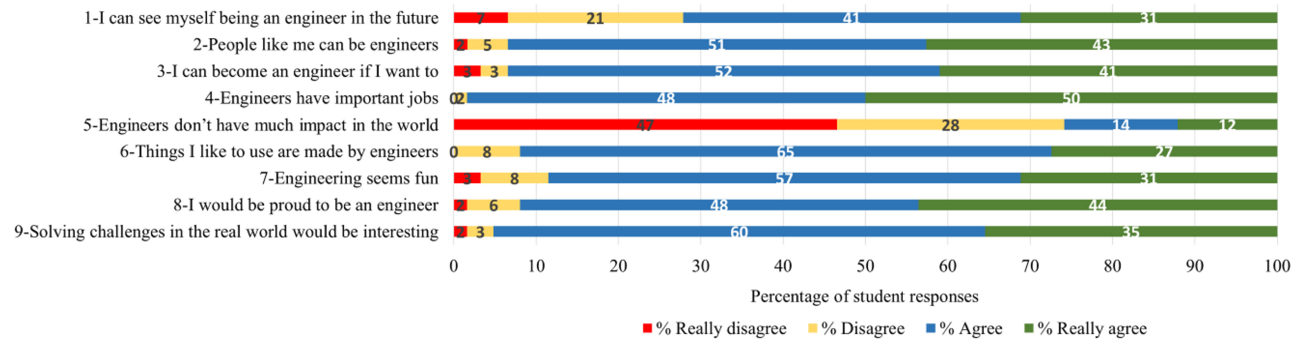



Fig. 9. Graph displaying the percentage distribution of students' responses to survey questions about their attitudes toward engineering and their potential interest in pursuing a career in the field of engineering.

on students' perceptions of engineering as a potential career path.

## VII. Discussions

While the outreach activity has several strengths and advantages, it is essential to consider potential limitations as well. Some possible limitations might include ensuring proper supervision and safety measures (use of personal protective equipment, avoid spilling, proper handling, and disposal) throughout the activity, accounting for certain waiting times during the elastomer curing process and the need for multiple molds when working with larger groups, among others.

Teachers with access to resources can easily incorporate our one-lesson activity into their curriculum, providing students with hands-on experiences in designing soft robotic actuators and fostering critical thinking skills. For more advanced learners, teachers can extend the activity to include servo motor control with platforms like Arduino, offering opportunities to explore additional robotics concepts. Parents can support STEM learning at home by encouraging simple robotics projects and 3-D printing molds, as well as a demonstrative hand for the fingers that their kids will develop using our activity. This involvement can further enhance their children's interest in science and engineering. STEM researchers should generate more outreach activities with a focus on designing them to be accessible and user friendly by simplifying the technology used, particularly for young children or as introductory science experiences. These efforts can provide effective and engaging STEM experiences for K-12 students, fostering a passion for science from an early age.

## VIII. Conclusion

In this article, we described a preparatory outreach program on the development of tendon-based soft robotic fingers. The activity was designed based on simplifying the technology used, eliminating the need/requirement of any programming, instrumentation or software combined with focusing on the interdisciplinary approach of soft robotics that brings material science, chemistry and robotics together. By using 3-D printed molds, commercially available soft materials and the method of mold casting technique, we achieved to develop a hands-on interdisciplinary STEM activity for K-12 students. The effectiveness of the activity was evaluated by directly inspecting the student-fabricated soft finger, while, the learning outcomes of students were assessed through pre- and post-tests, and their feedback was collected using the STEM outreach survey available on the IEEE-powered *TryEngineering Portal* [47].

In conclusion, the project-based learning approach used in the soft robotics outreach program proved to be a successful teaching method. The program provided students with opportunities to engage in hands-on, collaborative, and challenging learning experiences that fostered critical thinking and reflection. The results of the student feedback from STEM outreach survey showed that the program was successful in introducing students to the field of engineering and promoting their understanding of engineering concepts. The survey responses also suggested that the program had a positive impact on students' perceptions of engineering as a potential career path, with a significant number of students expressing interest in pursuing a career in engineering in the future. Overall, the results demonstrate that the program was successful in promoting STEM education and encouraging students to apply multidisciplinary knowledge in real-world problem-solving situations.

## Acknowledgment

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