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Improving Outreach Interactivity in the Virtual Environment – Evaluation of A Computer Vision Controlled Soft Robotic Hand to Broaden Participation in Bioengineering

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Abstract

Student attitudes toward mathematics and science are developed during middle and high school. Hands-on features of outreach activities can positively impact the disposition of middle and high school students toward STEM. Lockdowns and school closures limited participation in outreach during the COVID-19 pandemic. Even prior to the pandemic, these programs were limited for students in many low resource or rural schools. The necessity for virtual learning environments over the past number of years inspired the development of new outreach activities for young students to interact with engineering projects remotely. Most solutions presented in literature involve a completely virtual experience. To address students' desire to interact with physical products of engineering and leverage the benefits of physically interacting with engineering devices, we built and tested a new tool for outreach: a physical prosthetic hand that can be operated by students from their own homes. In this paper we describe the development an interactive experience to teach K12 students about prosthetics, medical devices, and soft robotics by controlling a laboratory-based physical robotic hand via webcam that is reliable in a variety of contexts. To evaluate this curriculum, we also present results of a mixed methods approach to collect quantitative and qualitative data on the tool and students' perceptions of engineering as a result of using the tool. Previous research has shown that new materials in soft robots may foster robotics interest for a diverse population of students and expand students' ideas about what robots do and how engineering can be used in human-centered design. We developed a soft robotic hand that can be controlled virtually by mimicking simple hand gestures via webcam. Open-source computer-vision software, commonly used in social media applications, recognizes human right hands using a webcam through video conferencing software. After developing the interactive tool, we tested it both in functionality and participant perception. Results from data collected in this work describe response times of the tool in virtual and in person scenarios with data collected from over 60 participants. We also detail the challenges to implementing with variable webcam resolutions and in busy classroom environments, as well as the criteria needed for successful implementation. We also present data on student perceptions of the activity. Data collected through Institutional Review Board approved surveys reveals positive attitudes toward the activity, student perceptions of robotic hands and the importance of realistic finger structures, specifically for students interested in bioengineering, and new ideas about how students relate robotics to human-centered design. The results from this study provide insight into (1) creating accessible outreach curricula, (2) expanding the applications of robotics in outreach, and (3) building pre-college curricula that impact student perceptions of and interest in engineering. The goal of the new outreach tool is to highlight human-centered applications of robotics and to enable remote outreach, broadening access to engineering. Post pandemic, this virtual, hands-on outreach may expand access to engineering for students in rural areas or with limited access to pre-college engineering.

Introduction

Student attitudes toward mathematics and science are developed during middle and high school [1]. Hands-on features of outreach activities can positively impact the disposition of middle and high school students toward STEM [1]. Lockdowns and school closures limited participation in outreach during the COVID-19 pandemic [2]. Even prior to the pandemic, these programs were limited for students in many in low resource schools [3, 4]. Computer-based STEM outreach platforms provide unique learning experiences and can broaden the available audience, speakers, and facilitators [5]. The necessity for virtual learning environments brought on by COVID-19, inspired the development of new outreach activities for young students to interact with engineering projects remotely. In this paper, we describe the development of an interactive experience to teach K12 students about prosthetics, medical devices, and soft robotics by controlling a laboratory-based physical robotic hand via webcam. Post pandemic, this virtual, hands-on outreach may expand access to bioengineering for students in rural areas or with limited access to pre-college engineering.

Adoption of new technologies and methods of communication helped to mitigate the negative effects of isolation during the COVID-19 pandemic [6]. In healthcare settings, discourse focused on virtual spaces and virtual reality to provide connection in cases such as palliative care [7, 8]. However, current virtual technology largely focuses on visual and auditory stimulation with limited capabilities regarding tactile engagement. We investigated the remote control of robotic prosthetics to engage students remotely. In comparison to traditional robots, soft robotic devices have advantages for human interaction including use of low-modulus, biocompatible materials [9] and biologically inspired designs [10]. Soft robot projects were recently shown to increase tinkering self-efficacy for female students in educational settings [11]. Additionally, hands-on activities for young students can be used to teach bioinspired design [12], and broaden students' understanding of robotics [13]. Recent research has seen the development of soft robotic hands, varying largely by design, method of control, and proposed application. Examples include those controlled by surface electromyographic (sEMG) signals [14]. Hand gesture controlled soft-robotic hands have been developed, with tracking done by Leap Motion cameras and commercial software [13, 14]. Air pressure requirements also vary widely. For example, one such hand, with a large degree of motion and fast reaction times, utilizes air pressures of up to 2 MPa [17]. We hypothesized that by altering actuator design, lowering pressure requirements and decreasing component cost, this technology could be accessible to schools for outreach. We had multiple objectives to this project:

1. Develop an interactive educational robotics toolkit that can be used in outreach, in classrooms, and in virtual environments.
2. Provide instructions so that teachers and students can build the interactive robot in their own classrooms.
3. Evaluate the interactivity of the robot hand in classrooms and outreach settings.
4. Evaluate students' impressions of how building robot fingers represents the work of engineers.

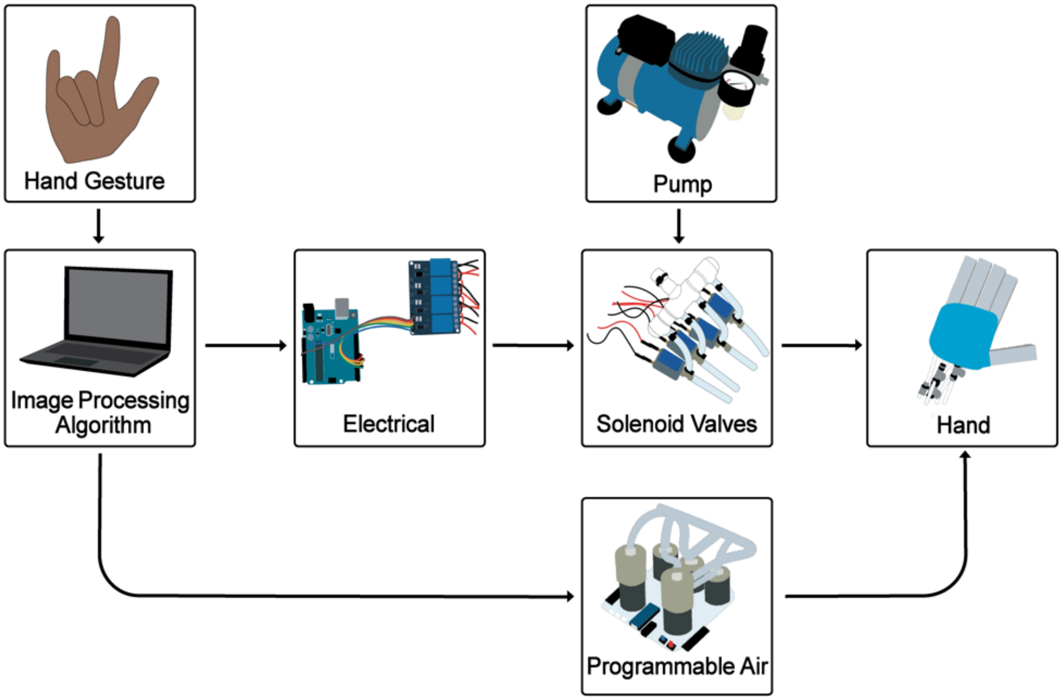


Figure 1. Framework from hand gesture to robotic hand actuation

Approach to Teaching Robotics in a Hands-on, Project-based Toolkit

This paper reports on the design, testing, and implementation of a new outreach approach: virtual yet physical interaction with a soft robot. The design presented is intended to be accessible and easily integrated into varied environments, demonstrated here for bioengineering educational outreach, but with potential applications for remote physical interactions, patient comforting through touch, and physical therapy. This paper describes the process of designing the hardware and software with detail such that others can replicate this activity or use the software to design their own remote-controlled bioinspired device. Figure 1 presents a flow diagram of the design. A user displays their right-hand palm to a webcam. Simple gestures are analyzed by Google's MediaPipe framework. Following calculations done by a custom script, the robot hand conforms to match gestures with fingers modeled as silicone pneumatic actuators powered by a pneumatic control system.

Soft Robotic Hand: Teaching Mechanical Design

To design the hand, we optimized a 3D printed palm, finger actuators, and connection joints. Given previous experience with classroom teaching and outreach [13, 18–21], our focus was simple and easy to use designs and components. The palm serves as the rigid connection between the actuators and controls (Figure 2.a). The connection between palm and actuators is a cubic casing (Figure 2.b), slot secured to the palm (Figure 2. a.iv-c.iv). Slots were positioned in a manner to resemble a human-hand geometry [22] (Figure 2.c.iv). Typically, thumb joints have two degrees of freedom allowing for extension/flexion and adduction/abduction. We simplified the system to only replicate flexion motion modelled as linear motion, which the actuators provide. Additionally, the length of the thumb was reduced, allowing finger length ratios to resemble an average human hand [22]. To fabricate fingers, we adapted the base mold and soluble insert from the previous Soluble Insert Actuator (SIA) designs [23] (Figure 2.d). Wall height of each chamber was shortened by 15% (Figure 2.d.iii) and spine insert was rounded (Figure 2.d.ii) to improve design durability.

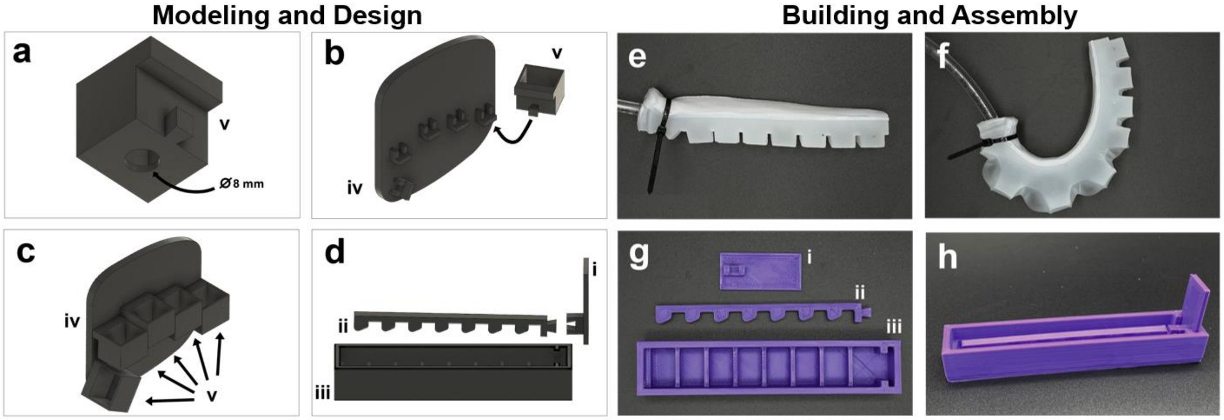


Figure 2. Design of the Robotic Hand (a-c) CAD render of the slotted connection between the plastic palm and fingers, (d) CAD render of the silicone mold, (e) relaxed silicone finger (P=0), (f) silicone finger actuated (P>0), 3D printed finger mold (g) disassembled, and (h) assembled

Software Design: Exposing Students to Artificial Intelligence

MediaPipe (Google, Mountain View, CA), an open-source framework for building multimodal applied machine learning pipelines, was selected for its accessibility. The software is freely available, such that after this module, high school students can experiment with their own designs. The platform also allows researchers and teachers to make connections for students to social media platforms that use this and similar software for face and hand tracking. Using 'Hand Tracking', images from a virtual participant's webcam are first processed by MediaPipe. We developed a custom algorithm (available in Appendix) to restructure data, packaging it into an array to send to the pneumatic control board. In use, the custom script calls for an image of an open and closed hand to calibrate the program. Next the users can display a unique gesture. The script maps the hand in 3D space and ports the gesture to the control boards.

Electronics: Simple Controls to Power Educational Robots

To actuate the hand, we adapted a pneumatic control board [24] (finger control) and used a Programmable-Air device as received (New York, NY) (thumb control). The control board uses solenoid valves connected to a compressed air pump and controlled by a relay board (Arduino) to control the air pressure in the fingers. Figure 3 shows the physical components that map to the design framework in Figure 1 as well as the complete setup displayed on a tabletop. The system is compact and portable for use in on-site outreach events and classrooms.

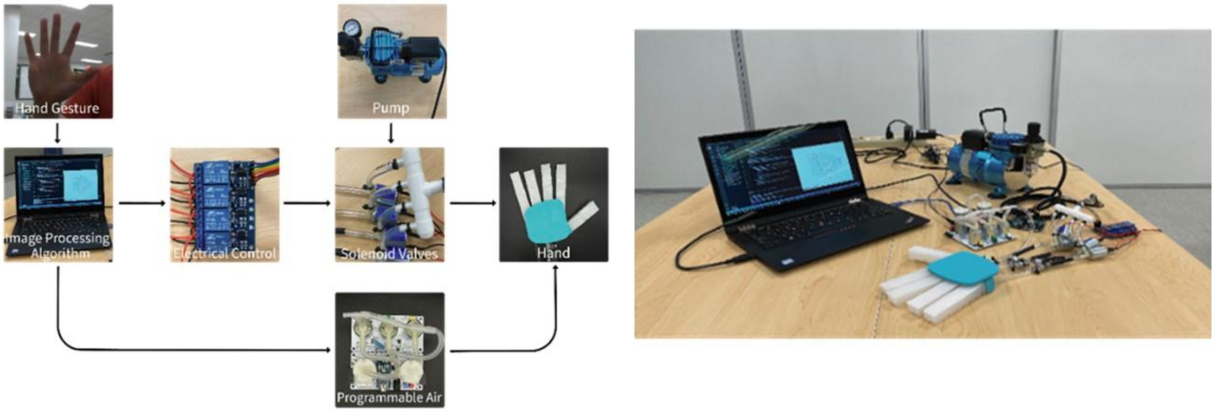


Figure 3. Assembled System of the Robotic Hand

In use, after gesture images are processed through MediaPipe, our software pulls 20 Cartesian data points from the MediaPipe results. The points can be seen in Figure 4, where MediaPipe draws on-top of the image. These data points are restructured into a multidimensional matrix that is then used to calculate the position of the hand in 3D space by position dot-product. The open hand is set as maximum angle and closed hand as the minimum angle. A threshold angle is set halfway between the min and max angles and used to determine the open and closed state. After serial connection between both control boards are made, and a byte of data is sent to each board, to decode and control the silicone fingers.

Results and Discussion

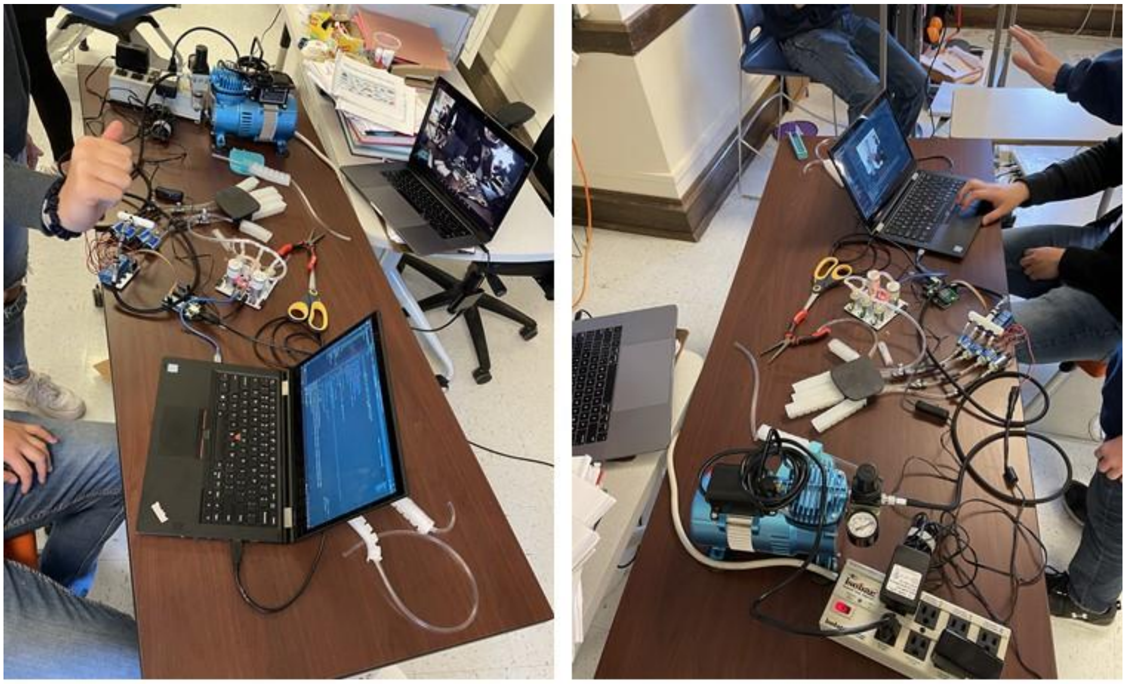
The resulting device is a responsive soft robotic hand that conforms to hand gestures presented to a webcam locally or over video conference. Fig. 4a-4h shows the robotic hand successfully imitating hand gestures presented through a laptop forward facing webcam. Prior to using in outreach, we tested the hand processing capabilities in a well-lit laboratory using a 720p webcam. In this environment we tested processing time for the calibration and gesture steps (n=50) (Figure 4i). Once tested in a controlled environment, we deployed the soft robotic hand in two outreach events.

Outreach Context

We piloted the soft robotic hand in: (1) a virtual outreach event, and (2) an in-person classroom environment. Online, the project was presented at a college-wide outreach fair held online due to COVID-19. Delivered as a 45-minute Zoom live-stream, the session was attended by 40 community members. Attendees learned about prosthetics, soft robot ealthcare applications of soft robots, and took turns controlling the hand. Participants were selected and their video pinned for the research team to run the software. The session was lively with great interest from the crowd. Later, we next had the opportunity to bring the hand to a school to observe student interaction, soft robot finger build, and identify areas for improvement. The study took place at a local high school that enrolls 8th through 12th grades. We invited 8th grade students to an after-school session to learn about soft robotics and test the hand. On two days, 16 students (60% male, 40% female) attended the voluntary 50-minute event in which students used webcams to connect to the hand and control it with a variety of gestures. During this session, we recorded data on processing time, success rate, and student response. We also invited students to build a finger and understand their impressions of the work of engineers.

Results – Interactive Web Cam Controlled Hand

During the online demonstration, 50% of participants were able to achieve robot hand actuation without camera setup prior to entering the live, virtual event. Factors such as mild blurriness, dim lightning, and highly compressed webcam feeds caused errors in recognizing the correct hand gestures over Zoom. Due to the large number of participants, there was not enough time to calibrate the software to each individual hand further leading to unsuccessful runs. This also contributed to errors in hand-gesture recognition which led to inaccurate actuations. This encouraged us to explore the technology further to make improvements for future events.



Closed Hand Calibration

Open Hand Calibration

Figure 4. Students interacting with soft robot hand during closed hand and open hand calibration steps in classroom

When we demoed the hand in person, we collected data to better understand success rate, as we could visualize users and hand in real time. On average successful gestures were achieved after 1.6 ± 0.78 attempts and 87.5% of participant trials resulted in a correct gesture within three attempts with 43.8% of students successfully achieving a correct gesture on the first attempt, an improvement over the virtual event. In this case, each student completed the calibration to improve results over the virtual event. We recorded run time from starting calibration to robot gesture display. On average the calibration plus gesture took 5.89 ± 2.7s per run. We analyzed the success of the calibration step. In total n=13 participants successfully completed the calibration on the first attempt as measured by the program registering the images and completing calculation. Of the n=3 attempts for which the calibration failed, one resulted in a successful gesture after three attempts, one resulted in an incorrect gesture after 3 attempts, and one never achieved a successful calibration after 3 attempts.

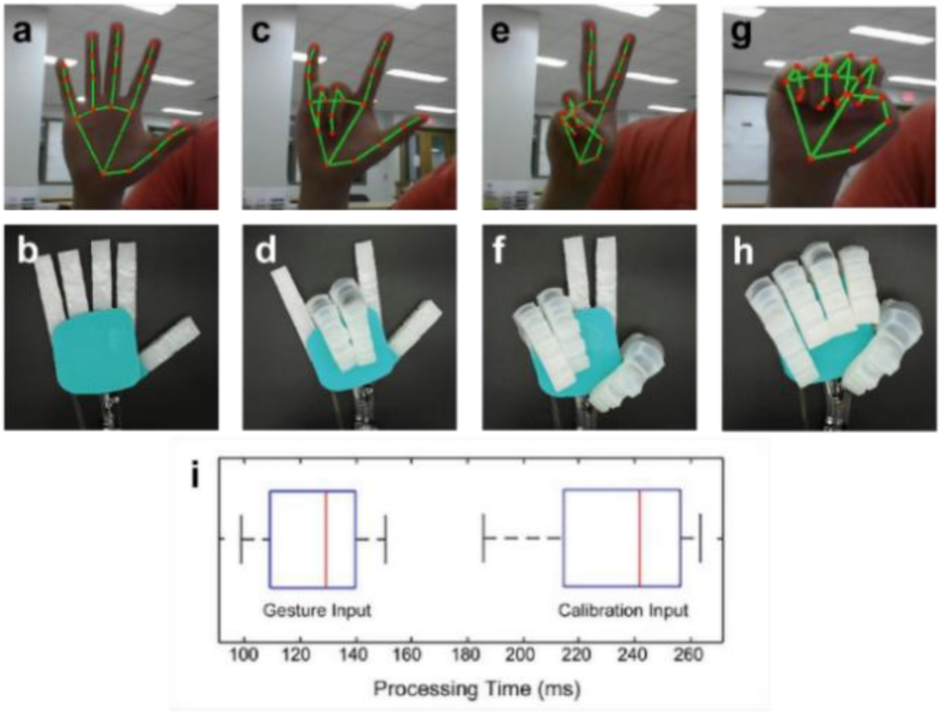


Figure 5. (a-h) Images of the MediaPipe processed hand data compared to the robotic hand. (i) MediaPipe processing time of the gesture and calibration input images

Overall, the students were excited to interact with the robot, one student noting,

> *“I thought that was pretty cool and interesting 'cause I’ve never done anything like that.”*

And another commented on the hands-on nature of the activity,

> *“I really like in science getting like hands on and actually being able to experiment with stuff because it just makes the entire experience more interesting.”*

And commenting on the desire for more related activities,

> *“I really enjoyed the class, we really need something like this at [school name].”*

While the demonstrations of the computer vision controlled soft robotic hand were successful, it was not without opportunities for further development. Larger scale data collection of remote events will help develop the algorithm to increase success rates in less controlled environments. In-person, the research team was able to ensure bright lighting and clear backgrounds were used. However, student gestures were unpredictable. One student attempted “rock, paper, scissors” but the software could not recognize a tilted hand. In addition, with any form of communication, censorship can be a concern. To maintain school and age appropriateness, we disabled inappropriate gestures.

With the goal of creating an inclusive product that increases access to engineering, we examined areas for bias or exclusion in our design. In our testing, we had a racially diverse participant group and noted no differences in success rates for participants with different skin tones. However, given the recent work demonstrating racial bias in facial recognition software [25], a large-scale study and careful evaluation must ensure that this activity does not perpetuate racial bias observed in technology. Lastly, all participants in this work were able-bodied, with five fingers on their right hand. In the future, we will investigate implementing left- and right-hand interaction and use hands that fall outside the average values for size and movement to create an inclusive product with our goal of broadening participation in engineering.

Results – Building the Silicone Finger

We gave students the opportunity to build a silicone finger used in the robot hand according to our previously published protocol [23]. Afterward, we administered a short survey (IRB Approved) to understand student perceptions of the silicone build and its relevance to their understanding of engineering work. We first asked students about first impressions. We asked the students, “What was your favorite part of the build?” and “What was your least favorite part of the build?” Thematic analysis [26] was used to group responses shown in Table 1.

Table 1. Responses to likes and dislikes after building a soft silicone finger.

Question: What was your favorite part of the build?	
Theme	Example Responses
Clear connections to biomechanics of human hands and biology	• *I really liked the way that the model helped me visualize muscles in the fingers.* • *Seeing how both creations related to the human body, with the fingers and muscles.*
Hands-on experience	• *It was interactive but we still learned it wasn’t just a play time*
Thorough instruction guides	• *I really liked how there was visual help along the way, and we were able to do the projects without help from staff*
Unique building materials	• *The silicone is so cool!*
Question: What was your least favorite part of the build?	
No comment	• *Nothing!*
Wanting more time	• *It would have been nice to have more time for the silicon actuator, so we could play around with the fingers and grippers together more.*
Messy materials	• *I did not like how it was very messy and my hands got sticky*

We next asked students, “Is this a project you would expect engineers to work on?”. Responses are shown in Figure 6.

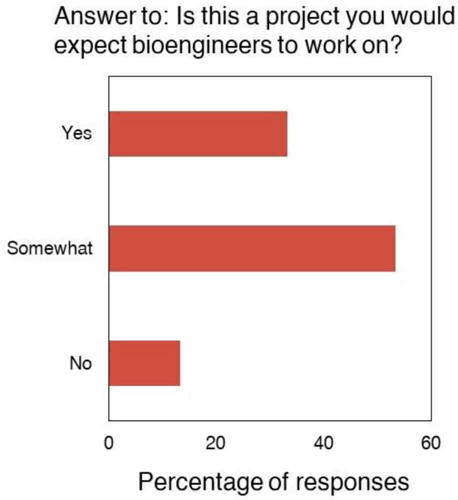


Figure 6. Quantitative responses to “Is this a project you would expect engineers to work on?”

We then followed up with an open-ended question to further understand students’ answers. Table 2 details the responses.

Table 2. Follow up to “Is this a project you would expect engineers to work on?”

Likert Scale Answer	Follow up to “Why did you select that answer?”
No	• *I feel like the work would be a lot harder* • *This activity seemed like a very easy project that a real engineer would not be expected to do*
Somewhat	• *It did not seem very difficult* • *I thought that engineers would be a part of prosthetics* • *I can see engineers working on prosthetics using similar methods to the silicon actuator to test different designs made of soft material. Bioengineering and prosthetics seem to be going in the soft robotics direction because of its benefits regarding their structure and compatibility with the human body. It would definitely be a lot more complicated then what we did today, but I can see engineers testing and prototyping their designs in a similar way.* • *It seems like something that they would test out* • *I feel like they have more resources* • *I did not expect engineers to be be using models like this because I thought they would be doing more complex things* • *I knew that bioengineers tried to reproduce human organs with other materials, but it was interesting to*

	see how simple things could replicate the movement of body parts and organs
Yes	• *We are making contraptions that can perform a specific task* • *Because it was engineering a finger to work like a prosthetic could work* • *The silicon mold was something researches did as well to have their own model that was more detailed.* • *Engineers need to be able to visualize how the body works and how their inventions will work. Even if it's made out of an unpractical material.* • *It has to do with the cells, tissues and anatomy of the human body. Though it is not made of digital tech, it is still of form of engineering/*

Discussion

Table 1 captures some of the advantages and disadvantages of the activity, particularly if teachers engage students in building the hand. New materials and connections to human anatomy are exciting for students. However, the stickiness of the materials can be surprising if poper precautions are not taken to wear gloves and cover tabletops. With regard to the webcam recognition aspects, the use of common filtering and tracking software from social media are exciting for young students, but webcam resolution can be a challenge and possibly create an experience where a student cannot interact with the hand.

STEM outreach often occurs in very short experiences. Keeping initial STEM experiences positive is important to sparking interest in STEM and adoption of STEM activities in classrooms [27]. However, when students find success in a STEM outreach activity, that may challenge their preconceived notions of what it takes to be an engineer. If students hold the belief that "engineering is hard", an easy to complete outreach activity may not seem like engineering. We believe we saw some of this in the data presented in Tables 1 and 2. Students clearly liked the project, found valuable aspects to it, were able to identify areas to improve it (stickiness), but when asked if this is the work of an engineer, many students responded that they believe what engineers do is "harder", "more difficult" or "more complicated". These results indicate the firm hold that early perceptions of engineering have on K12 students ideas about seeing themselves as engineers. In the future, more ties to engineering practice through videos or images can help students understand how similar this work is to that of engineers. Longer term studies can look at these perceptions over longer engagement in a camp or classroom to understand of these perceptions shape engineering identities.

Conclusion

Our results suggested that the soft robotic hand design is functional and practical, with reasonable reaction times and successful imitations of imaged hand gestures. While simple and easy to understand, such soft-robotic designs provide a unique and user-friendly venue for tactile interactions online. Future designs could build upon our robotic hand design and add more functionalities, such as real-time hand tracking or more body parts for complex human interactions. The COVID-19 pandemic has created unique design opportunities for engineering outreach. The soft robot hand provides an opportunity for further development, and application in K12 classrooms.

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