7. Exploring the Use of Fiber Crafts With Soft Robotics for Connected Engineering Learning

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Abstract: Soft robotics is an emerging field with promising inroads for inclusive approaches to STEM learning because of the range of creative materials and cultural practices that soft robotics invites to robotics. We investigated one promising way soft robotics could foster connected learning, as part of engineering learning by integrating creative fiber crafts productions with pneumatic actuators and observing engineering practices with the tools and materials. Particularly, fiber crafts materials have increasingly become valued design materials within engineering and soft robotics. Yet it remains underexplored how these materials can be introduced to engineering education to foster more inclusive learning that is connected to youth interests and practices. Drawing on a connected learning approach, this study examines the use of a fiber-crafts based soft robotics activity within a US middle school setting toward demonstrations of engineering practices and connected learning design principles. At the intersection of soft robotics and fabric, we present three cases that show that making fabric a core of a soft robotics learning activity can legitimize youth practices by connecting emotions, familiarity, and personal interests with core engineering practices.

Introduction

To address inequities within engineering, it is important to identify and design environments that build on interests and practices of youth in ways that directly connect to the discipline (cf. Master & Meltzoff, 2020; Hachey, 2020; Mulvey et al., 2022). Soft robotics, which can include silicone-based pneumatic actuation, are an emerging and promising direction to support equitable approaches to engineering (Jackson et al., 2021). Silicone-based pneumatic actuation can involve the making and using of particularly designed airtight containers that expand when inflated. Such pneumatic actuators can be combined with a range of other materials, such as fiber crafts, which have been associated socio-culturally with underrepresented people in STEM, especially women and girls (e.g., Barber, 1995). Additionally, fiber crafts present a promising source of innovation through mechanical properties (Cappello et al., 2018) as well as decorating as a form of technology innovation (Keune et al., 2022). Fiber-crafts based soft robotics also present a promising context for connected learning (Ito et al., 2013; 2020) including to legitimize and revalue material cultural practices of a broader scope as core to engineering and innovative technology design. One way pneumatic actuators have been researched in educational contexts is through the facilitation of the step-by-step production of a silicone-based soft actuator based on an open-source soft robotics toolkit (see Holland et al., 2014; Jackson et al., 2021). Yet it remains underexplored how pneumatic actuators can serve as creative design materials with which youth can explore mechanical structures of fiber crafts as a way into engineering learning.

In the present study, we asked: **How can the socio-material properties of a fabric-based pneumatic actuation activity bring about elements of connected learning environments?** By building on the connected learning model (Ito et al., 2013; 2020), particularly the design principles of (a) *legitimization of youth interests*, (b) *meaningful contributions made to real communities*, (c) *making progress or achievement visible across settings (Ito et al., 2020, p. 51-61)*, we explored the design of a fiber-crafts based soft-robotics activity within a middle school setting in the United States. We conducted two iterations of two sessions that were part of a longer course about fiber crafts for STEM learning (see Keune, 2022; Keune & Peppler, 2020). We analyzed video data that recorded the interactions and semi-structured interviews with youth based on a subset of the elements of connected learning environments (Ito et al., 2020) that are aligned with how youth practices with the materials supported practices of the engineering design process (NGSS).

We found that making fabric a core of a soft robotics learning activity legitimized youth practices by connecting emotions, familiarity, and personal interests with core engineering ideas. This has implications for the further design of the facilitation of soft robotics activities within educational settings. We close with recommendations of advancing connected learning design principles to consider making progress or achievement visible across individual project settings within the same physical settings.

Background

The current study is part of a larger body of work that looks at creative crafting materials that are historically linked to groups of individuals that are underrepresented in STEM fields, such as women in engineering (e.g., Peppler et al., 2020). The goal of the present study was to see how the material properties of a fabric-based pneumatic actuation activity can encourage connected learning within engineering learning. The motivation to begin the design process with fiber crafts as the material driver for the activity was to generate an engineering context that is approachable for all students. In fact, recent research in the learning sciences has begun to show that designing contexts for STEM learning by starting with materials that are socio-cultural, and with socio-historical practices associated with people who are underrepresented in these domains, such as women in engineering, can be relevant for all students rather than excluding some (Keune et al., 2021).

Soft robotics in education

Within K-12 educational contexts, robotics as a larger area of creative making have been considered a context for young people to learn STEM concepts in effective and equitable ways (Rahman, 2021; Bers, 2008). Robotics can help students understand STEM ideas through illustrative and iterative design (Jamali, 2019). One example of a robotics kit used in educational contexts is the LEGO WeDo 2.0 robotics kit, a 280-piece kit that includes a motor, two sensors, and a smart hub used for mathematics and competitions, among others (Jackson et al., 2021; Jamali, 2019).

Soft robotics is a growing area of engineering and represents an alternative to an area of engineering that is dominated by rigid materials (Hawkes et al., 2021). Combining mechanical engineering, computer science, and electric and electronic engineering, soft robotics introduce soft materials like silicone rubber to robotics, with the motivation to create bio-inspired mechanisms (Trimmer, 2014; Shibata et al., 2021). Possible applications for these devices range from transportation systems that can endure harsh conditions or exoskeletons that can be attached to people with motor complications to aid movements (Whitesides, 2018).

One area of soft robotics is pneumatic actuation, which refers to the various tools and instruments that convert energy, typically in the form of compressed gas or liquids, into control motion, and has been used in the biomedical field or food industry to handle fragile items. Pneumatics connect biology to engineering, for instance, by making it possible to replicate muscle movement, although not muscle mechanisms (Whitesides, 2018). This opens possibilities to work with materials that can inflate or deflate as well as grab objects in more natural ways. For instance, the open-source Soft Robotics Toolkit builds on the idea of producing a complex mechanism by breaking it down into its parts and connecting them together into a working system that moves independently (Holland et al., 2014). People can 3D print molds for creating silicone shapes that can be animated through air flow (Berndt et al, 2019).

Soft robotics allows for varied designs that can be used to appeal to a wider audience, or interest students for STEM fields in different approaches (Jackson et al., 2019). One example is how in soft robotics the unique mechanical qualities of fiber crafts have been used to innovate robotics devices for space travel (e.g., Xiong et al., 2021; Nguyen et al., 2019). This is significant because it frames materials that are not commonly associated with engineering but instead with socio-material practices of people underrepresented in engineering (e.g., women) as a core source of innovation within the field.

In the present study, we build on this opportunity that soft robotics brings to engineering learning and investigate the design of a fabric-based pneumatic actuator activity that honors and embraces youth's interest as well as socio-cultural practices of underrepresented groups in engineering. In this activity, youth created personally meaningful designs by exploring the properties of woven and sewn artifacts through inflatable silicone-based shapes.

Connected learning for designing inclusive engineering learning

To promote inclusive STEM learning, more support is needed to create learning environments that promote and celebrate culturally relevant and personally meaningful educational experiences (e.g., Mulvey et al., 2022; Hughes et al., 2020; Ireland et al., 2018). The connected learning model is useful for exploring STEM design activities toward fostering equity within engineering because the model considers the interests and passions of young people as a powerful starting point for fostering deep and long-lasting learning opportunities (Ito et al., 2020). Connected learning has an equity-oriented mission, which recognizes and honors the practices of young people as catalysts for engagement (Ito et al., 2020).

Connected learning includes four elements: (1) *Sponsorship of youth interests*, which recommends the recognition of youth passions through mentorship and resources, (2) *shared practices*, which highlights the importance of collaborative creation, competition, and joint research, (3) *shared purpose*, which highlights the importance of shared values and culture, and (4) *connections across settings*, which builds on learner networks to provide access to opportunities and communities. Developing learning and educational settings that promote the four elements through design principles can foster connected learning (Ito et al., 2020; p. 53). We focused on the following Connected Learning design principles for this study: (a) *Legitimization of youth interests, values, and practices*, because it brings forward design opportunities that connect to the familiar, an approach that has also been shown to support girls in engineering, (b) *meaningful contributions made to real communities*, which implements user-centered design approaches where youth design for others, related to higher number of engineering practices displayed by girls (Peppler et al., 2021), and (c) *progress or achievement is visible across settings*, which includes acknowledging youth for their domain-related practices by providing tools to share their work online with others (Keune et al., 2019). We are particularly interested in understanding how connected learning design principles can guide the design of a fiber crafts-based soft robotics activity and, in turn, how the socio-materiality of the designed soft robotics activity supports elements of connected learning. Better understanding of how the design embodies such design principles would help identify meaningful strategies for fostering engineering contexts that can support all learners.

Methods

This qualitative video-based research was conducted within a middle school setting in the midwestern United States. The study stands in the larger context of research on fiber crafts as a context for generative STEM learning (e.g., Peppler et al., 2020). To study the possibilities of combining pneumatic actuators as a way to animate soft structures of fiber crafts, the research facilitated two 70-minute sessions with two groups of six students each. The teachers allocated the students to the groups based on the friendships and interests of the students. The first group was joined by two boys and four girls, and the second group was joined by two girls and four boys. During the course, students worked on a craft table and used silicone materials and air sources for pneumatic actuation of fiber craft artifacts that were provided to the students.

The first iteration instructed students to familiarize themselves with the structure of a sewn design by removing stitches from a flat folded sewn twisted square. This made it possible to open the folded fabric and to close it back up. The stitches added memory to the fabric that opened flat and closed back up into the twisted square shapes. In session one of the first course iteration, youth explored circular and rectangular pneumatic actuators that could be attached to manual air sources (e.g., syringes connected to tubes, hand-sized bicycle pumps). Then, youth connected the fabric pieces to the actuators by sewing to transform the fabric's shape and to engage the mechanics of its folds. Afterwards, youth created their own pneumatic actuators by cutting out shapes from silicone rubber sheets and gluing them together before they connected fiber craft artifacts to their own actuator designs.

The second iteration provided youths with sewable actuators. During session one, students familiarized themselves with fabric artifacts and their mechanical features by removing stitches that held the artifacts' folds in place. Then, youth experimented with sewable actuators, which included a thin outer border with holes that could be sewn through to attach the actuator to the fabric. Attaching the fabric artifacts and the actuator made it possible to transform the fabric shape when inflating and deflating the actuator.

Data sources

We used two types of video data: (1) Videos captured in a 360° camera mounted on the ceiling top of the working tables for each group and (2) semi-structured interviews that discussed youth's creations. We used the 360° camera to get an overview of how the students engaged in the activities and interacted with each other. The interviews were taken while the 360° camera was recording, which meant that they provided a closer look and better image quality for individual students at a time along with a semi-structured interview that prompted the students to talk briefly but in-depth about their projects.

Data analysis

First, we created narrative summaries of the events in the 360° videos by focusing especially on three focal cases. We selected three cases that exemplified specific experiences with the fabric materials throughout the activities. We created a table for transcribing their interactions with each other and how they progressed in their projects. We then analyzed this information to observe relevant details in each iteration and discussed what the cases suggested for the further design of the soft robotics activity. In the analysis we explored how the youth engaged with engineering ideas and practices (e.g., planning and carrying out investigations, developing possible solutions, optimizing the design solution) based on US National Science standards (NGSS).

We further analyzed the data to understand how the design of the activity, as witnessed through the interactions of the youth, presented connected learning design recommendations (see Ito et al., 2020), and how these intersected with the displayed engineering ideas. The design recommendations we focused on were: (a) *Legitimization of youth interests, values, and practices* because it implies designing for opportunities to connect to the familiar, an approach to design that has also been shown to support girls in engineering, (b) *meaningful contributions made to real communities*, which includes user-centered design approaches that make it possible for youth to design for others, associated with higher number of engineering practices displayed by girls (Peppler et al., 2021), and (c) *progress or achievement is visible across settings*, which includes recognizing youth for their domain-related practices by making it possible to share their work online with others (Keune et al., 2019).

Findings

Designing personalized actuators and narrating with actuators

Devanie was one of the youth who participated in the first iteration of the course, which implemented sewing fiber artifacts, exploration of actuators, and connecting the actuators to the sewn fiber artifacts. Devanie explored actuators in combination with fabric artifacts through narrative storytelling. During the first session, Devanie engaged in an engineering design process as she explored how the actuators work by connecting a sewn artifact to a pneumatic actuator and observing how it changed its shape when inflating the actuator. Throughout the session, she engaged in the engineering practice Asking Questions and Defining Problems (MS-ETS 1-1). For instance, she explained that she was surprised by how the fabric changed shape, although disappointed that inflating the actuator just made it flat. Yet she also was interested in how the fabric shapes went back to their original form when deflating the actuator. During the second session she focused on designing her own actuator. She went through multiple iterations of her actuator design, starting with a star, moving on to design a small heart shaped actuator before settling for a larger heart-shaped actuator. It was interesting to see how youth created a range of different actuator shapes only to see that they all inflated as round bubbles. This is an example of Optimizing the Design Solution (ETS1.C), one aspect of the NGSS engineering design disciplinary core ideas. The possibility to draw and create personal designs of actuators also supported the Connected Learning design principle of *making progress or achievement is visible across settings* because participants, including Devanie, could start with personal shapes and see how no matter which shape they chose the inflated actuators would be similar across youth and shapes without containing the personalized aspects.

Nearing the end of this session while she waited for her actuators to dry, Devanie experimented with the pre-made actuators in combination with woven fabrics. She used one of the woven fabrics to represent a blanket on top of an actuator. She then drew a face on a piece of paper and attached it to the blanket and explained that it looked like a breathing person in bed (Figure 1). "*I put this little thing [the blanket], on top of that [the actuator], and then I start blowing it up. Then it slowly, it looks like it's breathing underneath the blanket.*" It was practices like this that showed how the design of the activity supported connected learning elements, especially *legitimization of youth interests*. The way she pumped air into the actuator to move the blanked replicated a biological system of breathing. The fabric as a cover of the actuator was a way for her to make meaning of the robotics materials in familiar ways. The fabric became an object for designing with familiar practices. Through the activity design, she was afforded with space to legitimize familiarity as part of engineering. Additionally, the activity made it possible for Devanie to *make meaningful contributions to the community* at the table. Devanie was part of the conversations with her peers, asking and providing opinions on design choices, as well as sharing her project in humorous ways.

Figure 1. Devanie showing her breathing person

Devanie's engagement with actuators showed that the personalization of actuator shapes may be an interesting activity to further consider to support engineering learning. Across the group, the youths shared work with the actuators made progress and achievements visible. It needed the group doing the design activity and the repetition of the design activity across several projects to see how the simple and flat actuator designs by the youth did not differ significantly**.** In addition, the possibility to play with ready-made actuators following the design of personal actuators legitimized youth practices as part of engineering, and made it possible for Devanie to contribute to the table in narrative and humorous ways. It was the sequential engagement with actuators actuator design followed, by designing with actuators that supported and expanded engagement with engineering practices.

Connecting actuators with fabric to engage mechanics

Martina joined the second iteration of the course. This iteration of the course facilitated the exploration of pneumatic actuators made by Author 1 prior to the session in combination with sewn fabric artifacts. Youth did not create their own actuators. Martina's exploration with the materials focused on combining fiber crafts with soft robotics, which produced a space that was generative for engineering design disciplinary core ideas while also supporting connected learning elements.

Throughout, Martina focused on how to connect fabric with silicone, engaging in an engineering design process that involved the exploration of material properties and how they interacted with one another as well as iterative solution findings. This aligns with the engineering practice Asking Questions and Defining Problems (MS-ETS1-1), because she looked into how the actuators operated when having different shapes, tested them, and developed explanations as to why the actuators behaved the way they did. For example, she demonstrated how her project slowly inflated by using a bicycle pump. Doing so changed the folds of the fabric. Martina mentioned that she had not yet identified how to get the fabric to close back up and to fold back into the flat-foldable state. To get this right required paying close attention to the interactions of the two materials, constructing explanations, and designing solutions on the placement of the stitches that connected the fabric artifact with the actuator. This is related to the engineering design disciplinary core ideas Developing Possible Solutions (ETS1.B) and Optimizing the Design Solutions (ETS1.C), as she aimed to change the folds of the fabric and experiment with different shapes of actuators, comparing possible outcomes and choosing the best possible approach. Martina conducted a series of tests on how best to combine an actuator with a fabric to inflate and deflate the flat folding artifact, working with the mechanics of the fabric that the stitches had introduced to them. Martina selected a circular actuator that inflated into an hourglass (Figure 2). As she iterated on how to connect the fabric to the actuator, she made material-specific observations that were relevant for her further solution finding process. For instance, she observed that one part of the hourglass inflated more than the other and concluded that the shape of the silicon could affect the inflation and deflation of the fabric artifact depending on where the actuator would be placed.

> *"I just thought it was a really unique shape. And I noticed that one side is bigger than the other. I was kind of confused about why, but I'm not really sure why. So I think I might want to [understand] why one [inflated] side is bigger than the other.*

She inquired about the material properties of the actuators and was determined to understand why one of the sides inflated more than the other, although both appeared of equal size while inflated.

Figure 2. Martina showing her hourglass shaped actuator.

The focused characteristic of the activity, including the ready-made actuators along with the task of connecting them with pre-made fabric artifacts, led to an interesting consideration of the complex interplay of size, shape, and placement of actuators, as well as how pneumatic actuators could animate the mechanics that the stitches produced in the fabric. Yet, connected learning design principles were less present. Legitimization for youth interests was present in the activity because the activity made it possible to create and explore creative and personal projects together with peers. However, the focus on connecting familiar practices to the exploration that was so central to Devanie's case, as well as the focus on producing meaningful contributions to the community at the table, took secondary roles in Martina's case. Her case points to the utility of including sewable features to the actuators and for facilitating the activity with the specific purpose of inflating and deflating a flat-foldable artifact to foster engineering. The focused design of the activity reduced some of the connected learning elements within the case.

Discussion

This exploratory study points to the use of fabric-based actuators as a material that can support engineering learning as well as invite connected learning by bringing elements of familiarity, narrative, emotions, and previous knowledge of the participant youth to engineering activities. The analysis of both cases showed interesting inroads for designing and testing soft robotics tools and materials that are integrated with fiber crafts and supportive of connected learning. Having participants design their own actuators, like in Devanie's case, made it possible to explore the effect of a range of differently shaped actuators created across several youth participants. We consider this as representative of the connected learning design recommendation of making progress and achievements visible across settings, where one setting is a project by each youth and several settings are the projects of several youth in the same physical location (e.g., a craft table). From this point of view, we can recognize the shared inquiry into actuator designs as a form of connected learning. The observation points to ways to expand how we currently think of connected learning across settings. However, further work is needed to inquire into this.

Further, the study points to fiber crafted artifacts to increase approaches to engineering learning, including that fiber crafted artifacts may help familiarize engineering by suggesting integration of narrative approaches, like replicating biological systems (e.g., a sleeping and breathing person). Another design iteration should focus on how to integrate facilitation and material aspects that encourage narratives and storytelling with the materials together with explorations of the pneumatics, while also laying a focus on introducing fabric as having complex structures with mechanical properties that can be used to tell animated narratives. The study showed that for the activity of creating actuators, as well as for the activity of exploring ready-made sewable actuators, integrating narrative possibilities could increase the alignment of the activity with connected learning design recommendations and connected learning elements, thus inviting a wider range of approaches to engineering.

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