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Soluble Polymer Pneumatic Networks and a Single-Pour System for Improved Accessibility and Durability of Soft Robotic Actuators

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Abstract

Soft robotic devices can be used to demonstrate mechanics, robotics, and health care devices in classrooms. The complexity of soft robotic actuator fabrication has limited its classroom use. We propose a single-mold method of fabricating soluble insert actuators (SIAs) to simplify existing actuator fabrication methods using common accessible materials. This was accomplished by embedding molded soluble structures into curing polymer with custom molds and later dissolving the internal structure, leaving behind a hollow pneumatic network. Compared with similar actuators, SIAs actuated with comparable deformations while withstanding higher pressures for longer durations. SIAs have simple and accessible fabrication, resulting in durable actuators. We propose this method of actuator fabrication for use in K-12 schools to engage young students in this emerging field. In addition to silicone actuators, we show application of SIAs in biodegradable actuator fabrication, in a simplified model for classroom demonstration, and use in a glove designed to teach students the tactile art of ceramics.

Keywords: actuator, fabrication, soluble inserts, robotics education

Introduction

Soft robots have a wide range of applications, from automated industrial packaging of delicate goods[1] to cardiac support *in vivo*,[2] because of their flexibility and compliance. The accessibility of soft robotics makes it applicable to the classroom.[3,4] At the forefront of educational soft robotics systems are pneunets actuators, made accessible through the Soft Robotics Toolkit.[5,6] This style of actuator uses embedded pneumatic networks created from an adhered system of two molded parts.[7,8] When testing this fabrication method, these actuators failed through delamination, a pressure-driven separation of the base and body molds along the seam. Students may lack the precision to fabricate these actuators, resulting in decreased performance.

Other methods to streamline actuator fabrication include dip casting,[9] a core-shell molding model,[10,11] and rotary casting.[12] However, these methods remain inaccessible to the K-12 classroom. The goal of this study was to design a fabrication process using household tools and materials that is simpler than the time-consuming, multistep, or resource-intensive methods already described. The final design must be durable, resistant to damage from handing or pressure for use in classrooms.

When conceptualizing a new fabrication method, several criteria were outlined: first, the actuator must be made from a continuous pour of silicone to eliminate the structural weakness inherent to two-part molding systems. Next, the actuator must be easy to make to increase accessibility and potential applications in the classroom. Finally, the actuator should have a design easily modified in terms of size and geometry. We present a method of building soft robotic actuators using a soluble insert design. Previous techniques have utilized paraffin wax melting, molding, and washing.[13,14] In this study, we aimed to simplify this process even further by direct 3D printing inserts or hand-cutting foams, a technique commonly used in K-12 art classrooms. To date most soft robotics classroom efforts have existed in an outreach capacity from practitioners to schools. Soft robotics

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demonstrations and lessons will see classroom adoption by teachers when fabrication techniques are refined for teacher and student ease and success.

In our effort to provide safe and modular materials easily accessible to even the youngest students, we demonstrate the application of everyday materials in molding techniques that can be dissolved in household solvents, even water. What makes this study unique in its application to K-12 schools is that the study presented here was conceived by high school students after experiencing the juxtaposition of their excitement to experiment in this area and their own frustrations trying to replicate work geared toward graduate level scientists. The initial idea for the monolithic molding was conceived during pneunet fabrication in a 12th grade engineering elective course. After proof-of-concept experiments in class, the soluble insert actuators (SIAs) were further developed by 9th through 12th graders in an extracurricular club. Soft robotics is applicable in the science education space, allowing high schoolers to freely experiment with the chemistry and physics of inflatable polymers, exploring applications interesting and relevant to them, such as art with wearable soft devices shown herein. This method of actuator fabrication was developed for students by students.

Design

To create such an actuator, a novel molding method was developed based on the design necessities of pneunets actuators: hollow pneumatic channels for inflation, an inextensible layer to restrict actuator motion, and a 3D-printable mold for ease of fabrication.[6] The new method combines all three established criteria replacing pneumatic channels with a soluble polymer (Fig. 1a). The hollow channels are created by a sacrificial structure, referred to herein as insert, which can later be dissolved. The inserts discussed in this study are modeled to replicate the shape of pneunets and can utilize a multitude of materials including polystyrene (PS), polyvinyl alcohol (PVA), acrylonitrile butadiene styrene (ABS), or even molded sugar. These materials and processes are readily accessible to K-12 students and teachers. The practices of foam shaping and 3D printing are commonly used in art and sciences classrooms in K-12 schools.

Both PVA and PS inserts were utilized in initial testing. However, when suspended in the silicone during the curing process, the inserts did not remain stationary due to the relative densities of PS and PVA (1.04 and 1.19 g/cm^3, respectively) in relation to silicone (1.07 g/cc). Thus, a design solution was developed using a dovetail-shaped structure, referred to herein as claw. The claw, affixed to a flat plate, is held rigidly in place by a slot in the actuator mold, eliminating translation or rotation. Once the silicone is poured and set, the actuator can be removed and the claw plate reused. The nature of interlocking pieces (Fig. 1) makes the fabrication process intuitive.

The final SIA iteration includes dividing walls in the mold, adding space between subsequent cells created by the insert. This cell division (CD) allows for the cells to inflate at a lower pressure, as demonstrated previously,[7] increasing the actuator's range of motion (Fig. 1b).

Materials and Methods

The steps required to fabricate SIAs using either common household materials, cardboard, and acetone, or less accessible, yet repeatable methods, 3D printing, are illustrated in Figure 2. To begin, fabricate the mold, claw, insert, and fabric sheet to the given dimensions (Fig. 2a). Cut and glue cardboard to form a base mold and claw plate, or 3D print (Afinia H800+, Chanhassen, MN) a base mold and claw plate out of insoluble filament (polylactic acid [PLA] filament; MatterHackers, Foothill Ranch, CA) (Fig. 2b). Downloadable files, as well as 3D printing instructions and tips, can be found in the Supplementary Data. Using a craft knife, cut an insert out of soluble PS (Foam Board Insulation Sheeting; FOAMULAR, Toledo, OH), or 3D print a soluble insert with PVA filament (PVA filament; MatterHackers) (Fig. 2c). Mix equal parts of silicone (Ecoflex™ 00-50; Smooth-On, Macungie, PA). Pour silicone into the base mold with the claw plate and soluble insert preassembled inside (Fig. 2d). Once full, place the fabric layer (craft fabric; Fabric Editions, Greenville, SC) onto the surface of the silicone. After curing, remove the actuator and claw from the mold (Fig. 3a). Wash the inside of the actuator with acetone several times to dissolve the PS insert; liquefied PS can be removed by simply turning the actuator upside down [Figs. 2e(i) and 3b]. Or place the actuator in a beaker of heated water and let rest for up to 24 h or

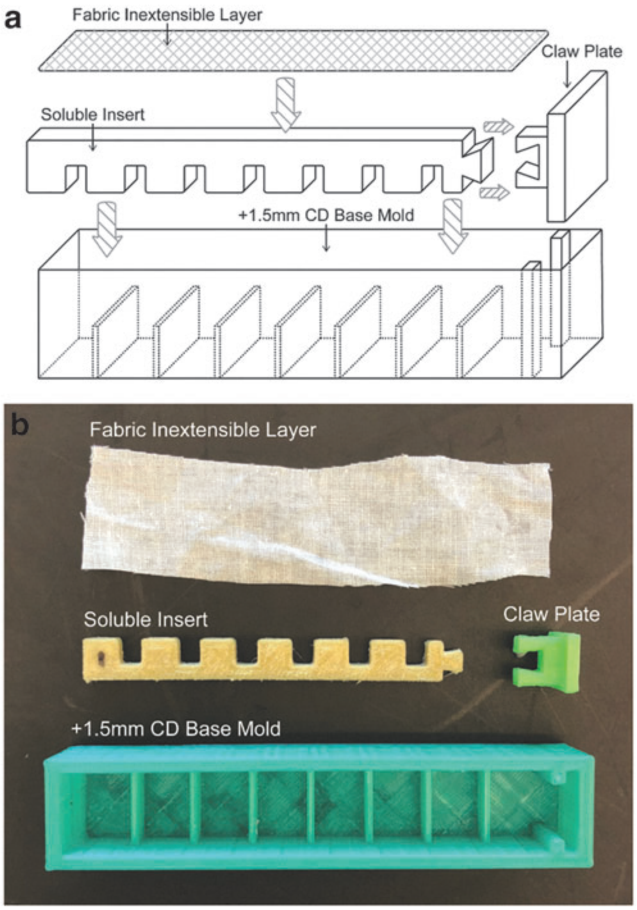

FIG. 1. Fabrication design for SIAs. **(a)** A schematic of the SIA fabrication system with *arrows* demonstrating how all elements are positioned during the fabrication process. **(b)** Materials required to fabricate an SIA. The insert can be made of any soluble material, in this case 3D-printed PVA. All elements slot together for ease of fabrication. PVA, polyvinyl alcohol; SIAs, soluble insert actuators.

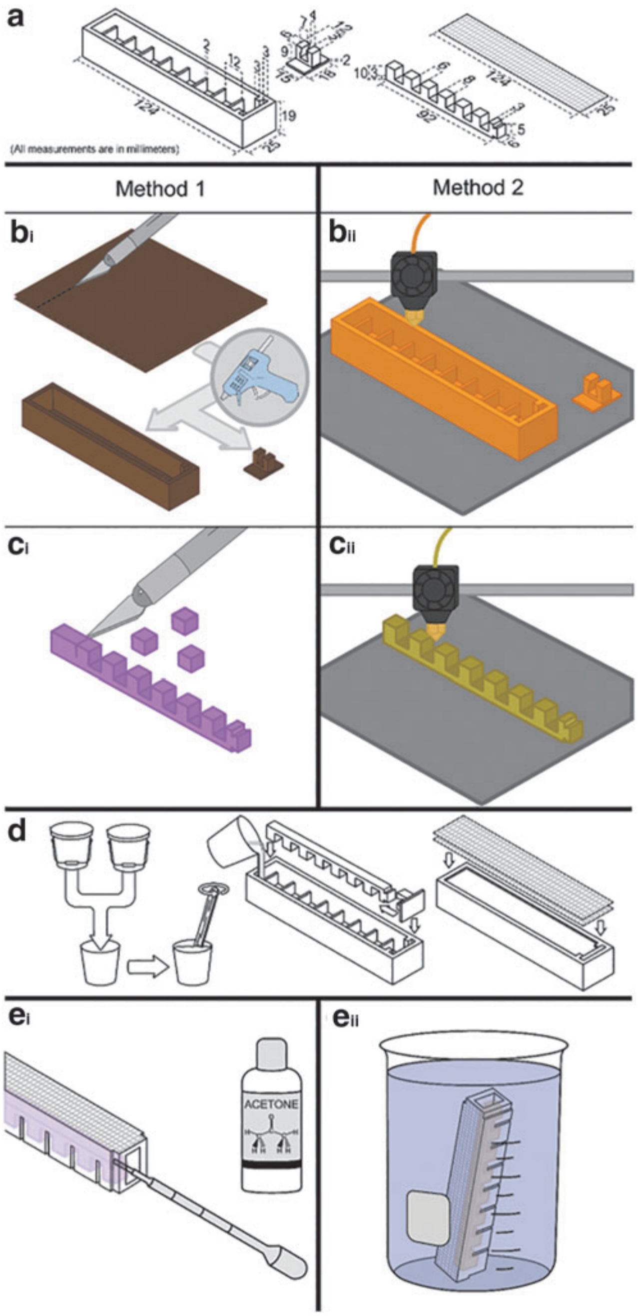

FIG. 2. Infographic containing all the steps necessary to fabricate an SIA including **(a)** dimensions of components, **(b)** fabrication of the base mold and claw plate, **(c)** creation of the soluble insert, **(d)** assembly and molding process, **(e)** and dissolution process.

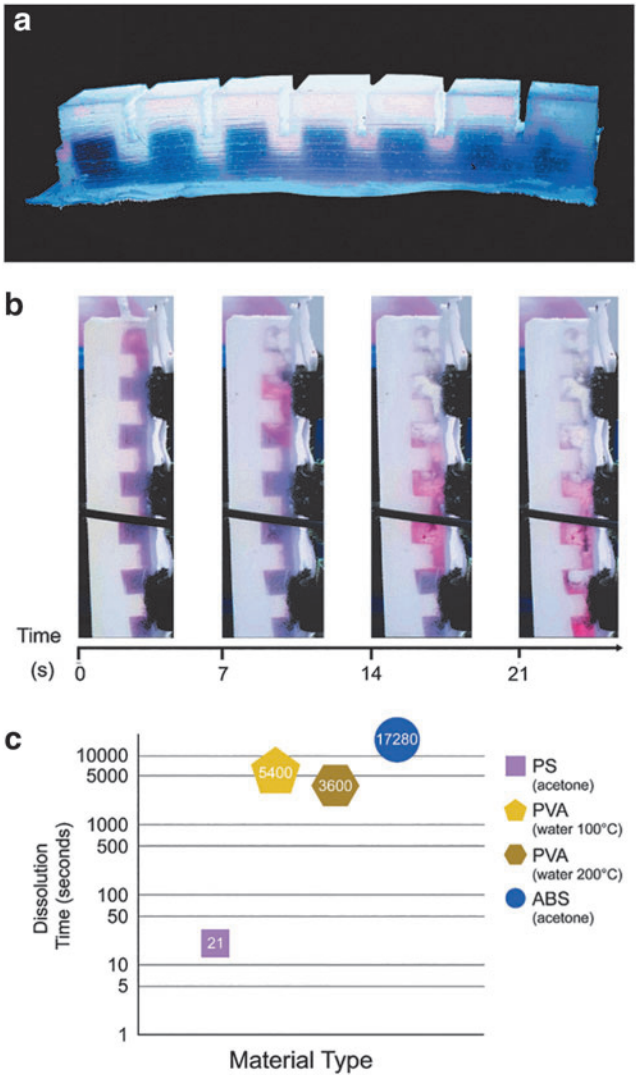

FIG. 3. **(a)** A completed SIA with undissolved PS insert visible inside. **(b)** Demonstration of the dissolution process using a PS insert and acetone solvent. **(c)** Data showing approximate dissolution times for inserts of various materials. PS inserts dissolved on the order of seconds, whereas PVA and ABS inserts dissolve on the order of hours. ABS, acrylonitrile butadiene styrene; PS, polystyrene.

until PVA inserts completely dissolves [Fig. 2e(ii)]. Once the insert is dissolved, inflate the negative space with compressed air to actuate.

The goals outlined previously were all fulfilled through the final SIA design: first, SIAs are fabricated from one continuous pour of silicone. The SIA fabrication process consists of only four parts: mold, claw, insert, and fabric. Components interlock, making fabricating SIAs quick and simple. Finally, depending on the need of the user, features such as the actuator's length, width, overall shape, and number of cells can be easily modified. The insert that creates the actuator's pneumatic networks is independent of the base mold, thus allowing a user to modify the geometry of networks and resulting bending shape of the actuator without a new mold.

Testing

Dissolution

To confirm the effectiveness of the final SIA fabrication, solubility tests were performed. Inserts were placed, undisturbed, in beakers containing their appropriate solvents. Their approximate dissolution times were recorded once the material had completely dissociated (Fig. 3c). PS dissolved in acetone on the order of seconds and did not require heat, making it a good choice for general-purpose actuators. PVA necessitated heat and dissolved in water in the order of hours.

Room-temperature water did not suffice in removing all material. Two heated water temperatures were tested but showed negligible difference in dissolution times. In addition, procedures requiring heat should ideally be avoided for classroom settings if not essential. ABS dissolved on the order of hours to days. Although the latter two 3D-printable materials take longer to dissolve, the accuracy at which they can be fabricated can be advantageous, for specific applications.

Actuation angle

Actuator performance was tested across multiple design iterations (Fig. 4). Actuators were characterized based on their features: with +CD or without (−CD). CD widths of 1.5 and 2.0 mm were chosen to allow for more room for air chamber expansion compared with the 1.0 mm widths used in pneunets. Similar naming convention was adopted for claws (−claw, +claw). Tubing was inserted into each actuator and affixed using a nylon cable tie. The actuators were pressurized at 793kPa (115 psi) using a manual power inflator (Ryobi, Fuchu, Hiroshima, Japan) for a 1 s pulse. A power inflator was chosen because the tool can be easily purchased at home improvement stores and requires no setup. The resulting shapes were analyzed to determine actuation angle. +CD actuators had increased actuation angle over −CD actuators, with actuation of >270 . +1.5 mm CD and −CD actuators actuated with a constrained range of motion, exhibiting a close-to-circular inflated state. The +2.0 mm CD actuator, however, exhibited less uniformity of actuation with a misshapen inflated state.

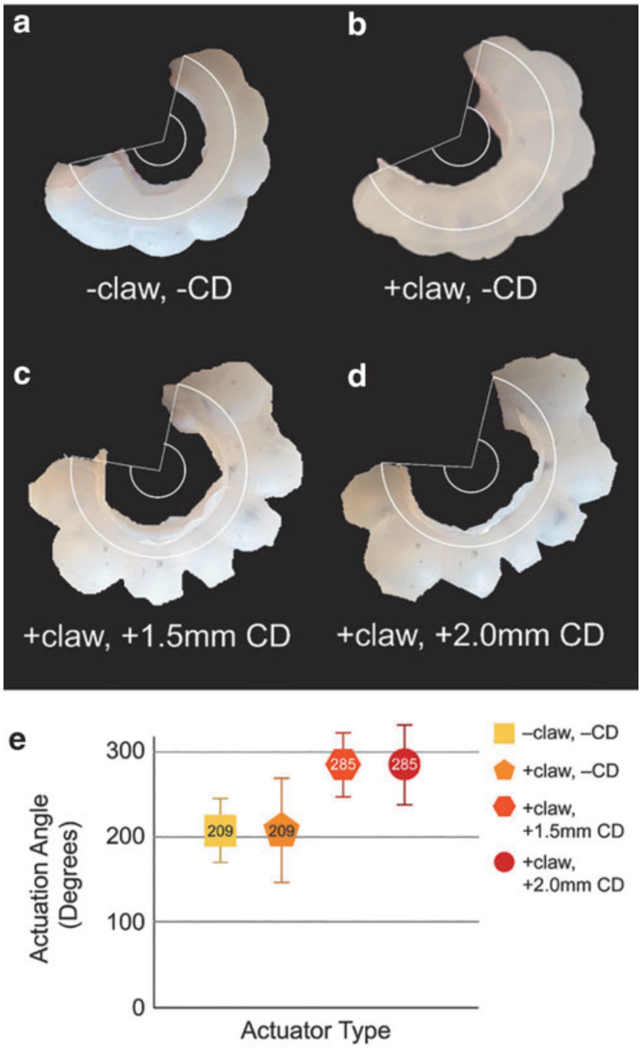

FIG. 4. Data related to the various actuation angles of actuators tested. **(a–d)** Visual representations showing the angles at which different actuator types can actuate. **(e)** Data averaged across three trials showing maximum actuation angle. CD increased actuator range of motion as expected, but too much of it caused inefficient inflation. Tests performed using a Ryobi power inflator at maximum 115 psi output. CD, cell division.

Durability

For purposes of developing soft robots for the classroom environment, durability is defined herein as resistance to damage. The durability of each actuator was tested using increasing pressure to determine time to rupture (Fig. 5). Five actuators were tested: four SIA iterations from the previous

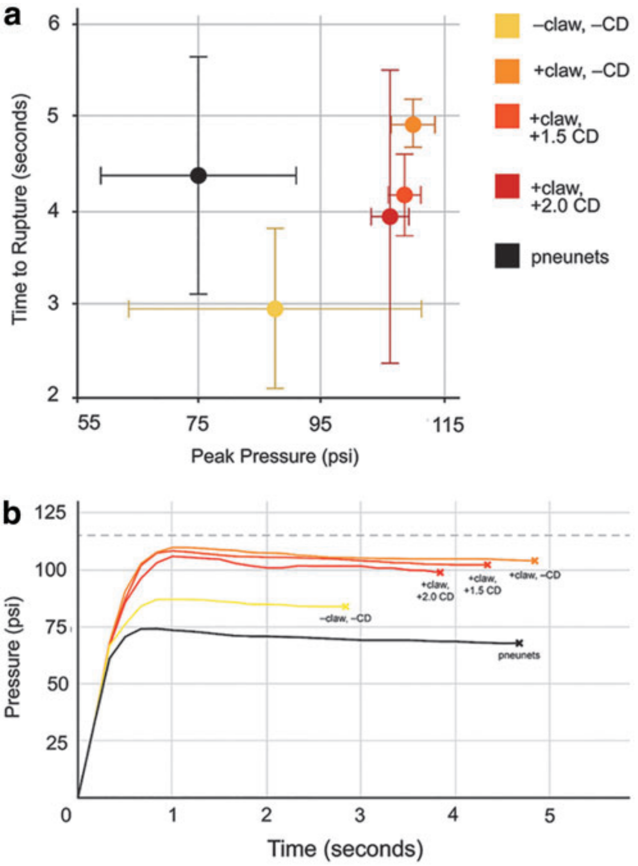

FIG. 5. The average of three pressure trials using five different actuator types. **(a)** Peak pressure (*x*-axis) and time to rupture (*y*-axis) demonstrate error range using their respective standard deviations. **(b)** Direct pressure output graphs recorded during testing. +Claw −CD and +claw +1.5CD performed the most consistently. −Claw −CD, +claw +2.0CD, and pneunets each performed less consistently, with larger variations in time to rupture and peak pressure. Peak pressure output of the power inflator indicated with a *dotted line* at 115 psi.

test as well as pneunets prepared from previous protocols[7] made from Ecoflex 00-50. +Claw –CD withstood the highest pressures for longest times, followed by +claw +1.5 mm CD, +claw +2.0 mm CD, –claw –CD, and pneunets. The latter two iterations were unable to achieve the peak pressure of 115 psi. Walls of the air chambers in –claw –CD had reduced thickness and significant leakage because the soluble insert floated unpredictably during polymer curing. Pneunets had small ruptures attributed to delamination that caused slow leaks. The final SIA iterations withstood high pressures with times to rupture comparable with those of pneunets. Thus SIA actuators proved sufficiently rupture resistant for the high-pressure low cycle count applications typical of classroom use.

Edible SIAs and removable insert actuators

In addition to fabricating traditional silicone actuators, gelatin actuators inspired by Shintake *et al.*[15] and Sardesai *et al.*[16] were made using commercially available gelatin candy (Haribo, Grafschaft, Germany) (Fig. 6). This was done to demonstrate applicability of SIAs for use cases requiring biodegradable actuators. Previously, Argiolas *et al.* demonstrated a soluble foam insert composed of silicone and table salt.[17] Although this method utilizes common household materials, safe for young students, we aimed to create a fully biodegradable, and even edible approach. This design, in addition to providing a completely food safe and edible approach, also addresses the problem of delamination present in both Shintake *et al.* and Sardesai *et al.* references using a soluble material to create seamless actuators.

Granulated and caramelized sugar, as well as food-grade 3D-printed PLA, were used to create inserts for these actuators (Fig. 6a). To optimize dissolution time for sugar-based inserts, three types of sugar (granulated, superfine, and confectioners') were imaged using a scanning electron microscope (Jeol JCM-5000 NeoScope™, Peabody, MA) and average particle size was analyzed using ImageJ (NIH, Bethesda, MD) (Fig. 6b–e). Inserts were fabricated and left to dissolve, undisturbed, in room-temperature water. The data collected led to the conclusion that smaller particle size results in quicker dissolution time, thus making it more suitable for edible SIAs. Lightly caramelized sugar was also used an insert material, as it proved more robust than the compacted sugar in its ability to maintain a rigid shape. This and PLA could both be extracted from the actuator using pliers once set, leaving behind a pneumatic network embedded in the gelatin. In contrast to SIAs, this modified method of manually removing inserts is termed removable insert actuators (RIAs). The resulting actuators were inflated to 115 psi and exhibited bending characteristics (Fig. 6f) similar to two part analogues.[15,16] This demonstrates the wide range of materials and fabrication methods that can be used to benefit soft actuators.

Classroom implementation

The goal of this study was to create soft actuators that are accessible to K-12 students. After adapting the gelatin-based RIAs, we asked whether insoluble PLA inserts could be used in silicone actuators. After insert redesign, to slope, and round edges (Fig. 7a), we found that PLA inserts could be easily pulled from cured Ecoflex 00-50 silicone if sprayed with silicone mold release before casting. The actuation mode exhibits similar characteristics seen in SIAs and pneunets (Fig. 7b, c), providing a facile actuator fabrication method for demonstration purposes. To test the feasibility of using this actuator design in classrooms, we invited students at a high school to build the actuators during an independent exploration program at the school. In groups of two, 12 students aged 13–18 years learned about actuators, discussed robotics-specific terminology, and built pneumatic actuators in two 40-min class periods (Fig. 7d). This insert modification demonstrates the modularity of the SIA/RIA platform. Although the sloped rounded inserts are amendable to quick

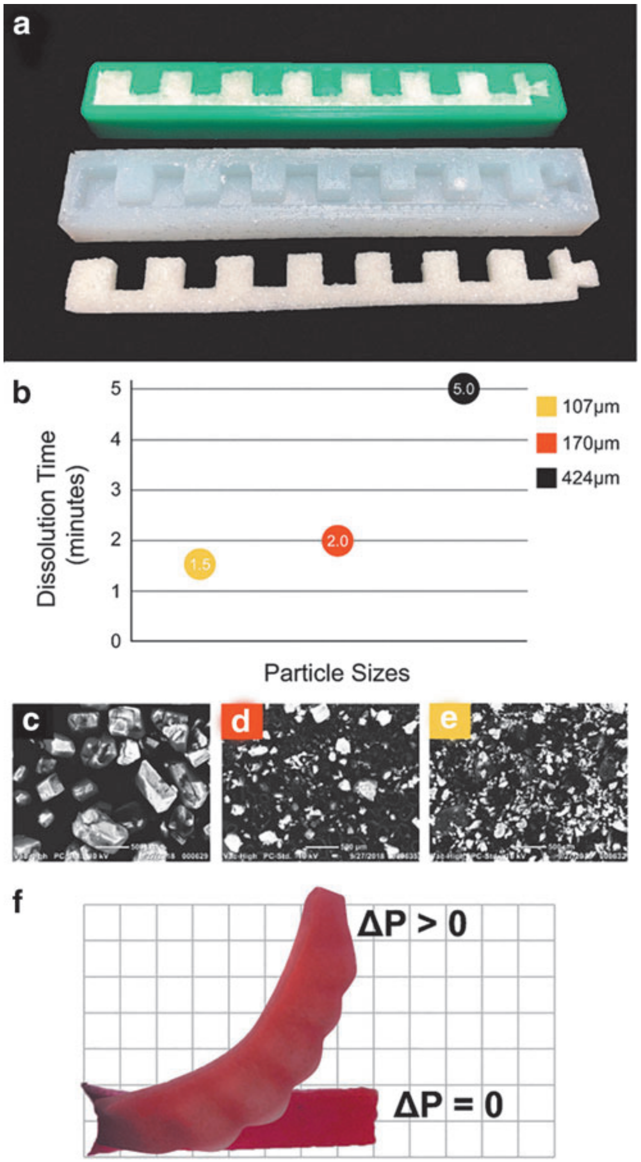

FIG. 6. Data relating to fabrication of edible SIAs. **(a)** Iteration of packed sugar inserts, first using a rigid mold and then transitioning to a flexible silicone mold. **(b)** A plot of average particulate size versus dissolution rate showing that smaller particles dissolve faster. **(c–e)** SEM images of sugar crystals of various particulate sizes taken on a JCM-5000 NeoScope™ electron microscope. **(f)** An actuation demonstration of an edible actuator, showing how cell inflation during pressurization causes a bending motion.

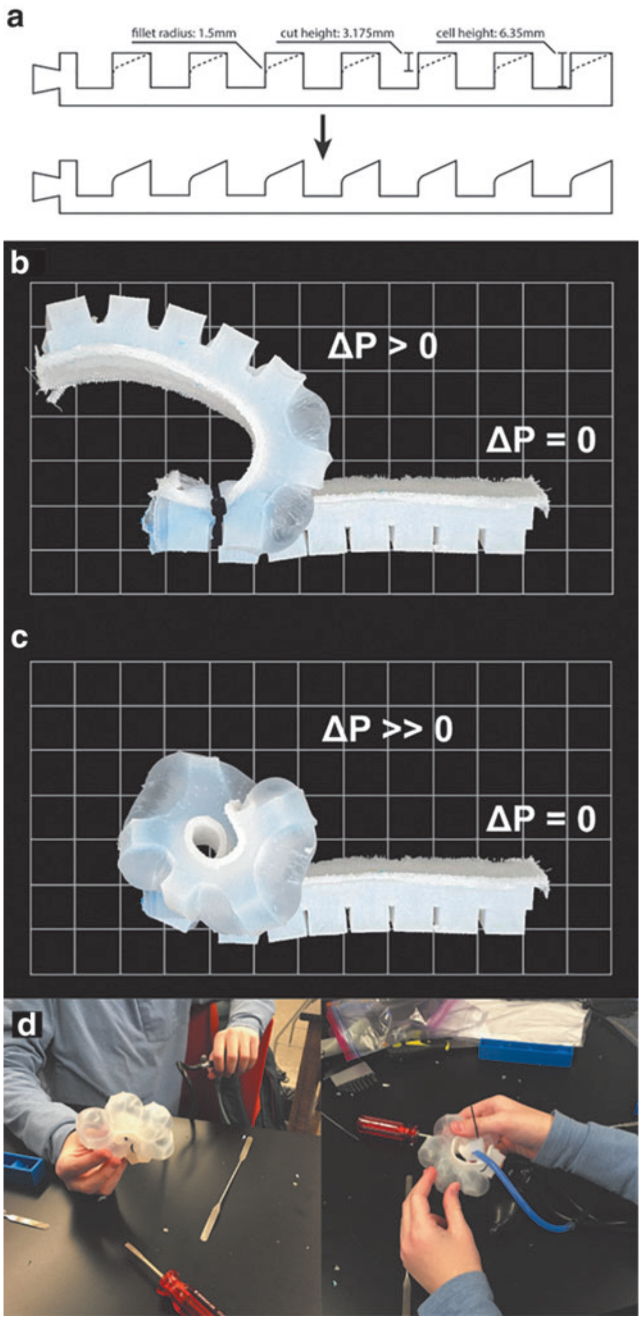

FIG. 7. Classroom implementation of RIAs. **(a)** Modification to insert for use in RIAs included sloping and rounding cells for ease of removal. **(b)** Silicone (Ecoflex 00-50) RIA under low pressure output (~50 psi). **(c)** Silicone RIA actuated to high pressure (115 psi). RIAs, removable insert actuators.

classroom exploration, soluble inserts allow for future exploration of more complex geometries and bending modes.

Actuator-assisted pottery

Many soft robotic devices include wearable mechanical assistance devices for impaired individuals.[18–20] To assess the applicability of SIAs, a test was performed assisting a student's hand while throwing a clay pot (Fig. 8). A use case

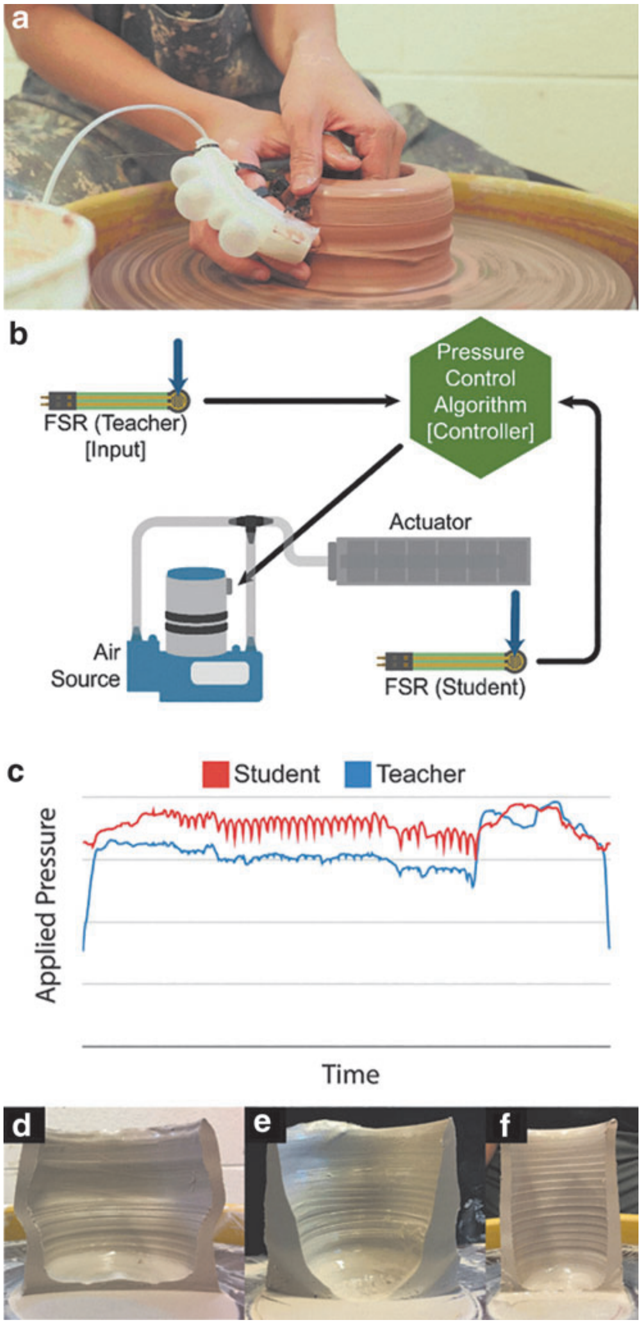

FIG. 8. Testing the applicability of SIAs in a teaching environment. **(a)** A student throwing a clay pot with robotic assistance. **(b)** A flow chart showing the process by which a teacher's motion influences a student's hand. Pressure applied to a FSR attached to the teacher's hand is measured and inputted into a control loop that matches pressure output by the student. **(c)** Data representing the pressure applied by the teacher and resultant pressure outputted by the student actuator. **(d–f)** Sample pots produced by an unassisted student, student assisted by an actuator, and a teacher, respectively. Internal walls and height notwithstanding, the actuator paralleled the motion of the teacher to make a straight outer wall. FSR, force-sensitive resistor.

involving the nuanced motions of the hand, similar to that in Mosadegh *et al.*,[7] was implemented to assess the precision of control that can be achieved by SIAs. A fluidic control board[21] was utilized to control actuator pressure, alongside a custom control algorithm. The physical pressure applied by a ceramics teacher was read through a force sensor (Adafruit, New York City, NY). These data were then converted to an actuator pressure that could be outputted through the fluidic control board. Lastly, the pressure data were run through a closed loop that monitored pressure applied via the actuator through the student and updated it according to teacher input. The result of this system was an actuator able to approximately parallel the motion of a teacher's finger while throwing a pot. Further study is necessary to achieve a closer match between absolute pressure values applied to the pot by a teacher and student through calibration of the instrument, sensors, and protocol. Consideration of variables such as teacher–student pair, rotation speed, clay temperature, and stiffness can improve the feedback loop through a more thorough calibration in future study. The qualitative differences between unassisted (Fig. 8d) and assisted (Fig. 8e) student performance are apparent in the verticality of pot walls in, when compared with the teacher's pot (Fig. 8f). Inner wall straightness involves thumb pressure and was, therefore, not considered for this application. This initial test served to demonstrate the future applicability of SIAs in rigorous environments.

Conclusions and Discussion

This research demonstrates the design of a novel fabrication process for soft robotic actuators using soluble inserts. Soluble materials can be molded into a variety of desired pneumatic network shapes and embedded into an actuator. Insoluble materials were shown to create simple demonstrations in K-12 classrooms. The independence of the insert from the base mold allows for interchangeable designs without reprinting the base mold. The ease of fabrication and customizability inherent to this new design lend themselves to numerous future applications, including more varied or intricate actuator motion by changing insert geometry. The creation of SIAs and RIAs achieved the goals of accessibility through simplicity and greater robustness through use of materials. Future endeavors may include the addition of a more robust valve mechanism, experiments with different flexible materials, or the integration into more complex robotic systems. This study coauthored by high school students also challenges convention that reserves innovation and research for graduate level scientists and engineers. This study shows that given time, space, and resources, young students can contribute to the field in unique and novel ways.

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Author Disclosure Statement

No competing financial interests exist.

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Supplementary Material

Supplementary Data

References

1. Soft Robotics Inc. www.softroboticsinc.com (accessed May 4, 2020).
2. Roche ET, Horvath MA, Wamala I, *et al.* Soft robotic sleeve supports heart function. Sci Transl Med 2017;9: eaaf3925.
3. Holland DP, Berndt S, Herman M, *et al.* Growing the soft robotics community through knowledge-sharing initiatives. Soft Robot 2018;5:119–121.
4. Zhang J, Jackson A, Mentzer N, *et al.* A modular, reconfigurable mold for a soft robotic gripper design activity. Front Robot AI 2017;4:46.
5. Pneunets Actuator. https://softroboticstoolkit.com/book/pneunets-bending-actuator (accessed May 4, 2020).
6. Holland DP, Park EJ, Polygerinos P, *et al.* The soft robotics toolkit: Shared resources for research and design. Soft Robot 2014;3:224–230.
7. Mosadegh B, Polygerinos P, Keplinger C, *et al.* Pneumatic networks for soft robotics that actuate rapidly. Adv Func Mater 2014;24:2163–2170.
8. Tolley MT, Shepherd RF, Mosadegh B, *et al.* A resilient, untethered soft robot. Soft Robot 2014;1:213–223.
9. Onal CD, Rus D. A modular approach to soft robots. In: 2012 4th IEEE RAS EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob) (Roma). 2012:1038–1045.
10. Martinez RV, Fish CR, Chen X, *et al.* Elastomeric origami: programmable paper-elastomer composites as pneumatic actuators. Adv Funct Mater 2012;22:1376–1384.
11. Polygerinos P, Wang Z, Overvelde JTB, *et al.* Modeling of soft fiber-reinforced bending actuators. IEEE Trans Robot 2015;31:778–789.
12. Zhao H, Li Y, Elsamadisi A, *et al.* Scalable manufacturing of high force wearable soft actuators. Extreme Mech Lett 2015;3(Suppl. C):89–104.
13. Schumacher CM, Loepfe M, Fuhrer R, *et al.* 3D printed lost-wax casted soft silicone monoblocks enable heart-inspired pumping by internal combustion. RSC Adv 2014; 4:16039–16042.
14. Marchese AD. Design, Fabrication, and Control of Soft Robots with Fluidic Elastomer Actuators. Ph.D. thesis, Massachusetts Institute of Technology, 2015.
15. Shintake J, Sonar H, Piskarev E, *et al.* Soft pneumatic gelatin actuator for edible robotics. In: 2017 IEEE/RSJ

International Conference on Intelligent Robots and Systems (IROS), Vancouver, Canada. IEEE, 2017:6221–6226.

16. Sardesai A, Segel X, Baumholtz M, *et al.* Design and characterization of edible soft robotic candy actuators. MRS Adv 2018;1:1–7.
17. Argiolas A, Mac Murray BC, Van Meerbeek I, *et al.* Sculpting soft machines. Soft Robot 2016;3:101–108.
18. Polygerinos P, Lyne S, Wang Z, *et al.* Towards a soft pneumatic glove for hand rehabilitation. In: 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Tokyo, Japan. IEEE, 2013:1512–1517.
19. Walsh C. Human-in-the-loop development of soft wearable robots. Nat Rev Mater 2018;3:78–80.
20. Polygerinos P, Galloway KC, Savage E, *et al.* Soft robotic glove for hand rehabilitation and task specific training. In: 2015 IEEE international conference on robotics and automation (ICRA), Seattle, WA, USA. IEEE, 2015:2913–2919.
21. Fluidic Control Board. https://softroboticstoolkit.com/book/control-board (accessed May 4, 2020).

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