Siloseam: A Morphogenetic Workflow for the Design and Fabrication of Inflatable Silicone Bladders

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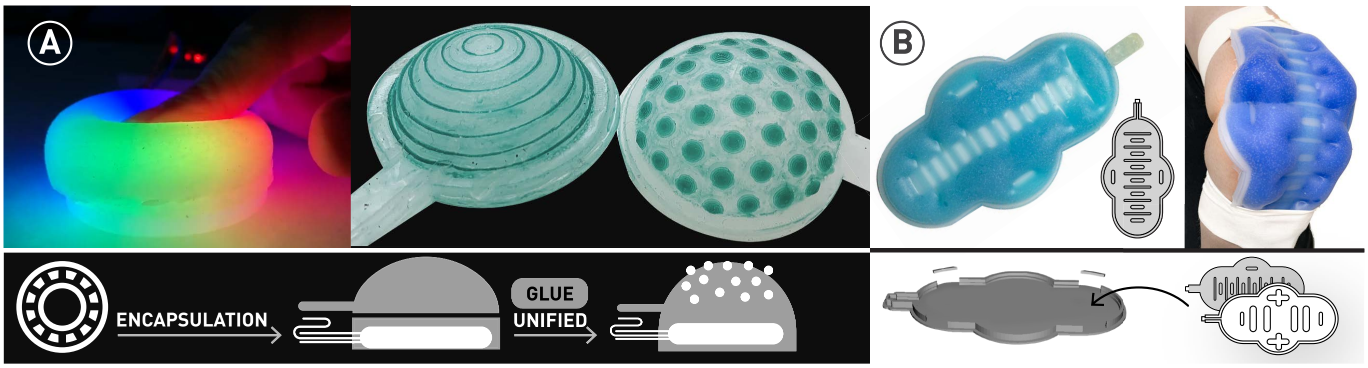

Figure 1. A) An LED ring and capacitive touch electrode are encapsulated in silicone to form an illuminated button. Different textured bladders are used to probe different haptic sensations and later integrated with the electronics using silicone as a glue. Air pressure controls the softness of the inflated bladder. B) A single mold is used to fabricate two bladders with different internal multi-chamber designs. When filled with a gel, the bladder serves as a hot pack, delivering heat to targeted areas of the body.

ABSTRACT
Silicone is a transformative design material found within a variety of emerging HCI practices including shape-changing interfaces, soft robotics, and wearables. However, workflows for designing and fabricating silicone forms require a time-intensive mold-cast-cure pipeline that limits the experiential knowledge that can be gained from working directly with silicone. In this work, we conduct a material-centric exploration of silicone and develop designerly workflows for creating inflatable silicone bladders. We present Siloseam, a creative framework that streamlines a bladder design and fabrication process, collects tacit knowledge involved in recovering from errors, and introduces new workflows that reuse existing molds. A set of exemplar artifacts demonstrates an expanded repertoire of silicone forms that leverage various configurations of airtight seams to create playful, haptic interactions. We discuss the remaining challenges in integrating silicone with a broader range of materials and opportunities for developing designerly workflows for other mold-and-cast processes.

Author Keywords
Craft; Materials; Computational Design; Wearables

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CCS Concepts
•Applied computing → **Media arts; •Human-centered computing** → *Interactive systems and tools;* Systems and tools for interaction design;

INTRODUCTION
Silicone rubber is a versatile material found in the design of heat-resistant and anti-stick instruments, expressive textured and graspable surfaces, and in the burgeoning field of soft robotics [21]. Recent advances in material science have developed a diverse repertoire of form-giving techniques that leverage silicone’s mold-cast-and-cure fabrication workflow to achieve reliable and replicable results. Despite the range of techniques, silicone’s presence in modern makerspaces and creative practices is limited. One explanation is the massive time investment in mold making and the large cost associated with refining, redesigning, and refabricating silicone forms. Especially in the cases where molds are 3D modeled, interactions with silicone in its liquid (and formable) state are confined to the brief period that it takes to mix and pour, or its *pot state*. With such a brief interaction period, both a maker’s ability to refine their mental model of silicone and their ability to engage in a reflective design practice is limited. *How might a silicone workflow communicate potential directions of the material, encourage deviation and exploration, and support shifts in design intention?*

In this paper, we draw from Ingold’s morphogenetic model of making [12] to guide the development of a creative design and fabrication workflow for *silicone bladders*, a fundamental building block of soft robotic and shape-changing interfaces.

Bladders refer to airtight, inflatable structures typically made of silicone rubber, mylar, or plastic. Such bladders are used in a variety of applications including balloons, condoms, shoe insoles [19], pneumatic actuators [27, 4, 1], artificial muscles, and in advanced mold composite manufacturing for creating geometries like bats, wing turbines, and oars [6, 21]. Bladder designs vary from single-chamber to hundred-chamber designs with multiple air channel interconnects [19]. Although broadly used, unified silicone design guidelines and fabrication methods remain a tacit practice [21].

We present the results of a material-driven exploration as a framework that can be leveraged by designers to create, iterate, and develop inflatable silicone bladders. This work builds on existing initiatives within the HCI community to provide designers access to advanced material, design and fabrication methods (e.g., soft composites [27], smart composites [13], electroactive polymers (EAP) [9], thermoreactive composites [24]). Our framework Siloseam[1] contributes:

- Design guidelines for navigating the affordances and resistances of silicone in bladder geometries, including a typology of common errors and ways to recover from them (Figure 5).
- A design tool to procedurally generate bladder designs from SVG files coupled with fabrication optimizations that leverage a tack curing schedule to fabricate bladders in under 5 minutes and test within 20 minutes (Figure 4).
- An iterative separator design routine that leverages vinyl or a water-soluble 3D-printed polyvinyl alcohol (PVA) separators to create complex *internal air channels* and *multi-chamber* bladder designs.
- A set of exemplar artifacts that demonstrate the generative potential of our creative framework including: a wearable necklace, a haptic notification wristband, tangible illuminated button (Figure 1A), and a body-conforming ice pack.[2]

This paper first describes the space of silicone fabrication techniques and material-centric design tools. We then describe our design process for developing our creative framework including a series of morphological experiments and a reflection on material, tool, and design frictions. Lastly, we present our exemplar artifacts and reflect on potential directions and challenges for silicone to be readily adopted in creative practices.

RELATED WORK

Creating inflatable, interactive artifacts has been explored by a variety of communities, including computer graphics, human-computer interaction, soft robotics, design research, the professional and fine arts, as well as Do-It-Yourself (DIY) practitioners. We review both design methods and fabrication techniques used by these communities of practice and map them to a workflow diagram depicted in Figure 2. We specifically detail silicone-specific processes and artifacts.

[1]Siloseam is a portmanteau of *siloxane*, a building block of polymer chains that make up silicone, and *seam*, a textiles term referring to the connection formed from sewing two pieces of fabric together.

[2]The Siloseam design tool, characterization experiments, and exemplar design files have been made available online: https://github.com/The-Hybrid-Atelier/siloseam

Silicone Formgiving Techniques

Silicone is a type of rubber that exists in a liquid or gel state that must then be vulcanized or cured (to harden the polymer) before it assumes a target form. As a stretchable, resilient, and skin-safe material, silicone is commonly used in medical applications and soft robotics. Schmitt et al. described a collection of techniques developed for such applications including compositing silicone with shape-changing conductive layer to make artificial muscles, through traditional mold and casting processes, reinforcement with mechanical joints, and via additive manufacturing of flexible materials; despite the varied techniques that have emerged, there is an overall lack of design guidelines for manufacturing [21].

The silicone curing process can be accelerated using a catalyst, but the full pipeline (from designing and printing a mold and curing the silicone) is a time-intensive process (about 4-24 hours). Metamolds [3] described one design-time optimization that uses computational design to create a two-part compression mold for complex geometries. Zoran demonstrated the utility of modular molds for exploring design variations of food composites [30]. Dip casting [26] – a technique commonly used for balloon, glove, and condom manufacturing – is an alternative to molding that submerges a mandrel in uncured silicone rubber and leaves no parting lines yet requires multiple coats and is better suited for thin-wall geometries.

Bladders are the fundamental building block for many inflatable forms. In the DIY community, plastic welding, or the fusion of two sheets of plastic with a hot iron is relatively common. MilliMorph [16] demonstrated a variant of this technique as part of a CNC heat sealing platform for fabricating thin film bladders at the microfabrication scale. A growing and refined set of computational techniques decompose 3D forms into flat plastic panels that can be welded into complex and interesting forms in plastic film balloons [10] and inflatables [22]. Popular DIY soft robotics repositories (The Soft Robotics Toolkit [11]) and tutorials (the Glaucus [1] and Robo Tentacle [4]) leverage a two-part mold and jeweler's wax to create air cavities (i.e., using a lost-wax process); other separation materials include polyethylene sheets [17], acetate [11], or 3D printed pipes [20]. Some techniques modify silicone after the curing process. MetaSilicone [28] introduced a technique for specifying macroscopic mechanical properties by injecting spheres into a silicone matrix. Testing and pneumatic control is largely derived from custom electronics[11], however a variety of DIY pneumatics controls have emerged included syringes [14] and integrated valve/inflation bulbs (commonly found in blood pressure monitoring cuffs) [4].

Similar to our work, PneUI [27] presented a soft composite framework to communicate to HCI designers and researchers the design potential of inflatable user interfaces. PneUI focused on the interaction between structural and functional layers (e.g., conductive fabric); our work instead builds off DIY techniques that focus on refining the structural silicone layer through more accessible design and fabrication workflows that foreground tacit knowledge.

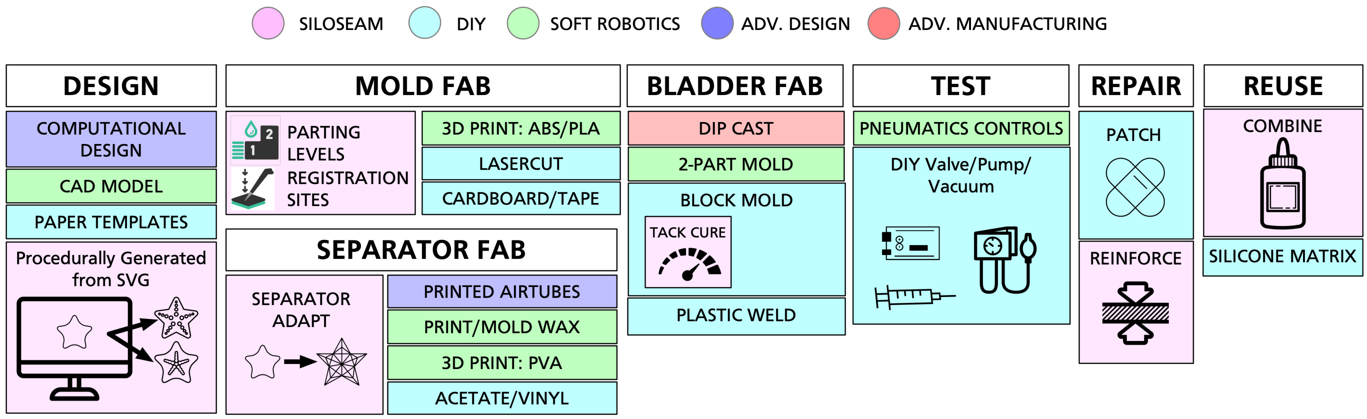


Figure 2. Diagram of how different Communities of Practices design and fabricate bladders. With Siloseam, we introduce both design and fabrication optimizations and methods of recombining, reusing, and repairing prototypes to support additional iteration cycles.

Electronic Composites and User Interfaces

As electrically non-conductive, silicone serves as an ideal insulator and is commonly used to encapsulate flexible electronics affording new opportunities for wearables and medical devices. Silicone Devices [18] introduced one such fabrication technique for stretchable circuit design using PDMS silicone and conductive PEDOT:PSS that could be integrated with complex surfaces. Bubble [29] demonstrated the potential for interactive wearable applications to assist users in gripping objects. Our work focuses on exploring the design dimensions of the silicone bladder in its own right, and discuss how a robust bladder design and fabrication workflow can support additional design ideation and adoption of soft wearables and electronic composites.

Silicone in Art and Design

Silicone's stretchability, transparency, and support for thin-wall geometries offer opportunities for design which many materials lack. Coupled with its skin safety, fashion designers such as Iris Van Herpen [25] fabricated fabric-like sheets of silicone to form her Seijaku dress collection using the trapped air bubbles from the curing process as an aesthetic dimension. Silicone has seen widespread adoption in the special effects and costume industry, largely using cast molds or a brush-on technique to shape hyperrealistic prosthetics or skin textures [7]. In contrast to fabrication workflows heavily-seated within advanced manufacturing communities, Siloseam contributes a designerly workflow that can offer designer's expanded access to explore silicone forms and affordances.

WORKFLOW DESIGN PRINCIPLES

To guide our workflow design, we draw from Ingold's *morphogenetic model of making* or the form-generating process where designs evolve from interactions with materials, tools, and the environment. Our goal is not to produce a design tool or fabrication technique that divorces the maker from interacting with the material, but instead to provide a framework for understanding silicone's potential to take on new forms.

Our process begins with a formative evaluation of common silicone bladder fabrication techniques reflecting on silicone's material affordances and resistances. From our formative investigation, we explore the bladder as a fabrication *primitive* – a fast, robust, and versatile building block that can be layered with more advanced techniques. We conduct systematic experiments on the primitive bladder's morphological dimensions, or aspects of a bladder's form and structure (i.e., seam allowance, layer thickness, aspect ratio). The final Siloseam framework collects our material encounters with silicone and synthesizes a streamlined design and fabrication workflow (Figure 4) and delineates *material potentials* - a term we use to describe directions to push designs into novel forms. A set of exemplars artifacts is then used to annotate this space.

Figure 3. Materials, tools, and equipment used in bladder fabrication and testing. From bottom left, clockwise, moving inward: A water bottle, nitrile gloves, air tube, EcoFlex-50 silicone, isopropyl alcohol, an infrared heat gun, vinyl, polyvinyl acetate, a inflation bulb with valve, a syringe, a scale, glass rods, metal spatulas, molds, tweezers, antistatic weigh boats, silicone colorant, barbed airtube connectors. Not pictured: an FDM 3D printer, an incubator, and vinyl cutter.

FORMATIVE EVALUATION

To better understand the challenges involved in silicone fabrication techniques, we followed three tutorials published in the open-source Soft Robotics Toolkit [11]: a hybrid textile-silicone sensor, a soft gripper, and a soft robotics actuator. We kept a regular diary of our experience, transcribing frictions and ambiguities in the fabrication process; we noted the following affordances and resistances:

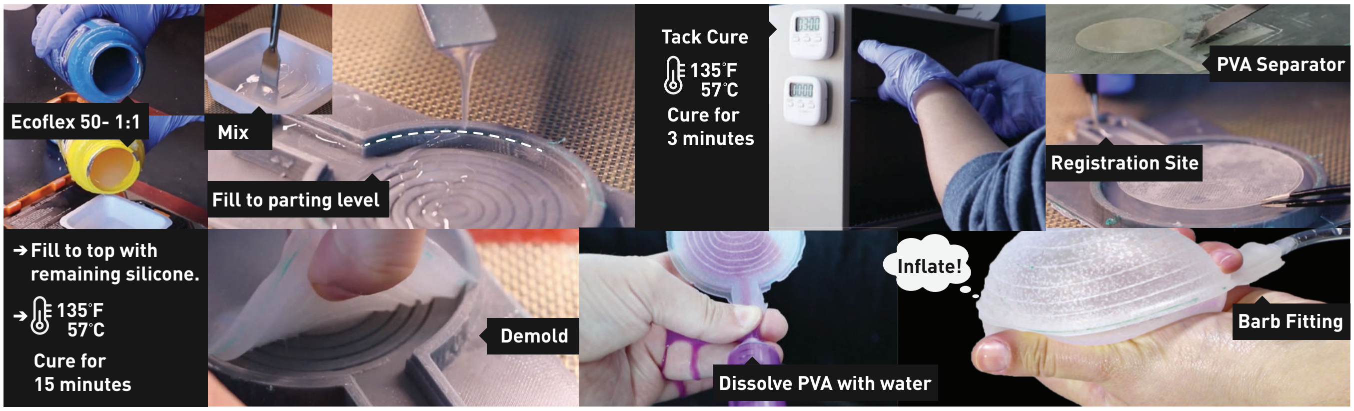


Figure 4. Bladder Fabrication Process. A single batch of silicone is prepared to fill a mold up to the parting level and speed cured to a tack state. A 3D-printed PVA seperator is laid on the base layer, using a registration site to help anchor and align the element. The remaining silicone is poured and speed cured. Once demolded, the bladder is injected with warm water to dissolve the PVA and the resulting bladder is inflated.

- **Material properties** - Silicone's non-stick properties make it a particularly forgiving material for demolding; conversely, designs that integrate silicone with other materials rely on mechanical joints versus adhesion. These tutorials leveraged this property to create air pockets by encapsulating a host of different materials (acetate, ABS/PLA, PVA), which could then be removed post-cure to leave a hollow cavity. In its pot stage, silicone was particularly viscous, requiring the need to spatula the substance to fill corners; this was more problematic for large planar geometries. As a rubber, silicone is particularly well-suited for airtight applications, especially as a gasket material; however, simply using barbed and Luer fittings still resulted in air tube leaks.
- **Cost and sustainability** - The fabrication process was time-intensive taking on average two days to complete. This was largely complicated by long cure and post-processing times. Prototypes remained untestable until fully cured and failed prototypes were not reusable or repairable, nor were overestimations of mixed silicone.
- **Workability** - The process was overall messy; despite gloves, a dedicated station, and care, uncured silicone managed to find its way into unintended locations. This was largely a result of the large amounts of pouring, weighing, and mixing inherent in preparing the silicone, further exacerbated by the multiple mixing instances required.

Base Primitive - Bladder Fabrication

From our formative evaluation, we observed that a simple bladder fabrication procedure has the following general steps depicted in part in Figure 4:

1. Pour a base layer of silicone in a mold; allow to cure.
2. Place a separator material on the base layer. The separator could be anything that does not stick to silicone (e.g., acetate, vinyl, wax, and PLA/ABS elements) and does not inhibit curing (e.g., wood, resin).
3. Pour a sealing layer of silicone; allow to cure.

Since the bladders require at least two cured layers, it requires at least two iterations of the mix-cast-cure silicone process; each iteration takes the full cure time of the silicone system, typically a couple of hours. These bladders are then connected to an air source using a barbed connector (McMaster-Carr 6463K118) and routed with flexible, plastic air tubes.

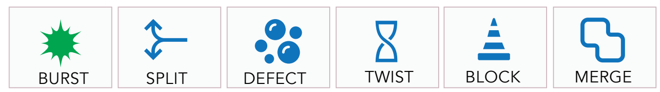


Figure 5. Bladder Fabrication Error Typology.

Error Typology

Despite having the appropriate materials, tools, and equipment (Figure 3), each fabricated form failed due to a variety of fabrication reasons which we detail in our error typology. To present a more complete typology, we also include the additional 70 bladders that were designed and fabricated during the course of this work. To assist with bladder design terms (in *italics*), Figure 7 depicts the anatomy of a bladder. The errors encountered and their recovery mechanisms include:

- BURST - Bursts represent the natural result of pushing silicone to its maximum stretch limit, or % elongation at break (ε) (Table 1). Navigating this error is largely a matter of selecting a more stretchable silicone or constraining the maximum volume of the form. The limiting factor for determining when a bladder will burst is the smallest cross-section of the bladder geometry.
- SPLIT - Seam splits, or the separation of two layers of silicone, occurs when silicone layers are too thin or when a fully cured silicone layer prohibits complete fusion with its proximal layer. This error is alleviated by fusing layers when they are in their tack stage (not fully cured, but sticky) or by increasing layer thickness.
- DEFECT - Defects were the most common error largely resulting from air bubbles that arose after the silicone was set to cure. While this is mitigated by degassing the silicone or carefully pouring and popping bubbles, we found DIY tutorials [4] that simply *patched* holes with additional silicone, often leveraging silicones with quick cure times (e.g., Ecoflex 00-35 Fast). This also served a prudent recovery mechanism for other defects including separators becoming dislodged and misaligned in the overall silicone body. Flat, connected separator designs coupled with a longer base cure time aided with preventing misalignment defects.
- TWIST - Some inflation behaviors cause mechanical torque, similar to those one might see in balloon animal construction. This is alleviated by purposefully designing the bladder to not have any detached elements (designing in *shared*

seams, or two or more chambers that share a seam boundary) or holding the bladder in place with a mechanical constraint.

- BLOCK - Some separators cannot be removed from the bladder (e.g., vinyl, ABS) that can potentially block internal air channels and prevent airflow to different chambers when inflated. Using a removable separator like water-soluble PVA or meltable wax mitigates this issue, albeit with additional post-processing steps.
- MERGE - Designs with multiple chambers have shared seams which alter the number of forces acting on what would otherwise be a robust seam. Shared seams are subject to split, but because they are internally confined, the corresponding air chambers merge together. This issue is more profound for *inset seams*, or seams that are surrounded by an air chamber on all sides and consequently receive forces from all sides. Seam merges can be prevented by imposing an expansion limit or reinforcing the seam through thicker layer geometries.

Refining the Base Primitive

In the following sections, we describe a set of experiments to better characterize a basic silicone bladder and the effect of different morphological design decisions (e.g., size, shape, thickness) on bladder performance. Our iterations through this process allowed us to streamline the fabrication process and reduce silicone bladder fabrication times to 5 minutes (20 minutes before testable). For designers and makers interested in building an accurate mental model of silicone behaviors, these sections detail experiments that help clarify different design dimensions.

We first describe optimizations to the mold design process, our characterization routine, proceeded by the set of characterization experiments on bladder design and separator design. Following our characterization experiments, we reflect on the tacit knowledge gained through trial and error as well as workflow adjustments that allow for a more iterative and exploratory design cycle.

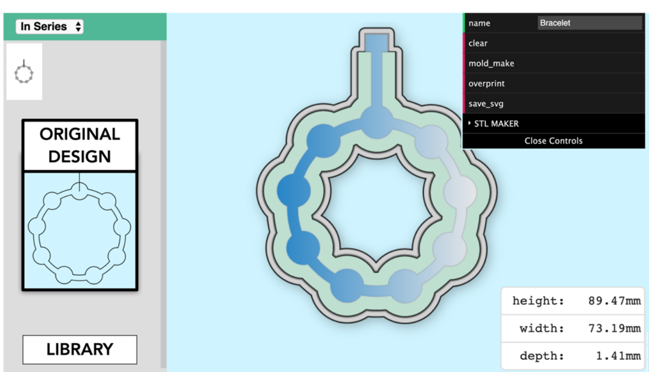


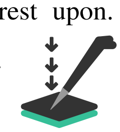
Figure 6. Design tool for silicone bladders. Given an SVG input, the separator and mold designs are procedurally generated.

Mold Design

The molds used in this work were initially hand-designed from a scalable vector graphics (SVG) file and extruded into a 2.5D model using a commodity CAD program. All molds are designed as one-piece block molds with no undercut or overhang geometries to improve the demolding process. The molds are fused deposition modeling (FDM)-printed in ABS with a 0.2 mm layer height[3]. To maximize quality and reduce post-processing time, the mold base was oriented coplanar with printbed, limiting geometries to the printbed size ($\approx$ 200 mm x 200 mm). From this workflow, we automated the path manipulation instruction using `paper.js`[4]. The routine first resolves all specified paths to their corresponding real-world geometries (e.g., a line representing an air tube is converting into a rectangle with the dimensions of an air tube). It then unites the resulting paths to form the *separator geometry*. This geometry is then offset twice: once to provide a seam for the bladder construction, and again to build a mold wall for the casting process. Both the seam allowance (distance from the separator to the outside edge of the bladder) and the layer thickness are exposed as parameters to the user.

As an optimization, we streamline the fabrication process by introducing the following geometries: A 1 mm-wide **parting level** is introduced at the boundary of the base and sealing layer to indicate when enough silicone has been poured. The excess material (flash) can easily be cut without compromising the integrity of the bladder.

The separator is extended outside the inlet location and provided a platform, or **registration site**, to rest upon. Since the rest of the separator is suspended in the bladder, this platform allows the maker to register the location of the separator with a set of tweezers to be docked and properly positioned.



Characterization Procedure - Testing Rig

To assess the fabrication quality and bladder integrity, each fabricated bladder was systematically inflated and videographed until rupture. Our testing rig included a regulated air compressor set to 20 PSI, 1/8" inner diameter silicone air tubing, barbed fittings for the bladder-to-tube connections, and a quick-connect accessory for tube-to-tube connections. Bladders were filmed from above with an overhead camera (50 mm f, 22.3 x 14.9 mm sensor size, 50 cm from the surface). From the resulting video, we computed the diameter of the inflated bladder using the pinhole projection formula and kept a detailed log describing observed defects, rupture characteristics, and fabrication errors. From these parameters, we informally calculate the **% elongation at break**[5] by using the diameter of the bladder (adjusting for the seam width) at the time of burst.

$$\% \text{ Elongation at break} = \varepsilon = \frac{B}{b} \times 100 \qquad (1)$$

Elongation (ε) is calculated as the inflated hemispheric circumference B over the initial diameter b. Table 1 provides

[3]Mold resolution can be improved with SLA printing techniques, however additional post-processing steps are needed to ensure proper curing of platinum-cure silicone [2].

[4]https://github.com/The-Hybrid-Atelier/siloseam

[5]% elongation at break (ε) elongates material samples with the smallest possible cross-section in a single direction until rupture. Although forces from air pressure are applied uniformly in all direction in bladders, we expect to see larger ε values since the geometries we evaluate have larger cross-sections (defined by layer thickness) than a standardized ε characterization.

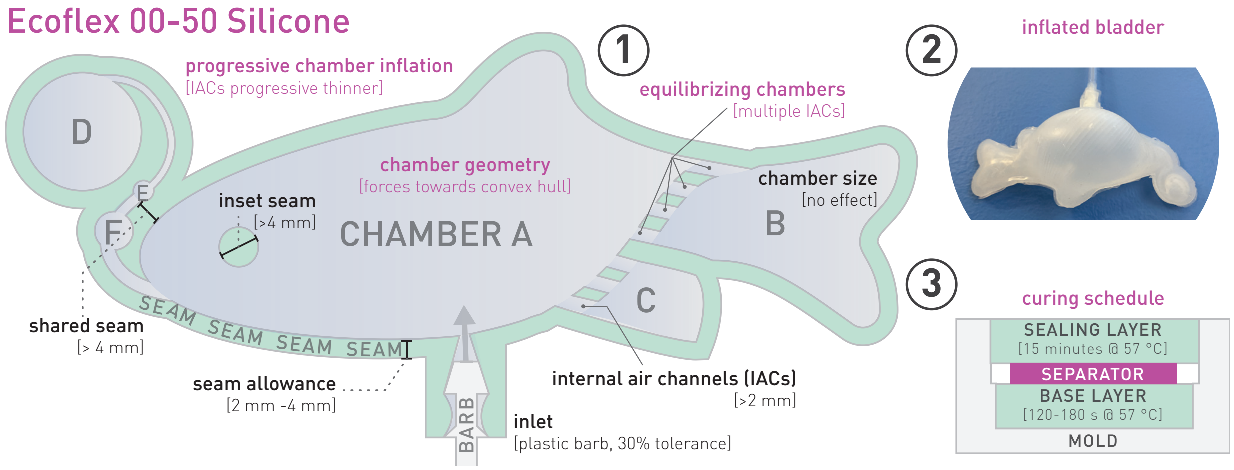


Figure 7. Bladder Design Guidelines for Ecoflex 00-50. 1) Anatomy of a bladdder, 2) the bladder inflated, 3) the optimal curing schedule and layer and composition of the bladder.

Silicone System	Pot Life	Full Cure@ 23°C	Speed Cure @ 57°C	ε
Ecoflex 00-35F	2.5 min	N/A	5 min	9.0
Ecoflex 00-50	18 min	3 hr	17 min	9.8
TAP Plastics	15-18 min	2 hr	11 min	2.8

Table 1. Platinum-cure silicone rubber systems

manufacturer-reported elongation (ε) for each silicone system as well as other relevant material datasheet values.

BLADDER DESIGN

Several design considerations affect a bladder's robustness, space of possible forms, and fabrication complexity. The *seam strength*, or the bond between silicone layers is influenced by the curing schedule (how long and at what conditions the layers were allowed to fuse), the amount of material present at the seam, and the overall geometries of the air chamber. We describe a set of experiments to determine the creative and functional boundaries of bladders with each experiment spanning a morphological space. To increase internal validity, these experiments use a common well design where a single block mold has multiple geometries for creating several bladders at once[6].

Experiment 1: Curing Schedule

Since bladder construction requires two separate curing phases, curing times represent the main bottleneck for rapid prototyping of bladders. One solution is to *speed cure* by introducing a catalyst or changing environmental conditions. Many silicone formulas already include a platinum catalyst that reduces cure time to around 2-3 hours, however a common technique is to cure above room temperature (Table 1). Although this method has a proclivity for introducing air bubbles, the results remain largely functional. Specialty Resin Chemical [5] reported that every 10 degrees above 21°C (70°F) can reduce the cure time by half. The accelerated cure time t_A can be calculated as:

$$t_A = t_C \times \frac{1}{2}^{(T_A - 21)/10} \qquad (2)$$

[6]Characterization molds are included in the supplemental materials

where t_C is the normative curing time at room temperature and T_A is the accelerated cure temperature. To reduce the overall curing schedule to under 20 minutes, we chose a curing temperature T_C of 57°C (135°F); respective speed cure times for different silicone systems are shown in Table 1.

In our formative exploration, we found that fully curing the base and sealing layer prevented a strong seam from forming, with the seam rupturing at layer divisions. Instead, we fused layers when the base layer was in a tack stage (sticky to the touch) to promote both better fusion and increase the surface tension to support a separator layer.

Setup To determine the optimal curing schedule, we investigated three different silicone systems (Table 1) as follows: For each silicone system, we created a set of five 30 mm⌀ circular bladders with an 4 mm seam allowance, a vinyl separator, and equal layer thicknesses (2 mm). The bladders were speed cured at @ 57°C, varying the base layer cure time (90 seconds - 210 seconds, @ 30 s intervals) and a sealing layer cure time of 15 minutes. As a control, a bladder was fabricated with the full cure at room temperature. This setup was selected to allow us to visually inspect seam behaviors and control other bladder design variables.

Results Speed curing the base layer to a tack stage produced comparable results to full cure schedules, improved seam strength, and reduced overall fabrication time from 6 hours down to 20 minutes.

For all 00-50 bladders, we achieved average values of $\varepsilon = 11.3 \pm 0.9$ in line with the optimal performance characteristics of 00-50 (ε = 9.8). The strongest seam (at ε =12.9) occurred at 120 s base cure time, compared to the full-cure condition (at $\varepsilon = 11.5$). For TAP bladders, fully curing the base layer did not allow for fusion with the sealing layer (SPLIT). However, at tack cure times, we found an average ε of 7.1 ± 0.8 indicating that a tack cure schedule is needed to reliably hold layers together. In comparison, TAP bladders were more transparent than EcoFlex bladders, but not as stretchable. For 00-35 bladders, the pot life (2.5 min) was too short for creating bladders.

Air bubbles, introduced during the mixing stage, were the most common failure condition from the fabrication process (at all curing schedules) (DEFECT). We navigated this error in future iterations by "patching" defects with 00-35 silicone. Additionally, placing the vinyl separator required careful dexterity in order to avoid an edge of the vinyl sinking into the base layer (DEFECT), although longer base cure times provided sufficient surface tension to reliably support the separator.

Speed curing the base layer to a tack stage (180 - 210 s @ 57°C) is important to achieve an optimal seam strength. 00-50 is the most reliable silicone system, whereas 00-35's limited pot life makes it an excellent candidate for patching errors.

Experiment 2: Seam Allowance

The *seam allowance*, or material between the inner chamber edge and the outer edge of a bladder, affects both the seam strength and provides a maker with a margin-of-error when laying down a separator between casted layers. In this experiment, we created a set of five bladders varying seam allowance (1 mm to 4 mm, sampled linearly). All other design variables were held constant: 30 mm⌀ circular geometry, a vinyl separator, equal layer thicknesses (2 mm for each layer), and a 120 s base/15 min seal cure schedule.

All bladders, regardless of seam allowance, held their seams ($\varepsilon = 11.8 \pm 2$). We found a more comfortable fabrication experience with bladders that had at least a 3 mm seam.

Experiment 3: Layer Thickness

Achieving a uniform layer thickness is difficult due to the high viscosity of many silicone systems. While a thinning agent can be added to aid with distributing silicone evenly for thin-wall geometries (< 1 mm), we found that thinning the silicone has an inverse effect on tensile strength. We elected to leave this as a bladder fabrication constraint (min. wall thickness = 1 mm). In this experiment, we surveyed the effect of all combinations of a set of thicknesses (1 mm, 2 mm, 3 mm) for the base and sealing layer thickness.

Results All bladders with 1 mm layer thicknesses failed. As seen in soft robotics literature, the bladders with uneven thicknesses expanded anisotropically, i.e., the thicker layer resisted expansion forces, causing only the thinner side to inflate and created a bending motion. This behavior is often used to create a motive force, such as in robot end effectors used to irregularly shaped objects.

Bladder wall thickness greater than 2 mm can be reliably fabricated using single-block molds. Using non-uniform thicknesses (different thickness for base and sealing layer) can be used to create shape-changing bladders or actuators.

Experiment 4: Bladder Geometry

Lastly, the bladder's geometry can affect both the seam length and cause uneven pressure distributions that can lead to ruptures. Even though multiple forms can be formed into a bladder, we focus on geometric features that can affect performance and fabricability, specifically:

- *Size/Seam Length* - Since the seam strength results indicate that good fusion occurs between the base and sealing layer, we hypothesize that bladder size (and by extension seam length) would not affect the fabrication process nor the bladder performance. To test, we used circular bladder geometries from 2 mm to 15 mm radii, sample linearly across bladder perimeter (i.e., seam length), and ran our performance evaluation.
- *Angles* - To determine the effects of bladder shape, we sampled both angle and aesthetic variations: a 5-point star (36°), an equilateral triangle (60°), and a square (90°), each with at most a 30 mm cross-section. We also tested each shape with a 3 mm rounded corner to assess whether bladders hold additional integrity when acute geometries are eliminated.
- *Aspect ratio* - Aspect ratio can constrain the expansion limits of a bladder as well as influence the ability to place and register a separator between the base and sealing layers during fabrication. We fabricated a set of 5 bladders with 1:1 to 1:5 aspect ratios with a minimum 20 mm cross-section.

Results As expected, the smallest cross-section limited the maximum expansion of the different bladders. Assuming an elliptical cross-section during inflation, each bladder burst when the smallest cross-section expanded on average by $\varepsilon = 9.6 \pm 1.4$ times its initial length, corresponding with the manufacturer's reported $\varepsilon = 9.8$. Round corners versus sharp corners did not affect bladder performance, but the star geometry seams moved towards the convex hull of the shape.

The smallest cross-section of a bladder geometry is a good indicator of the bladder's expansion constraints. While a bladder can have intricate geometries, pressure forces within the bladder will ultimately equilibrate when the bladder approaches the convex hull of the initial bladder shape.

SEPARATOR DESIGN

The separator allows a cavity to be formed between silicone layers, which can then be filled with air, gel, or liquids. We explore the compatibility of different materials and rapid prototyping techniques to readily design chamber shapes, quantities, sizes, and interconnections (Figure 8).

Separator Material

Acetate. Acetate is a clear, transparent plastic used as a DIY separator material. It is often hand-cut and therefore prone to fabrication errors. Acetate cannot be removed from complex bladder designs unless it is excised and patched.

Vinyl. Vinyl is one of the most versatile separator materials. The fabrication process with a vinyl cutter is quick, accurate, and maker-friendly since multiple copies can be cut for batch-production or fabrication debugging. Since vinyl often comes in a roll, it is important to iron the vinyl flat to ensure the curved geometry does not cause a DEFECT during fabrication. We found that such vinyl separators could be suspended over the mold, aligned and anchored on the registration site, and lowered into the mold. Large complex geometries require the base layer to be fully cured and vinyl to be transferred using tape, which proved difficult since vinyl does not adhere well to silicone. Like acetate, vinyl remains in the bladder and can cause BLOCK errors. A vinyl separator works best for simple, single-chamber geometries.

PVA. PVA (Polyvinyl alcohol) is a water-soluble FDM-printable material. When printed at sub-millimeter thickness,

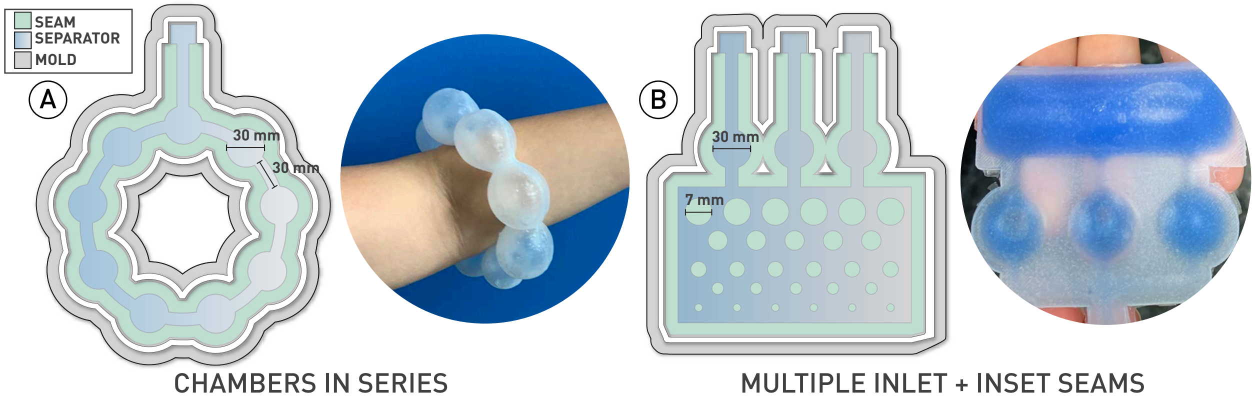


Figure 8. Separator Design Patterns. a) A nine-chamber bladder is connected with a single internal air channel; b) A three-chamber bladder is connected in parallel with a common sink chamber.

it serves as the most versatile separator. An additional post-processing step is required to remove the PVA from the bladder. PVA can be dissolved by injecting the fabricated bladder with water (2-3 hours) or accelerated by warming the bladder (30 minutes, 57 °C). PVA also affords the ability to create 3D cavities and can be further tuned for removability by using a sparse infill density. Since PVA is rigid, aligning and registering this separator in the mold is a simpler process.

Wax. Although not experimented with, wax is a common separator material but requires its own set of two-part molds to fabricate. When heated, the wax can be melted out of the bladder (lost-wax process) and be reused.

Incompatible materials Fabric is an excellent fusion material since silicone can embed itself through the weave of the thread. It can be used to bind and integrate silicone bladders into textile practices. Wood and resin are incompatible since they prohibit silicone from curing.

Air Channel Design

Internal air channels (IACs) affect how chambers inflate. Here we experimented with different routing configurations:

In Series. A set of nine 30 mm ⌀circle chambers were spaced in a ring structure with a 30 mm gap between each chamber; a single 3.5 mm IAC was routed in series to each air chamber(Figure 8A). During the inflation process, all chambers expanded almost equally from each other (the closest chamber to the air tube was last to inflate). When the design was modified in later designs to have unequal chamber sizes, we found that inflation would focus on the largest chamber (Figure 7); this could be corrected by increasing the IAC width to distribute pressure but requires fine-tuning.

In Parallel. In this design, a set of three 30 mm ⌀circular chambers were connected in parallel to a common chamber (Figure 8A). The figure shows an additional variant where the common bladder has a series of inset seams of different diameters (from 2 mm to 7 mm intervals), creating an effect similar to a button sewn into a seat cushion. Upon inflation, we encountered immediate MERGE errors with the inset seams; increasing the thickness of the bladder was one way we maneuvered this constraint. Parallel routing constructions suffered fewer effects from non-uniform air pressures.

MATERIAL POTENTIALS

To showcase the generative potential of the Siloseam framework, we describe and reflect on *material potentials*, or properties or behaviors we observed when working with silicone that point towards novel forms and interactions. We present a set of exemplars, positioned in the interactive wearable space, and describe how material potentials drove and evolved our design intention and their respective workflows (Figure 9).

Form Expressions

Internal Fill In our ice/heat pack artifact, we demonstrated how the internal properties of bladders could be altered by injecting functional materials (Figure 1B). When filled with a gel, a multi-chamber bladder can deliver targeted cooling or heat parts of the body from the different amount of gel (and heat capacity) held by each chamber. By filling the bladder before the point of expansion, the bladder is able to take on more complex internal geometries without compromising bladder integrity.

Pressure When connected to a pneumatic control system[7], our tangible light button was able to dynamically change its resistance to user presses by increasing or decreasing the air pressure within the bladder(Figure 1A). This playful interaction can be used to throttle user interaction, requiring the user to instead wait for actions to become available again or fight the interface to receive new input.

Textural Gradients Through informal interactions with users, we noted playful and sustained engagement with our initial prototypes, especially as users explored the haptic sensation of silicone expanding against their skin. We decided to fabricate a series of hemisphere-shaped bladders with different textures (spike, wave, and concentric circles) (Figure 1A). Textures were added to the mold design through 2.5D texture mapping, as implemented in HapticPrint [23]. The combination of texture and expansion created *textural gradients*, or haptic stimulation caused by the movement of tactile cues across the skin. We applied a colored silicone to texture geometries to highlight these haptic affordances.

Subdivision The ability to rapidly prototype separators allowed us to explore how different chamber designs could be

[7] https://www.programmableair.com/

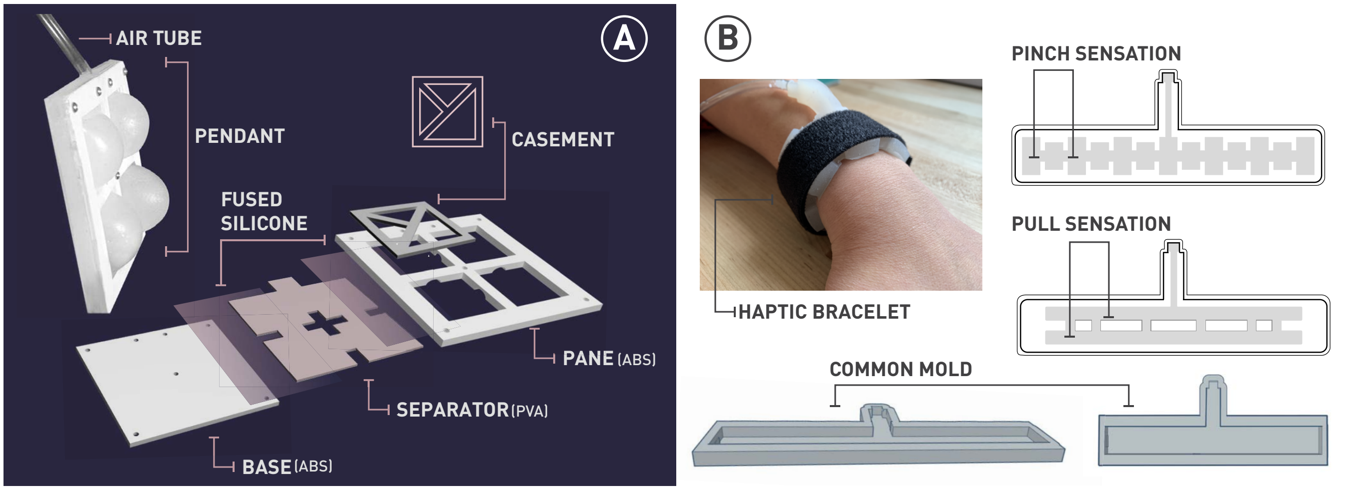


Figure 9. Silicone Bladder Exemplars: A) A mechanically-held seam necklace with interchangeable chamber designs, B) A bladder is fabricated from a common mold and used to prototype haptic sensations on the wrist.

used to control pinching, compression, and expansion sensations. In our haptic bracelet (Figure 9A), we used a single bladder geometry – a long, thin strip – that wraps around the wrist held against the skin with a hook-and-loop band. We found that subdividing the bladder along the strip increased the pinching sensations, whereas partitioning across the strip increased expansion or pulling sensations. While haptic perception is limited on the wrist, we see opportunities to add tactile cues to increase perceivability.

Workflows

Composition Workflow Combining silicone with other materials is difficult because of its non-stick properties. We did encounter that two different silicone geometries can be combined with uncured silicone as a glue. When combined with a fast curing silicone like Ecoflex 00-35F (5 min), the interaction mimics other cured adhesive workflows like when working with epoxies. Our goal when fabricating our tangible light button was to create a composite of an LED ring, a capacitive touch sensor, and silicone bladder (Figure 1B). Our workflow began by taking our electronics (8-LED NeoPixel Ring and MPR121 electrode) and encapsulating them in the base layer of our bladder fabrication primitive. Demolding this prototype, however, resulted in tears and other errors around thin-wall geometries. We decided to instead re-encapsulate the electronics on their own, allowing us to prototype different bladder geometries independent of the electronics. By resting and inflating bladder designs atop the encapsulated electronics, we were able to reflect on different bladder compositions without needing to reintegrate electronics. The resulting bladder was silicone-glued to the electronics layer, and a responsive touch interaction was programmed to alter light and pressure based on touch events detected by the captouch sensor. Notably, this workflow allowed us to separate electronics and bladder concerns and rapidly prototype different light behavior and haptic interactions.

Iterative Separator Workflow If the global geometry of a bladder remains the same, a mold does not need to be redesigned or reprinted. Removing the most time-intensive constraint of the process points to additional opportunities to increase the design complexity of internal geometries. Morphologies such as the number or configuration of chamber geometries or the routes, length, and widths of internal air channel routes, can be dialed in using rapid separator prototyping techniques (e.g., vinyl cutting) and refined with removable separator techniques (e.g., PVA). This motivated us to explore how different haptic sensations might be rapidly prototyped. In the design of our haptic bracelet (Figure 9A), we aimed to understand how different morphological dimensions map to haptic sensations on the wrist: Does increasing the number of chambers alter the "pinching" sensation reported as enjoyable by our users? Is the wrist sensitive enough to mirror the same haptic perception as the palm or fingers? Can users distinguish between selective inflation of a left and right chamber? A top and bottom chamber? Multiple chambers arranged in series? The multitude of different designs to answer and evaluate these problems would be prohibitively time-intensive if we needed to make custom molds for each design. Instead, by constraining the overall geometry to the bracelet geometry, this workflow allowed us to use the same mold and rapidly adapt the separator design to investigate these questions and *tune* the different haptic sensations (Figure 9B).

Reconfigureable Workflow A necklace artifact was developed to explore how custom aesthetic forms may be adapted from single-chamber silicone bladder (Figure 9B). The silicone form was used as a pendant and attached to an air-tube, a 3V micro air pump, and a quick-connect valve as the closing clasp. This artifact approached the potential of subdividing bladders by introducing a mechanical seam. This seam was created by using a traditional pressure vessel design using the bladder as a gasket material. A 3D-printed *frame* and *base* was used to compress the bladder with 8mm nuts and bolts in select regions and *divide* the single chamber into four compartments. The frame was designed with air channel geometries that would guide the airflow through the four sections. Since the frame held the silicone form in compression, we added additional *casements*, or mix-and-match inserts, to the existing frame geometries to further constrain and *divide* the four original air chambers. Through this reconfigurable architecture, this artifact allowed us to explore different silicone behaviors and forms without needing to refabricate the bladder itself.

DISCUSSION

In this section, we discuss remaining challenges around the integration of silicone bladders with existing practices, opportunities to expand visuo-haptic aesthetics, and how our process might be applied to a wider range of emerging materials.

Aesthetics and integration with materials

While silicone has many potential forms, one tradeoff is the difficulty in integrating this material with other materials. Our survey of strategies reveals mechanical joints as the most reliable method, which can be prohibitively difficult to integrate into existing practices. In the wristband artifact (Figure 9A), a hook-and-loop fastener was used to superficially constrain the silicone against the skin. Binding the silicone to the bracelet would require mechanical joinery. One opportunity lies in the creation of connectors that allow silicone to interface with thread, paper, fabric, or leather (e.g., snap connectors). Wearables need to leverage the existing design languages of jewelry, clothing, and other bodywear to see silicone adopted in these practices. Dunne et al. [8] provides an overview of the necessary foundations of wearability and social factors of the wearable system. In the necklace exemplar (Figure 9B), ABS material is used to create the mechanical pressure vessel; while functional, ABS does not carry the same aesthetically delightful sociomaterial characteristics common in many jewelry materials (e.g., rare metals and wood) In contrast, skin-friendly materials like leather could provide an equivalent pressure vessel construction. Accessing such leather-centric workflows that are already seated in craft could further allow silicone to enter a morphogenetic model of making.

Democratizing access

The techniques presented in this work were fabricated using commodity digital fabrication equipment found in many makerspaces. In the DIY making community, molds have been made with packaging tape and cardboard; however, it can be more time consuming to create organic shapes with cardboard. While wood and resin inhibit curing, a wide range of alternative materials can be used as a separator. We described how three different separator materials – acetate, vinyl, and PVA – and how techniques associated with each material helped us gain access to a wide variety of internal chamber geometries. While pneumatic control remains a significant implementation hurdle, recent low-cost and open-source toolkits such as Programmable Air[8] indicate a new horizon for the adoption of pneumatic-controlled interfaces. Our exemplars did not integrate an electronic pneumatic control interface, but leveraged handheld inflatable bulbs with air release valves (commonly used in medical blood pressure monitors) to quickly prototype and evaluate bladder inflation and deflation behaviors. We found that integrating these devices into our testing workflow increased the ability to explore different silicone behaviors, which helps to refine mental models around silicone.

[8]https://www.programmableair.com/

Visuo-haptic aesthetics

The haptic, visual, and interactive qualities of the tangible light exemplar (Figure 1A) have the potential to enhance digital manipulatives used to engage multiple senses of young learners [31]. Such learning objects could support communicating tacit haptic information by coupling visual light cues and pressure sensor readings. For instance, the tangible light could communicate the force to exert on clay during pottery throwing techniques, the hand pressure to apply during CPR procedures. Increasing air pressure inside the bladder when progressively activated can serve as a manner of communicating hysteresis (i.e., a residual input limit). Drawing from Lederman et al. haptic exploration procedures [15], this artifact leveraged inflation, textural flow gradients, capacitive touch, and pressure sensing to discern *lateral motion*, *pressure*, *volume*, and *static contact* exploration. To fully support a vision for programmable haptics, opportunities exist in supporting *holding and dynamic weight*, *contour following*, and *temperature shifts*.

Fabrication polymorphism

We presented a method to create complex bladder forms while maintaining a simple and reliable fabrication process. In our framework, we examined what we term a *castable*, or a material in a liquid state that cures/sets into a solid form using molds. A significant portion of fabrication insights came from mold making and casting literature, yet silicone is one of many kinds of castables including plastics, metals, clays, plasters, glass, sugar, wax, and chocolate. While the bladder design and fabrication was optimized for silicone, many of the proposed techniques could port over easily to plastics, which are already used for creating bladders, but would fail for others. How might techniques developed for silicone automatically port, be adjusted, or synthesized to work for other castables that share similar workflows as silicone? We see additional opportunities to develop an ontological mapping of material constraints to techniques so that knowledge from different communities of practice can be more readily shared.

CONCLUSION

Siloseam is a creative framework that presents a comprehensive fabrication process to create bladders with custom internal air channels and chamber designs. The framework was formed from over 70 iterations refining the bladder design and fabrication process. In this process, we generated new fabrication workflows that support iteration, collected tacit recovery mechanisms into an error typology, streamlined design and fabrication processes (tack curing, procedural generation of mold and separator geometries), and shared morphological experiments to uncover different design dimensions. By sharing our process, experimental setup, observations, and workflows for creating exemplar artifacts, we hope to motivate others to see the potential of silicone as an everyday material with innovative, aesthetic, functional, haptic, and joyful forms.

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