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Injection Molding of Soft Robots

Michael A. Bell, Kaitlyn P. Becker, and Robert J. Wood*

To date, injection molding has not been a practical manufacturing method for soft robots due to machine costs, large volumes of liquid silicones required, and the inability to change materials quickly between shots. Injection molds are typically machined from metals to allow for high pressure and clamping forces, which further limits the ability to rapidly prototype soft robots when molds could cost thousands of dollars. To circumvent these issues, a low-cost injection molding system and process are pioneered. In this article, the apparatus, design process, economics, and workflow are described using standard stereolithography and polyjet 3D printers to rapidly iterate on soft robot designs. The mold design process is further detailed to allow for proper material flow, clamping, alignment, and rapid curing times. Static mixing nozzle efficacy is characterized with common silicone materials compared to manual mixing and centrifugal planetary mixing. Lastly, a number of applications that could only be achieved through injection molding due to geometry, embedded components, or cure times are presented.

1. Introduction

Soft robots are primarily manufactured in low-volume laboratory settings, traditionally by mixing silicones by hand ($1s), turbine mixer ($10s), stand mixer ($100s), or planetary mixer ($10,000s). In industrial manufacturing of silicone products, liquid silicone injection molding is used to quickly and repeatably produce parts. These liquid silicone injection molding machines ($10 000s–$100 000s) are set up for mass manufacturing of one part, loaded with tens to hundreds of liters of one type of silicone, and do not allow for quick and easy replacement of molds or materials. The two desirable characteristics of these machines are their capacity for high-pressure injection molding and the ability for continuous, in-line mixing. Mixing is accomplished in either a static mixer, which can contain dozens of speciality designed static elements to promote mixing as material passes through, or an active mixer which has a powered impeller to mix both materials as they pass.

1.1. Molding State-of-the-Art

The current state-of-the-art in manufacturing fluid-driven elastomeric soft robots is in improvements creating complex internal voids, embedding rigid or functional components such as magnets or tubing, or using new production methods such as directly 3D printing soft actuators.[1]

The creation of internal voids and undercuts is inherently a challenge when molding. The traditional method is to glue two parts together,[2] or dip a cured half in uncured material.[3] Soluble or wax cores can allow for complex voids which are later removed out drain holes.[4–6] Soft cores are flexible (usually softer than the desired molding material), and enable voids to be created while being able to be reused multiple times.[7] Using a technique from industry, rotational molding that is normally used to make large plastic products such as kayaks, can be used to create internal voids in soft actuators, but control of the wall thickness becomes difficult for features such as bellows.[8] Alternatively, dip-coating can control the internal geometry but control of the external wall thickness is difficult.[9]

Strain limiting layers are the most common type of reinforcements embedded into soft actuators, such as paper or fabric sheets to prevent extension of an actuator.[10,11] In order for embedded components to adhere to the silicone, components can be dipped and stuck to a structure,[11] or molded during the casting process.[10] Small magnets or nuts can also be embedded, but require a mesh to grip enough silicone to prevent the magnet or nut from pulling out during use.[12,13]

3D printers and materials have recently become more capable of directly printing soft actuators, potentially eliminating the need for mold making and casting.[14,15] Thermoplastic polyurethane (TPU), which is widely and cheaply used in shoes and clothing, has the potential to be directly printed producing robust bellows.[16] Recently, Voxel8's ActiveLab Digital Fabrication System (Voxel8, Somerville, MA, USA) has been able to print varying stiffness TPU with large overhangs while curing on-the-fly. Another method, embedded 3D printing, allows complex microchannels to be produced using sacrificial materials to create void space after silicone is cured.[17]

1.2. Injection Molding Soft Robots

We have developed a low-cost injection molding method ($10s–$100s) that incorporates the high pressure and in-line mixing capabilities of industrial liquid silicone injection molding machines into a versatile machine for prototype and low volume production. Our setup allows for low-volume

M. A. Bell, K. P. Becker, R. J. Wood
Harvard John A. Paulson School of Engineering and Applied Sciences
150 Western Ave, Allston, MA 02134, USA
E-mail: bell@seas.harvard.edu

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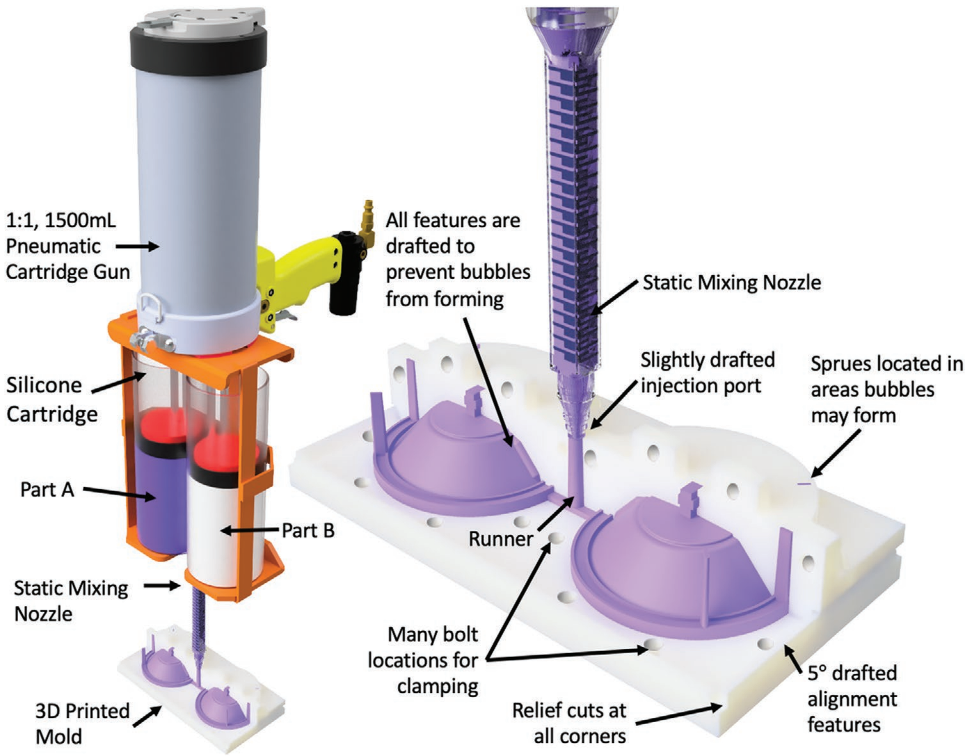

Figure 1. Left: Overview of injection molding, using a 1:1 1500 mL pneumatic gun, 1500 mL cartridge, and static mixing nozzle. Right: Detail of mold and subsequent part showing key features.

silicone cartridges (ranging from 600 to 1500 mL), with mixing efficacy equal to, or better than, planetary centrifugal mixing. Our method produces up to 2.7 MPa of cartridge pressure, allows for the use of hundreds of different types of off-the-shelf mixing nozzles, and eliminates the need for silicone degassing after mixing. In our experience, it takes a new trainee 5–10 castings to achieve a defect-free part as seen in **Figure 2**, as it takes time to learn how to properly mix the material, pour the material in strategic locations to reduce bubbles, and degas, for a traditional molding operation. Whereas for injection molding, defect-free parts are produced from the first shot by eliminating user error in mixing, pouring, and degassing. The comparison of both processes assume the mold has been properly designed. The pressure-induced flow from injection molding also eliminated bubble related defects, and enabled higher resolution (0.4 mm for injection vs. 0.7 mm for casting) molding with complex arrays of features and embedded components.

Our laboratory-scale injection molding setup allows for the use of a greater variety of materials, such high viscosity (⩾30 000 cps) or fast curing silicones (⩽2 min) that would be challenging to mix, degas, and mold with methods typically

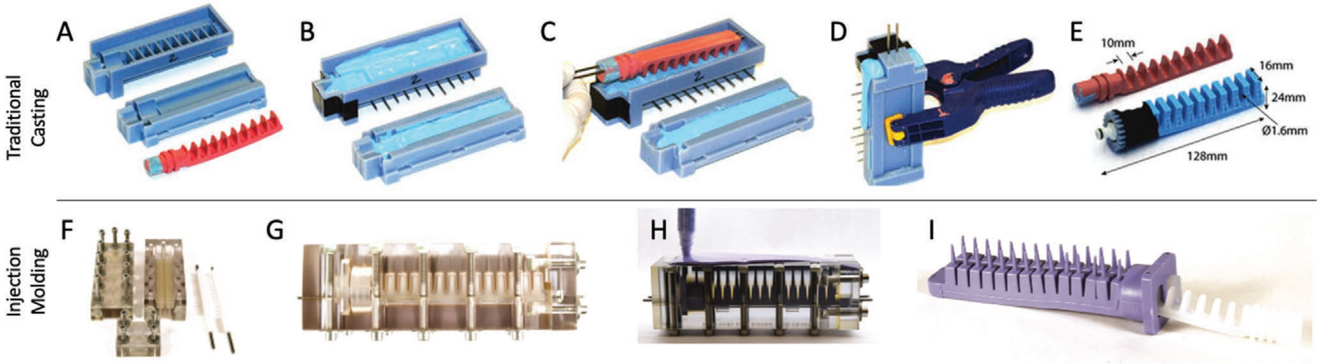

Figure 2. Comparison between traditional casting methods and injection molding methods for a soft gripper. Traditional casting: A) Top and bottom molds with a soft core, B) filling both molds with Smooth-Sil 950 silicone, C) insertion of the soft core with rods into the silicone, D) clamping and then curing, and E) completed actuator. Injection molding: F) Top, bottom, and cap mold with soft cores; G) soft cores inserted into mold with screws clamping all parts together, H) injecting Smooth-Sil 945 silicone into the mold using a static mixing nozzle, and I) final gripper with soft core removal showing untrimmed sprue material.

Table 1. Timing by step of injection molding versus casting, similar mixing and degassing times are assumed for manual and motorized mixing.

Step	Injection Molding [min]	Casting [min]
Cartridge preparation	1	0
Mold release application	1	1
Pre-molding assembly	5	0.5
Mixing	0	3
Degassing	0[a)]	3
Pouring/Injecting	0.5	1
Post-molding assembly	0	0.5
Demolding	5	1
Process time	12.5	10
Wet molding time	0.5	7.5

[a)]Cartridge degassing is done during the cartridge pouring and packaging, as detailed in Section S1, Supporting Information, and duration is dependent on the material. For the purpose of comparing the timing of casting a mold, the cartridges are assumed to have been already prepared and ready for use.

used to mix and cast soft actuators. The repeatability of injection molding can also be leveraged to eliminate bubble defects. With a given flow pattern, bubbles will reoccur in the same location and can be resolved with venting or rerouting flow. With a combination of the pressure-induced flow and assembly of molds prior to molding, injection molding can also achieve more complex mold and part geometries while reducing the skill required for mold assembly and pouring.

2. Molding Methods

2.1. Traditional Casting

The majority of soft robot components are currently created by casting silicone into open halves of a two part mold, as depicted for a one-sided bellows-based robotic finger in Figure 2A–F. For a simple two-part mold, the top and bottom are placed with their interiors facing upward as shown in Figure 2A. In this example, a soft core is also used as a third piece of the mold.[7] Silicone is mixed, by hand or machine, degassed, then poured into both halves of the mold as shown in Figure 2B. The molds may then be degassed once more to remove air bubbles. The core is aligned into one half of the mold and the two mold halves are then sandwiched together and clamped as seen in Figure 2D. Excess silicone exits primarily through designed vent holes and some through the seams of the mold as it is clamped together. Without practice and care, casting in multipart molds can be messy and air bubbles also frequently get trapped in the mold during the pouring and clamping process. A common solution to mitigate bubble inclusions is to place the mold into a pressure chamber after clamping to reduce the size of entrapped air bubbles. With careful design flow and venting, however, injection molding can reliably eliminate bubble entrapment in the molding process. Furthermore, the features that can be resolved while casting viscous silicones is limited by the viscosity of rubber, especially in thin cavities (<2 mm), while the added pressure of injection molding can force flow into small mold features. Similarly, injection molding can help to saturate fabrics and meshes inside of a mold, whereas fabric and mesh must often be pre-dipped into silicone or massaged by hand before placement in the mold for casting.[12]

2.2. Injection Molding

The most notable difference in the process flow with injection molding is the fully assembled mold prior to introducing material, as detailed in **Table 1**. Figure 2 compares the traditional casting process to an injection molding process for a robotic finger. As seen in Figure 2G,H, the injection mold is fully clamped (with screws and nuts) before being injected. This allows the user time to properly place any inserts, such as the soft cores seen in Figure 2G, ensuring alignment and proper spacing to be in the exact center of each bellow cavity. In previous casting methods, these soft cores are inserted into a pool of silicone, with no visibility as to their alignment beneath the silicone, and can further shift when both mold halves are clamped. The two traditional molds are held together with a spring clamp, to prioritize speed and prevent rubber from spilling out of the mold before closure. The spring clamps are a convenient solution to quickly secure the mold but are limited in clamping pressure and often leave flashing around the parting line of the mold. Fastening of the injection mold is more time consuming but provides enough clamping force to prevent rubber from seeping through the parting lines of the mold. Once the injection mold is clamped, a nozzle is placed over the injection port and silicone is injected. The only process variability is time and injection pressure, which is easily controlled and eliminates the user's skill in mold mating and clamping (as shown in Figure 2C,D).

2.3. Traditional and Injection Molding Cost Comparison

The costs associated with molding a 50 mL silicone part, such as a PneuNet actuator, can be compared as seen in **Table 2**.

Table 2. Cost comparison between traditional casting and injection molding for a 50 mL PneuNet-type bellow actuator.[7,18]

	Injection Molding	Traditional Casting
Cartridge cost ($)	$4.39	–
Material cost, Smooth-Sil 945 ($ mL^{-1})	$0.03	$0.03
PneuNet bellow-type actuator volume (mL)	50	50
Nozzle dead volume/cup loss (mL)	6.5	5
Over pouring (mL)	5	15
Mixing nozzle/cup costs ($)	$2.07	$0.10
Defect rate (%)	1.00%	20.00%
1-Part molding costs ($)	$3.92	$2.20
4-Part, defect-free molding costs ($)	$9.54	$10.20

The upfront costs of injection molding pays off with four or more parts produced; however, the defect rate is significantly lower, resulting in more consistent and reliable parts.

About one in five PneuNet-type actuators fail during casting, typically from bubbles immediately discovered or found during use.[7] Although bubble defects can be repaired, we consider a 20% defect rate. Alternatively, for the same molds redesigned for injection molding, a defect rate of closer to 1% is achieved by eliminating bubbles and increasing consistency of molding, in addition to greatly increasing the complexity of the part.[18] From the table, injection molding has no cost advantage making a single part; however, as the volumes increase to four or more parts, injection molding becomes less expensive. Overall, the per-part costs associated with injection molding is a few dollars, and is minor when taking into account the cost of the 3D printed mold and silicone material, which can run up to $140 for a similar part as discussed in Section 4.1.2.

3. Liquid Silicone Injection Molding Methods

3.1. Industrial Liquid Silicone Injection Molders

Injection molding of liquid silicone rubber (LSR) is the industry standard for high volume, mass manufacturing of silicone parts for myriad everyday household items. Industrial LSR machines with shot sizes large enough to handle soft actuators, such as in Figure 9, can cost around $185 000, weigh 4800 kg, and take up 2.4 × 1.2 × 3.6 m (8 × 4 × 12 ft) of space (REP V410, REP international, Corbas, France). To create a part, the mold is installed into the injection molder, and barrels of two-part silicones and optional additives are pumped through specialized metering units.[19] The machine then clamps the mold together with 8–25 MPa of pressure, and precisely dispenses both components through a static mixer into the mold with pressures from 1–10 MPa.[20–23] The mold is heated typically between 120 and 160 °C to allow quick curing and fast cycle times.[22,24–28] The part is then removed, and the processes is repeated.

The molds for these machines are generally machined out of metals due to the high pressures and clamping forces, with aluminum molds capable of hundreds of thousands of cycles and steel molds up to ten million cycles.[29,30] Some 3D printing technologies can be used to make prototype injection molds, but can degrade rapidly from material flow and temperature cycling, and are generally only used for 10–100 shots (Formlabs High Temp Resin, Formlabs, Somerville, MA, USA).[31]

3.2. Low-Volume, Prototype Injection Molding

Soft robots and soft actuators generally do not require more than 100 mL of materials per shot, with molds made using 3D printing instead of machined metals. The quantity of parts molded can also be in the single digits, with numerous experimental molds being used. For this reason, the system we developed for soft robots utilizes volumes of silicones in the 600–1500 mL range, with a mold setup or material changeover taking a few minutes. We utilize a cartridge system and off-the-shelf construction-type cartridge guns, with disposable static mixing nozzles. Figure 1 illustrates the cartridge gun, two-part cartridges, static mixing nozzle, and mold.

3.2.1. Cartridge Guns

Cartridge guns are used for a wide variety of dispensing needs, typically found in hardware stores for uses such as caulking, glue, or epoxy. Multi-component cartridge guns can be found in common sizes ranging 50 mL to 1500 mL (750 mL × 750 mL), in common ratios of 1:1, 2:1, 4:1, and 10:1. They can be actuated manually (most common, $10s), pneumatically ($100s), or electrically ($100s). All guns are designed to be portable and hand operated, typically used for the construction industry, and thus are recommended to be mounted to a table or stand for use in injection molding.

We have found larger cartridge sizes to be most useful for molding soft robots, in 600 and 1500 mL, since the time required to fill a small and large cartridge is similar. As shown in **Figure 3**C, our baseline for an injection molding setup has options for 1:1, 2:1, and 10:1, in either 600 or 1500 mL. Trial size units of silicone material (950 mL), such as provided by Smooth-on, fit well within a single 1500 mL cartridge.

An example first purchase for injection molding would include a manual, 1:1 ratio, 1500 mL gun, capable of 455 kPa of pressure, and costing $99 as listed in Table 5. This allows for mixing 1:1 materials such as Smooth-On's Dragon Skin, Ecoflex, Smooth-Sil 945, or Quantum Silicone's True Skin. A further upgrade would be a pneumatic cartridge gun ($572), which allows continuous flow, and higher and controllable pressure (up to 827 kPa). Using pneumatic cartridge guns in a laboratory setting requires either acoustic shielding around the exhaust ports as seen in Figure 3C, and/or hearing protection at high pressures, as the release of the large volume of compressed air was measured at 103 dB. Electric guns are much quieter, but are more expensive ($694), only achieve pressures slightly higher than the manual guns (482 kPa), and are only available in battery powered configurations.

3.2.2. Cartridges

While some silicone manufacturers, such as Smooth-on, make pre-filled cartridges of silicones, they are generally small volumes (400 mL or less), come only in a limited number of silicones, and are considered a one-time use for applications such as face masks or mold making. To use standard soft robotic silicones for larger volumes and multiple uses, two types of empty cartridges can be purchased and then filled. The first type of cartridge contains parts A and B in a single integrated part, and the second type of cartridge has A and B in separate parts that are paired together with a retaining nut. The former is best for a 1:1 ratio, while the latter is most common with ratios such as 2:1, 4:1, or 10:1. **Table 3** shows relevant costs for the cartridges and pistons from Nordson EFD (East Providence, RI, USA), $2.20 and $4.39 for 600 and 1500 mL 1:1 cartridges including the pistons, respectively. Cartridge configurations in 1:10 (750 mL × 75 mL), 1:1 (750 mL × 750 mL), 1:1 (300 mL × 300 mL), and 2:1 (300 mL × 150 mL) can be seen in Figure 3C.

3.2.3. Mixing Nozzles

The simplest option for mixing is using disposable static mixing nozzles, although active mixing nozzles can be used for special

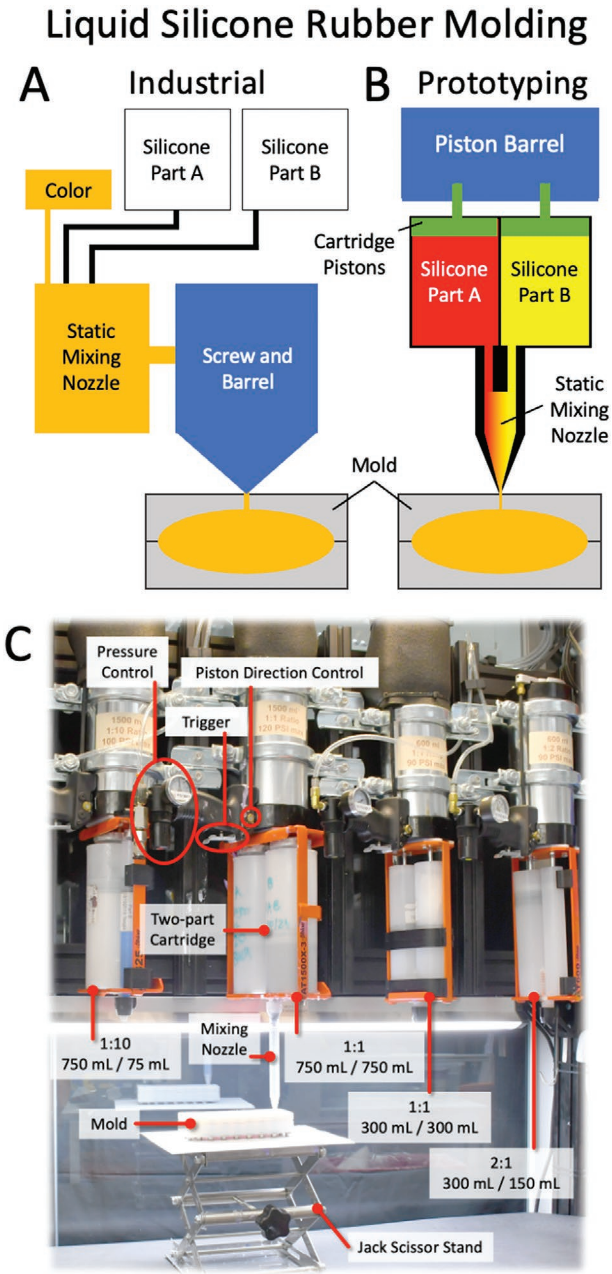

Figure 3. A,B) Schematic comparison between industrial and prototyping injection molding: A) An industrial liquid silicone injection molders pumps both parts of silicone and with a colorant through a static mixing nozzle into the screw and barrel. It is then injected into the mold. B) The prototype liquid silicone injection molder uses a piston barrel to push silicone parts A and B through a static mixing nozzle directly into the mold. Colorants are already added to the silicone. C) Overview of the injection molding station, supporting four pneumatic cartridge guns: 1) 10:1 at 750 mL/75 mL; 2) 1:1 at 750 mL/750 mL; 3) 1:1 at 300 mL/300 mL; and 4) 2:1 at 300 mL/150 mL. The mold is raised on a jack scissor stand until contact with the mixing nozzle is made. Pressure control, piston direction (actuate/retract), and trigger are shown for operation.

materials but are a significant cost and require cleaning after use. Most disposable static mixing nozzles come with mounting threads that can be screwed directly onto the cartridge outlet, but also come in a style that requires a retaining nut to hold the mixing nozzle onto the cartridge.

The selection of which static mixing nozzle to use is an experimental exercise, but can be narrowed down to a handful of nozzles based on the rubber viscosity. Manufacturers of mixing nozzles, such as Nordson EFD, provide guides to narrow the selection process.[32] For silicones, 20–30 mixer elements are recommended, and for viscosities between 5000–50 000 cps (which encompass most silicones used for soft robots), element diameters from 5.4–8.0 mm are suggested.[33] Greater numbers of mixing elements increase mixing uniformity, but this comes at the expense of pressure drop and an increase in retained dead volume. Likewise, the larger the diameter of the mixer the less pressure drop, but this can reduce mixing and increase retained dead volume.

Six types of mixing nozzles are generally employed, as listed in **Table 4**, with costs ranging from $2–$4. Characterization of mixing efficacy for Ecoflex 00-30 (3000 cps), True Skin 30 (15 000 cps), and Smooth-Sil 945 (30 000 cps) are further presented in Section 5.4.

3.2.4. Materials

Most silicones used for soft robots can be used in an injection molding cartridge system. The main factors to consider are:

1. Material must be available in mixing ratios of 1:1, 2:1, 4:1, or 10:1 for compatibility with available cartridges. Cartridge dispensing is controlled by volume, not weight, which may affect the mixing ratio recommendations for some materials, although a variance of 5% can be tolerated without significantly impacting the final material properties.[34] Thus, materials listed as mixing by weight may have acceptable final material properties even if mixed by volume.
2. Material shelf life in a cartridge is based both on material settling, and ageing of the material. Cartridges should be stored on their side to allow even settling down the axis of the cartridge. When these cartridges are then used, an equal proportion of settled material will mix as the cartridge piston advances. Nevertheless, testing specific materials for shelf stability is recommended according to ASTM D412.
3. Very high material viscosity (⩾50 000 cps), or uneven material viscosity between parts A and B may lead to limited injection pressures, or require flow restrictors on the lower viscosity material to prevent material backflowing to the opposite side.
4. Additives, such as colorants, accelerators, or inhibitors should be pre-mixed into the manufacturer's recommended side, part A or B, before filling the cartridge.

Table 3. Costs of different cartridge options from Nordson EFD. Two piece cartridges require both parts A and B, and all options require two pistons. Costs for 100 pieces as of February 2021.

		1:1 Combined	Two Piece Cartridges		
			1:X or X:1	2:X	10:X
600 mL	Cartridge	$1.42	$0.96 (300 mL)	$1.41 (150 mL)	$2.89 (30 mL)
	Piston		$0.39	$0.33	$0.76
1500 mL	Cartridge	$2.63	$0.88 (750 mL)	–	$1.15 (75 mL)
	Piston		$0.88	–	$0.45

Table 4. Specifications of the Nordson EFD static mixing nozzles, with pricing for quantity 100 as of February 2021.

	Mixing Elements	Width [mm]	Length [cm]	Retained Volume [mL]	Cost
Optimixer 17	17	7.4	10.2	4.7	$2.28
Optimixer 25	25	7.4	14.2	6.5	$2.07
Optimixer 33	33	7.4	17.3	7.5	$2.19
Optimixer 41	41	7.4	20.6	10.0	$3.60
Turbo 0.4 x 20	20	11.2	19.1	15.1	$2.49
Turbo 0.4 x 26	26	11.2	22.9	17.0	$2.66

Some materials come in non-standard ratios, which makes dispensing difficult. Wacker Elastosil M 4601, a Shore 28 A hardness material and popular in soft robotics for its 700% elongation at break,[2,7,35] comes in a 9:1 ratio. To injection mold this material, it is first mixed in the desired quantity using a centrifugal planetary mixer (or by hand), and poured and degassed into a one-part cartridge. It can then be injection molded into the desired mold, but is a one-time use as the material will cure in the cartridge. The material can also be fitted into a 10:1 cartridge, by adding silicone oil as a filler to bring the ratio to 10:1, which is less detrimental to the material properties than dispensing a 9:1 material in a 10:1 ratio.

Unless absolutely necessary to have a non-standard ratio material, we encourage contacting manufactures to find materials in standard dispensing ratios. Elastosil M 4601 in our molding has largely been replaced with True Skin 30, Shore 30 A hardness, which has a superior 1000% elongation, higher tensile and tear strength, all at a 1:1 ratio.

4. Advanced Molding Discussion

While minor fabrication details are often relegated to an appendix, it is important to consider details of the fabrication in the process of developing more robust and reliable soft actuators and the molds that create them. The subsections below are included because they were important developments and details that we have not found in other literature, and they have enabled added functionality to the molding process as well as the soft devices created. The ultimate benefits of some of these details include higher operating pressures and actuator life cycles with seemingly subtle or no changes in geometry, and robust integration with rigid and soft components.

4.1. Molding Materials

Mold finish and surface roughness are important considerations for molding soft actuators. Artifacts from the 3D printing process can create thin spots and surface textures that are more prone to tearing.

Most of the example molds shown in this paper were produced on Polyjet printers (Object Scholar and Connex) because it was a readily available high-resolution printer and the transparent mold walls printed in Vero Clear (Stratasys) facilitated in the trouble shooting process. While these printers have the capacity for high resolution and smooth surface parts, surfaces printed against support material and surfaces that transition from support to no support material can introduce roughness into the mold walls. In particular, vertical and overhung walls require support material. Once the support material is removed, it reveals a roughness that is less than 0.5 mm in magnitude, but because the layer height at which the variation in wall thickness occurs is small, these behave like small cracks in the wall of the actuator, which will reduce the burst pressure and cycle life of an actuator. Examples of the resulting surface roughness with and without support material are shown in **Figure 4**A. To avoid this, all interior mold walls that define the inflatable portion of the actuator were vertical or had a small draft angle. A draft angle is normally included in rigid injection molded parts to facilitate removing rigid parts from a rigid mold. A draft angle is not strictly necessary for soft parts but was found beneficial for this purpose of creating a smoother molding surface and greater actuator longevity.

Until redesigning molds to minimize support material adjacent to inflated structures, the most common actuator failure point for the bellows deep-sea gripper presented by Galloway et al.[7] occurred within the regions that were defined by surfaces that once touched support material in the mold printing process. The problem of surface texture also arises with parts from fused deposition modeling (FDM) printed molds. This can be mitigated with an acrylic spray coating or partially dissolving the surface of the mold with acetone vapor, but these techniques will also affect the mold fidelity. Printing a mold with SLS (selective laser sintering) of nylon will reduce layer-associated roughness but increase overall surface roughness. SLA (stereolithography) printed molds similarly reduce layer roughness but have rigid support attachment points that must be taken into account because they can leave residual features at the attachment points. Moving away from 3D printed options, metal molds can also be milled, which are the standard in mass production. Metal molds will have a greater longevity and resist creeping under heat and pressure but are more expensive and machining limitations will be more restrictive on practical geometries.

4.1.1. Silicone Poisoning on Resin Molds

Another important consideration is that molds produced using photopolymer 3D printers (including inkjet and stereolithography-based systems) are often found to partially inhibit the curing of silicone elastomers, since these 3D printing resins frequently contain chemicals that are known to cause silicone poisoning, including polyurethanes, polysulfides, and epoxies.[36] The issue also becomes exacerbated as the ratio of

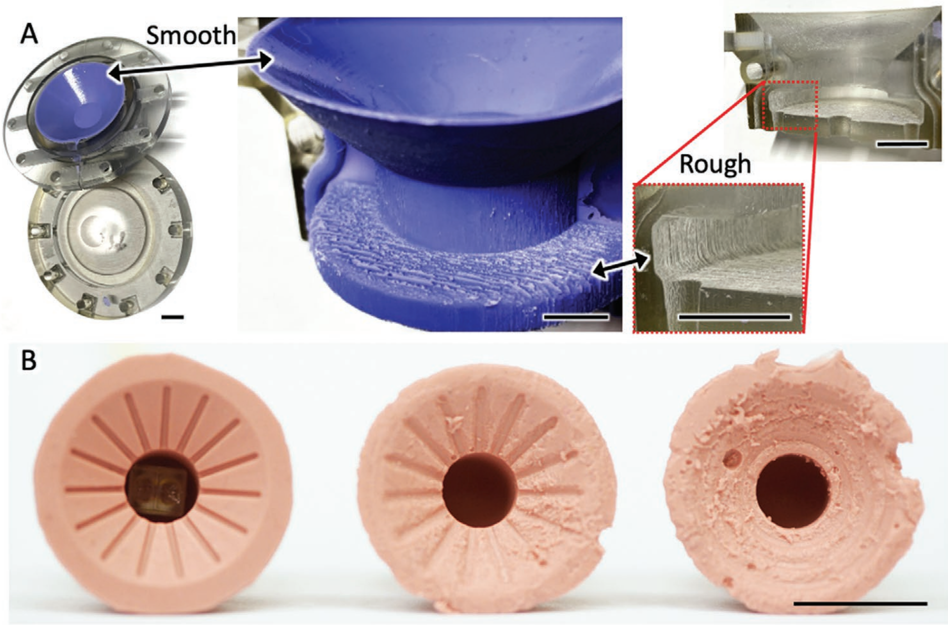

Figure 4. A) Surface roughness of mold features printed with and without support material on a Connex printer in Stratysis resin. B) Example parts from similar molds at three levels of cleaning to demonstrate the cure inhibition of residual resin on a mold printed with a FormLabs 1+ printer. The left part was made from the same mold directly after the center part was molded, demonstrating the benefit of "sacrificial molding." The scale bars represent 1 cm.

the surface area to molding volume increases. To mitigate this problem, the as-printed molds had either their support material (from the PolyJet parts) thoroughly removed via a high-pressure washing station, or residual uncured surface resin (from the SLA parts) removed by extensive rinsing in isopropanol. The resulting cleaned molds were then baked overnight in a vented 65 °C oven. Alternatively, an expedited processes was developed using a 1:1 concentration of water:Simple Green in an ultrasonic bath at 65 °C, reducing the post-processing time to one hour after the Polyjet support material was removed. A "sacrificial molding" of rubber that would be discarded was also a useful final cleaning step. An example of the improved cleaning and molding quality that can be achieved from a sacrificial molding step is shown in Figure 4B. While the mold can also be further baked or sonicated, which may partially resolve the issue, the more reliable solution is to simply treat this as a sacrificial casting, clean the mold of any residue, and start again. If, however, a part is cured enough to be removable from the mold, but is still soft and tacky due to cure inhibition, an extra baking step can further aid in the curing processes. Aside from various cleaning procedures, the use of a mold release can aid in part removal from the mold, but will not resolve the problem of cure inhibition. Parts made from sintered nylon, FDM filaments, and metals do not exhibit this cure inhibition problem, but the mitigation steps listed above were sufficient for the cost and convenience of the printers employed in the present study.

4.1.2. 3D Printer and Material Costs

There is a large difference in costs for the 3D printers capable of producing injection molds for soft robots. For smoothest mold surfaces, resin-type printers are preferred due to smooth blending of liquid resin between Z-axis layers. As of August, 2021, the Objet30 printer starts at $20 000 with a 29.4 × 19.2 × 14.9 cm build volume, and a layer thickness of 16 µm. The Formlabs Form 3 starts at $3500 and has a 14.5 × 14.5 × 18.5 cm build volume, and a layer thickness of 25 µm. Recently, we have had good success with a much more affordable SLA 3D printer–the Photon Mono X, which starts at $589, has a build volume of 19.2 × 12.0 × 24.5 cm, and a layer thickness of 10 µm.

Other 3D printing technologies to consider include FDM, which can use lower cost material or have material with higher strength, and also generally provide a larger build volume. On the high end, Markforged Onyx One printer costs $4500, has a build volume of 32.0 × 33.0 × 35.5 cm, a layer thickness of 100 µm, and prints Onyx. On the lower end, a Original Prusa Mini+ costs $349, with a build volume of 18.0 × 18.0 × 18.0 cm, layer thickness of 50 µm, and is capable of printing a variety of low-cost thermoplastics such as acrylonitrile butadiene styrene or polylactic acid (PLA).

Mold material cost and properties are a factor in deciding which material to use. As of August, 2021, the retail material costs for Objet Vero Clear (the most commonly used material in our work due to transparency) costs $0.37/cc, and is capable of being baked at up to 80 °C, allowing it to speed up the curing of silicone. Vero Clear (and, generally, the other Objet rigid materials) is brittle at room temperature and can crack easily when prying mold halves apart, so it is advisable to have the mold 40–60 °C which softens the mold and makes it more ductile when prying. Another material option is Formlabs Tough 2000 Resin, which costs $0.18/cc, is also capable of being baked at 80 °C, and is more tough than most object materials–allowing prying without breaking. Markforged's Onyx material is a mix of nylon and chopped carbon fiber, is one of the strongest FDM materials, and costs $0.19/cc. Generic PLA material for

FDM printers (such as a Prusa) costs as low as \$0.02/cc. Onyx is capable of temperatures of up to 145 °C, which allows for baking of silicone parts, while PLA's low glass transition temperature of 50 °C prevents any heating of the mold. Onyx is generally used for rigid inserts in molded parts, due to the high stiffness and high temperature tolerance.

In context of mold costs for Figure 9K, which produces a large bellow-type actuator, runs \$140 in Vero White, \$80 in Fomlabs Tough 2000 Resin, ⩽\$86 on a Markforged in Onyx, and ⩽\$9 in PLA (Markforged and FDM printers are capable of open cell infill, reducing the material usage). With design considerations for support material and printing orientation, we believe the Formlabs Form 3 or Photon Mono X are the most cost effective with the best surface finish for mold making.

4.2. Soft Cores

The soft core molding method is a key improvement to the fabrication process of monolithic soft actuators, as a way to create seamless structures with complex internal geometries. High aspect ratio internal features can be achieved where any rigid core would be mechanically constrained. Soft cores were first introduced by Galloway et al.[7] to create bellows-style actuators, which builds upon the fast-PneuNet actuators described by Mosadegh et al. The fast-PneuNet actuators are made using a two-step molding technique where the actuator is molded in halves, which are partially cured and then wet-bonded together.[10] The seam from wet-bonding is a common source of actuator failures and the operating pressures demonstrated with that process were less than half of the operating pressures that have been achieved with actuators molded with soft cores. Marchese et al. present a molding method using dissolvable cores, but this is a time consuming process that requires creating a new core for each production and time to dissolve the core.[4] Other methods to create internal voids include Negshell casting by Preechayasomboon et al., in which thin-walled, 3D printed cores can be left in place and have little effect on the final actuator.[37] The reusable soft cores introduced by Galloway allow for the entirety of the actuator to be molded in one step for a seamless soft body that can withstand higher operating pressures. Furthermore, the injection molding setup introduced in this paper facilitates the use of soft cores by avoiding the need to position the core in an open mold of freshly poured rubber.[7] In our experience, misalignment in this step accounts for the majority of molding defects. In contrast, the core and mold can be aligned and assembled prior to introducing liquid rubber for the injection molding process.

To maximize actuator operating and burst pressures, we found that it is important to carefully trim the flashing or excess rubber from the parting lines resulting from the soft core mold. These should be trimmed down to the surface of the core with a preference for cutting into a core over leaving excess flashing. Remnant flashing translates to a thin spot in the skin of the actuator after molding. This thin spot is structurally similar to a crack, due to the shape of flashing, and leads to a stress concentration in the actuator wall and possible rupture. To facilitate trimming and to mitigate deleterious effects of flashing, the parting line of a mold can also be moved to more accessible edges for trimming. The parting lines can also be strategically placed for potential defects to occur in lower strain regions of the actuator. Injection molding in combination with higher clamping forces in the mold assembly can also minimize flashing but care should be taken in this fabrication strategy because minimal flashing can be harder to trim and still detrimental to actuator robustness. Similarly, trimming flashing to the point where it is smaller but not eliminated makes successive trimming more difficult and still poses a risk to actuator robustness. A diagonal flush cutter (a cutting tool for plastic), fresh razor blade, or scalpel have been the most effective tools for trimming flashing while applying light tension to the flashing if there is enough to hold safely. Shorter or minimal flashing will tend to bend and slip beneath the blade and is challenging to trim effectively.

The silicone rubbers used for a soft core were chosen because of their high elongation to failure, allowing large stretches during the removal process while avoiding plastic deformation such that the cores can be reused. Elastosil was initially used for the soft cores for its low cost and high elongation to failure (700%), but was difficult to injection mold with a ratio of 9:1. However, True Skin 30 (Quantum Silicones, distributed by Industrial Sales and Distribution, Westerly, RI, USA) has a comparable price to the lines of Smooth-on products frequently used in soft robotics and touts a 1000% strain to failure, in a 1:1 mixing ratio. This is helpful for creating reusable cores for more complex internal geometries that require more deformation to successfully remove the core. It is also helpful in scenarios involving a high ratio of surface area to core volume, which leads to higher forces applied to smaller cross-sectional areas and thus higher forces on, and elongation of, the core during the removal process. A shore hardness of 30 A provides a balance of stiffness that can support the weight in the nodes of the bellow actuator (with the help of stainless steel skewers supporting the center of the soft core and clamped to the rigid mold), but can also deform easily enough to facilitate removal. Elastosil and True Skin are able to endure higher strains and resist plastic deformation relative to similar 30 A durometer two-part silicones.

4.3. Fabrics and Mesh Inserts

Fabric and mesh inserts play a key role in many soft actuators, generally serving as the strain limiting material.[38] They can also serve as a way to anchor rigid inserts, such as embedded magnets or nuts, by being first adhered to the rigid insert then impregnated with the surrounding silicone. An example of a mesh used to secure rigid inserts is demonstrated by Bell et al. in the incorporation of magnets within an elastomeric matrix.[12] A similar strategy can be used to reinforce boundaries between successive layers of rubber that would otherwise be at risk of delamination. This was used by Becker et al.[9] to create fluidic channels in large arrays of actuators, where cheese cloth was incorporated into an early stage of the molding process, and portions shielded from the first application of silicone were later used to mechanically anchor additional rubber.

Cheese cloth, glass fibers, fabric, and metal meshes have all been used successfully.[7,9] [12,38,39] With traditional casting methods, the fabric or mesh inserts are often pre-dipped into uncured silicone to allow penetration of the silicone into the fabric. When injection molding, the pressure is sufficient to obviate the need to pre-dip the mesh material. In either case, however, the porosity and surface area of the fabric or metal mesh, as well as the viscosity of the silicone should be taken into consideration. Fabric can simply be laid onto low viscosity silicones, such as Ecoflex, without worrying about bonding. Higher viscosity silicones, such as Smooth-Sil 945, require pre-dipping to facilitate silicone impregnation of mesh or fabric.

Fabrics and meshes can generally be hand cut to shape, but this can be done more precisely with laser cutting or a similar technique. **Figure 5**A,B shows a high-precision laser cut mesh used to hold a 1/4 × 1/8" cylindrical magnet inside of a dome-type actuator. The mesh was designed to fold around the magnet and allow silicone to impregnate in the mesh openings to restrain the magnet.

4.4. Mounting, Rigid Inclusions, and Soft to Hard Transitions

Although minimal adhesion may be obtained from rigid objects to silicone, molding inclusions benefit from porosity to allow silicone to penetrate through a network of openings to mechanically bond. In the case of mounting a soft actuator to the rigid hub shown in Figure 5C,D, the 3D printed adapters use a 3D network of 1.5 mm openings that, when injected, allow silicone to create a mechanical network holding the soft actuator.[40]

Fasteners such as nuts are very useful inside of soft actuators for ease of mounting, plumbing, or quickly changing out end effectors, but are at risk of delamination from soft rubbers. Figure 5E shows an embedded nut within the tip of a dome actuator along with a number of modular end effectors that are quickly swappable.[13] To allow the nut to stay fixed in position and to resist pulling out, a 0.7 mm laser cut metal washer was designed with hole porosity from 1 to 3 mm. A press-fit nut was then pressed into the center of this washer. During molding, the washer and nut combo were suspended using a screw, and injected silicone was easily able to impregnate the washer fixing it in place.

Larger volume rigid inclusions can also be included within actuators, such as arrays of rigid ossicles seen in Figure 9A. Here, dozens of ossicles limit the rotation of the actuator while providing rigidity. The ossicle inclusions were 3D printed with minimal interconnections to each other, and suspended inside of the mold. After injection molding and fully curing to incorporate the ossicles into a soft rubber form, the connections were then broken to allow freedom of movement.

4.5. Plumbing and Integration

A primary challenge for molding soft actuators is plumbing. A number of methods have been used, such as biopsy punching small 2 - 3 mm holes, inserting tubing or barb fittings, and using Sil-Poxy (Smooth-on) to adhere the tubing to the actuator. Custom 3D printed fittings that function like a modified barb fitting, such as the ones use by Galloway et al., can be used to plug an opening. However, without the porous features described above, these modified fittings require external compression such as heat shrink tubing or thread around the barb fitting to seal. Galloway et al. also used an adaptation of a panel mounted pneumatic fitting to create a seal with a vented screw with custom washers inserted through a small hole in an actuator wall and threaded into a plastic coupling.[7]

A simple method for plumbing is to directly embed the tubing into the actuator during molding – allowing silicone to cure and adhere to the tubing. The adhesion is highly dependent on the tubing material. We tested many tubing materials for adhesion to silicone, including polyurethane, and silicone rubbers. As seen in **Figure 6**, six tubes were tested in two different types of silicone (Smooth-Sil 945 and True Skin 30). Silicone tubes performed the best, while tubes made of a rubber blend or polyurethane had no adhesion to Smooth-Sil 945, and minimal bonding to True Skin 30. We find from the data that harder silicone tubing results in higher pull-out forces.

For peristaltic pump applications with embedded tubing, we use the tubing shown in Figure 6A, made by Boxer GmbH and distributed by Clark Solutions (Hudson, MA) in diameters from 1 to 3 mm (#9000.507, #9000.509, #9000.508). The tubing, as shown in Figure 5C,F, can be adhered with just 6 mm of axial silicone overlap. During molding, the tubing has to be plugged to prevent silicone ingress. In Figure 5F, this is achieved with soft cores that have barb features that seal the tubing, and are pulled out from the inside once cured.

5. Design Guide for Prototype Injection Molding

Material flow and air escape paths are critical considerations for soft actuator mold design. For single cavity molds, material is injected through the sprue, gate, and then throughout the mold until finding an escape path through open risers. To prevent trapped air from creating voids in the molded part, risers should be strategically placed to allow air and material to escape.

5.1. Sprue and Gate Location

On single cavity molds, which are the most common type, the sprue and gate are combined into a direct sprue-gate. The location of the direct sprue-gate can be centrally located allowing material to evenly flow outward, or placed at one extent of the part allowing the material to fill the part until reaching the furthest end of the part. Considerations should be taken for the complexity of the internal features, as the location immediately beneath the direct sprue-gate will have the highest pressures and thus be able to penetrate inserts or complex features more thoroughly. **Table 5** lists the suggested dimensions for molding components. A simple solution for long, flat, and level molds, is to have a gate at one side of the mold as shown in Figure 2I, and then use a spacer to prop up the distal side of the mold externally. Alternatively, this elevation can be incorporated into the mold design. Many of the mold designs shown through this paper are not flat and benefit from the vent features discussed below.

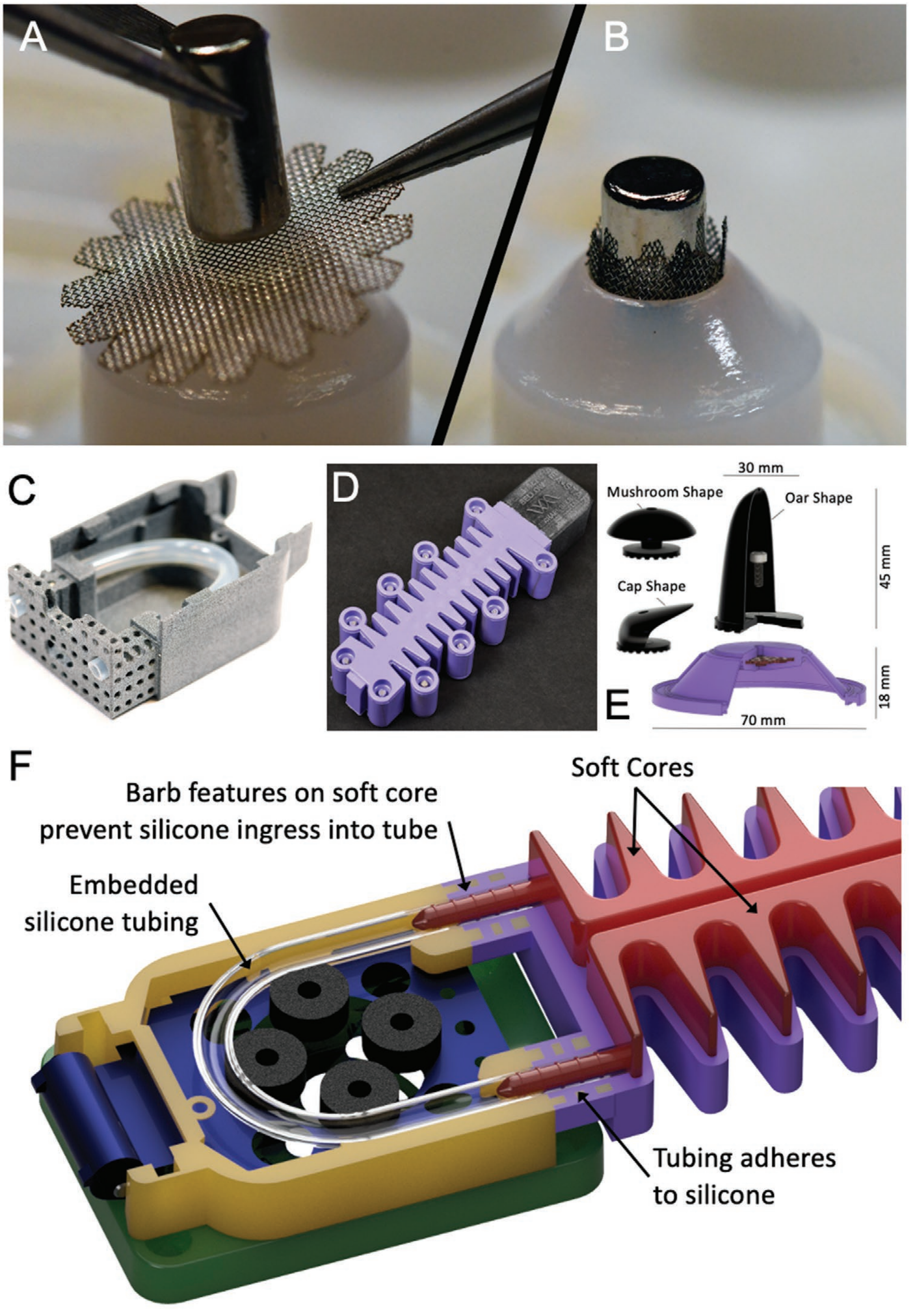

Figure 5. A,B) Inserting laser cut mesh inserts to constrain an embedded magnet: A) Insertion of the magnet showing the laser cut mesh; B) folded up metal mesh around the magnet with enough porosity to bond to the surrounding silicone. C–E) Examples of interfacing soft actuators to hard materials. C,D) A hard mounting cap that is 3D printed with a 3D network of porous holes is embedded within an injection molded actuator, which is shown in (D). E) A modular dome actuator contains an M3 press-fit nut into a laser cut stainless steel porous washer, allowing for quick change out of the end effector with an M3 screw. F) Integrated tubing directly into a soft actuator during the molding process. A barb feature on a soft core is used to plug both openings of the tube while silicone is injected around the tube and adheres to the tube once cured. The soft core is removed after molding, unplugging the tube and creating the internal features of the actuator.

On multi-cavity molds, such as shown in Figure 1, materials are injected into a central sprue, distributed through a runner, and into the cavity via the gate. Typically, these multi-cavity molds contain identical copies of the desired part.

5.2. Vents and Risers

To prevent trapped air from creating voids in the molded part, vents should be strategically placed to allow air to escape as

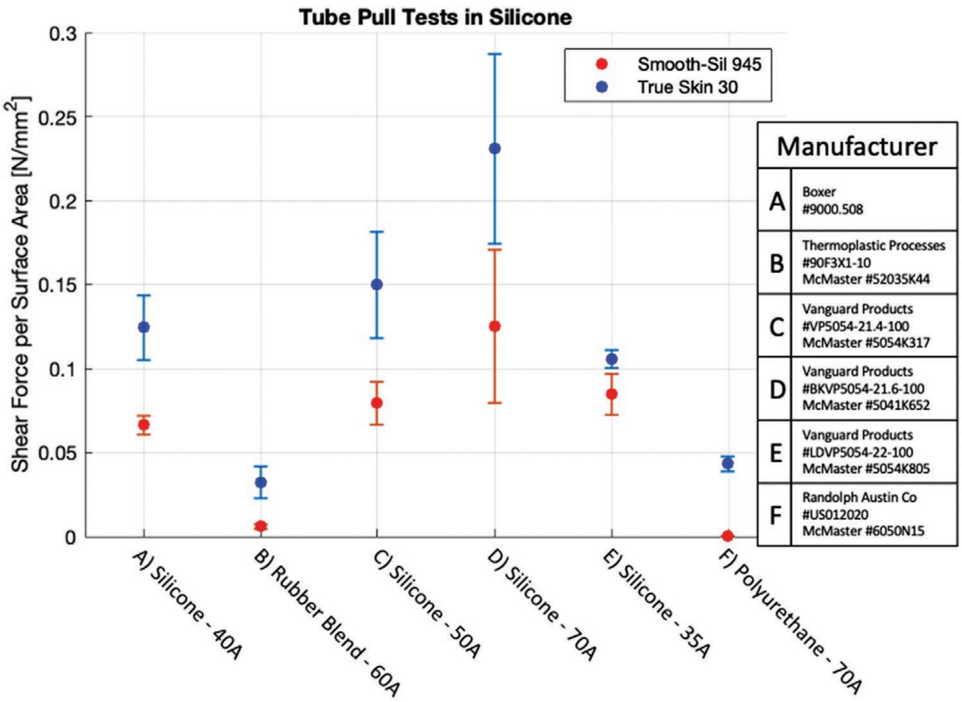

Figure 6. Tubing pull-out force tests when cured into silicone. All tubing was 5 mm OD, 3 mm ID, with 10 mm depth cured into silicone. The inside of the tubing was hollow. Five samples were taken for each tubing and silicone combination, with one standard deviation reported in error bars. A test fixture with a 6 mm hole was used to hold the silicone block back while an Instron clamp pulled the tubing through during the test. Shore hardness is reported on *X*-axis adjacent to tubing material type.

labeled in Figure 1. A guiding principle in the strategic orientation of a mold is to identify the internal volumes most likely to trap bubbles and arrange for the adjacent surfaces to be proximal to the top of the mold to facilitate the addition of vents. An example of this can be seen in Figure 2, where the flat side of the soft robotic finger, which poses a lower bubble risk, is on the bottom side of the mold, while the tips of the bellows that are prone to trapping bubbles are oriented upward and each is individually directly vented to the top of the mold. As with casting, it is important that the exit point of each vent is above the highest point of the part to avoid an incomplete molding as a consequence of siphoning. Risers in our implementation are larger vents with the purpose of venting silicone, which serves as an indication that silicone has reached the furthest points of the mold.

In traditional injection molding, vents can be manufactured as small as 13 µm in metal molds, but features this small are not achievable due to the limits in 3D printing resolution and the inability to clean out silicone blocking a vent this small in 3D printed molds.[41] Instead, we have been able to achieve vents as small as 400 µm in diameter on an Stratasys Objet500, which serves as an open riser to allow material to escape. Material exiting through distributed vents also gives a visual indication that silicone has reached all corners of the mold. Clear 3D printed molds (such as Stratasys VeroClear or Formlabs Clear Resin) give an excellent visual of the mold flow during injection to inform future mold revisions. Bubbles may be observed in the rubber as it begins to exit through the vents and the injection molding process can be stopped once the occurrence of bubbles in the purged material subsides. If bubbles are formed during the injection molding process even after consideration went into the placement of vents and risers in the model, a small drill bit can easily be used to create a new opening without reprinting the mold.

To facilitate cleaning and reusing 3D printed molds with this laboratory-scale silicone injection molding setup, we recommend using vent holes that are larger than those used in traditional, high-volume injection molding, and smaller than is sometimes used for casting in multi-part molds. We acknowledge that casting can also be achieved without the use

Table 5. Pricing for cartridge guns in 600 and 1500 mL options, for manual, electric, and pneumatic actuation.

	1:1			2:1			10:1		
	Man.	Elec.	Pneu.	Man.	Elec.	Pneu.	Man.	Elec.	Pneu.
600 mL	\$67[a)]	\$598[b), d,e,f)]	\$444[c), d,e,f)]	\$139[b), d,e,f)]	\$598[b), d,e,f)]	\$444[c), d,e,f)]	\$68[b)]	–	–
1500 mL	\$99[a)]	\$694[b)]	**\$572**[b)]	–	–	–	\$139[b), d,e,f)]	\$624[b)]	\$568[b)]

[a)]JES Innovations; [b)]Albion Engineering; [c)]PC Products; [d,e,f)]Same Gun. Noted cartridge guns can be changed with included parts for different ratios or sizes. Bold option indicates recommend gun for first purchase. Options shown are the lowest cost for each category, with prices as of February, 2021.

Table 6. Guidelines for molding components.

	Dimensions [mm]	
	Min	Max
Sprue	3.5	6.0
Runner	Sprue Min	Sprue Max
Gate	2.5	6.0
Open riser	1.25	2.0
Vents	1.0	2.0

of vent holes, with proper mold design and injection pressures (and many times applying vacuum to the mold prior to injection). A typical vent hole size we have used is 0.5 mm at the exit point on the surface of the mold, with a 5° taper that opens towards the molded part. The purpose of this is to facilitate removal without damage to the part, and avoid having residual material stuck in the mold. As part of the removal process, it can also be helpful (though not critical) to first cut excess rubber from the exterior of the mold. Otherwise, the connection points at the exit of the vents must be torn to remove the molded part. Similarly, we recommend a gate diameter of 5 mm and taper of 5°, with a 3 mm chamfer for the injection port, when using the Optimixer static mixing nozzles with a tapered tip. This should be adjusted for other nozzle tip geometries.

5.3. Mold Clamping and Alignment

A successful mold has poka-yoke features to prevent assembly mistakes, and alignment features such as an elastic averaged kinematic coupling to ensure alignment of the two or more mold cores.[42] Molds should be fastened with proper hardware and follow general Cone of Influence guidelines for nuts and bolts.[43]

5.3.1. Assembly, Poka-Yoke

The simplest method to poka-yoke (Japanese for "mistake-proofing") a two-part mold, such as a rectangular shape, is chamfering an edge at 45° as seen in **Figure 7**C. Once alignment features are added as described below, the part cannot be clamped incorrectly. The 45° chamfer is also a quick visual to align the edges during assembly.

5.3.2. Alignment, Elastic Averaged Kinematic Coupling

Many methods have been used previously to align two or more part molds for soft robots, typically using dowel pins or screws. Both of these methods are prone to alignment errors unless rigorously designed, and even so can cause alignment or release issues once the mold is heated. As seen in Figure 7A, the recommended method for mold alignment is designing an elastic averaged kinematic coupling on the perimeter face of the mold. The coupling consists of a raised 2 mm × 2 mm lip at 5°, where the mating mold has a 3 mm tall × 2 mm cutout at 5°—creating a face to face contact on the sloped face. The additional 1 mm gap allows a flat head screw driver to be used to separate the molds around the full perimeter. All external and internal corners have a relief area where no lip exists, to allow expansion and contraction of the mold and account for any 3D printer errors.

In addition to this coupling, it is recommended that all mold parts be printed on the same 3D printer, using the same material, to eliminate potential scaling or curing problems between parts.

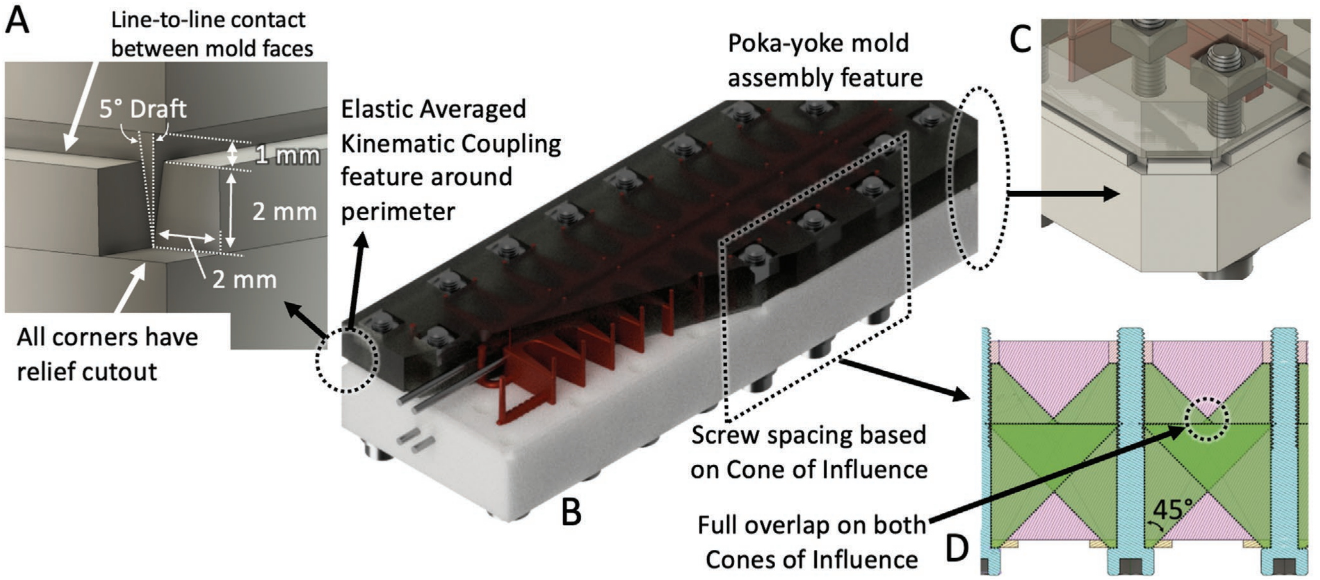

Figure 7. Mold design guidelines for injection molding. A) Elastic averaged kinematic coupling design showing sizing and draft angles for line-to-line contact; B) full mold showing cutaway; C) poka-yoke assembly feature with a 45° cut to prevent simple assembly mistakes; D) cone of influence drives the fastener spacing, ensuring clamping forces are properly distributed to seal the mold faces.

5.3.3. Clamping, Cone of Influence

Traditional injection molding machines hold molds in a hydraulic press, allowing quick closure and opening for cycle times between 0.5 and 7 s.[25] For prototyping, molds are instead clamped with screws around all perimeter faces, to allow for high forces but without the cost of making steel molds and loading into a hydraulic press. We prefer M5 screws with square nuts embedded in one part of the mold, and screws with large flange washers on the opposite face. Square nuts better resist torques compared to a hex nut in a soft material, such as 3D printed plastics. An electric screw driver with a torque limiter is used to quickly drive the screws, whose quantity could be up to 30 per mold (as seen in Figure 9C).

To ensure proper distribution of clamping forces around the mold and prevent flashing or bulging at the mold faces, a good design follows the cone of influence of a bolted joint.[43] The modulus of the 3D printed molds are one to two orders of magnitude less than the bolting hardware, so the mold material should be considered to have little structural integrity and thus rely on the forces between the bolt head, washers, and nut for clamping. As illustrated in Figure 7, the Cone of Influence starts at the bottom of the bolt head, and extends a maximum of 45° to toward the nut. A separate cone likewise extends from the beginning of the nut toward the bolt head. The lateral spacing of screws should ensure that the cones emanating from the nuts and bolts overlap at the mold faces, which will ensure a seal. Molds designed with too few fasteners, or clamped with a spring clamp, will fail by cracking, leaking, or bulging under injection pressure.

5.4. Mixing Efficacy: Centrifugal Planetary Mixing, Manual Mixing, and Static Mixing Nozzles

Silicones are typically mixed with a centrifugal planetary mixer (such as a Thinky or FlackTek SpeedMixer), stand mixer, or by hand. To give reassurance that materials traditionally mixed in a centrifugal planetary mixer were equivalent to static mixing nozzles, tensile tests were performed according to ASTM D412 for three commonly used silicones, with six types of static mixing nozzles as presented in **Figure 8**. The three silicone rubbers were also mixed by hand following the supplier recommendations, stirring for 3 min (with a wooden mixing stick from Smooth-On), scraping all edges during the mixing process, and degassing in a vacuum chamber at 29 in. Hg (736 Torr) for 3 min immediately after mixing. Material was cast into a sheet, and punched with an ASTM D412 Sample Cutting Die (Type C).

The mixing results for all materials showed no statistically significant difference between mixing methods, except a couple outliers. Hand mixing generally was equivalent to centrifugal planetary mixing. Static mixing nozzles generally performed equivalent or slightly better than hand or planetary mixing. Centrifugal planetary mixing noticeably heats up the material more than the other options, reaching up to 40.0 °C as observed immediately after removing the material, based on 2-min mixing at 2000 RPM (as recommend by Thinky). Mixing by hand or through static mixing nozzles did not noticeably heat the material during testing. Preventing material from heating is desirable to prevent premature curing of the silicone.

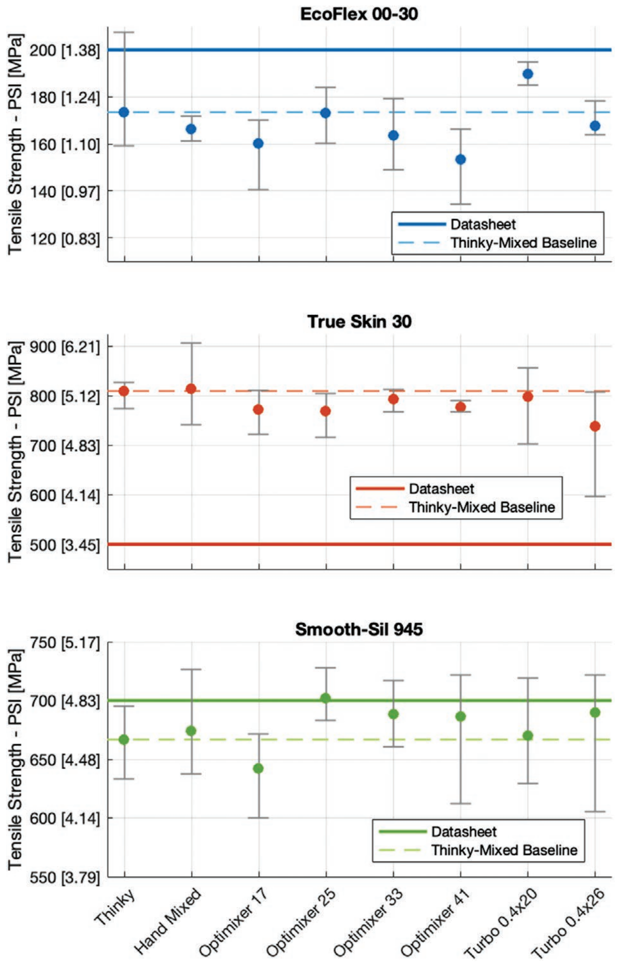

Figure 8. Silicone mixing tensile test results, for a centrifugal planetary mixer (Thinky ARE-310) and six static mixing nozzles, following ASTM D412 – Tensile testing of Elastomers with $n \geqslant 5$. Ecoflex 00-30 (00-30 hardness, 3000 cps), True Skin 30 (30A hardness, 15 000 cps), and Smooth-Sil 945 (45A hardness, 3000 cps) were tested. Error bars represent one standard deviation.

The results of this test show that more mixer elements do not necessarily outperform lower-mixing element mixers with respect to the resulting material strength. For example, materials mixed with the 41 element Optimixer exhibit similar or slightly reduced tensile strength as materials mixed with the 25 element Optimixer. In addition, the former costs 70% more and retains 50% more dead volume. The larger element width of the Turbo mixers allow much higher flow rates which could be compelling to fill molds faster and with less pressure drop through the mixing element.

In our investigation of mixing efficacy using a centrifugal planetary mixer, hand mixing, and static mixing nozzles, we have found static mixing nozzles can equal or outperform all other options with regards to the resulting material tensile strength. While there are certainly static mixing nozzles that have superior performance, only one or two types of static mixing nozzles would be needed for most silicones found in

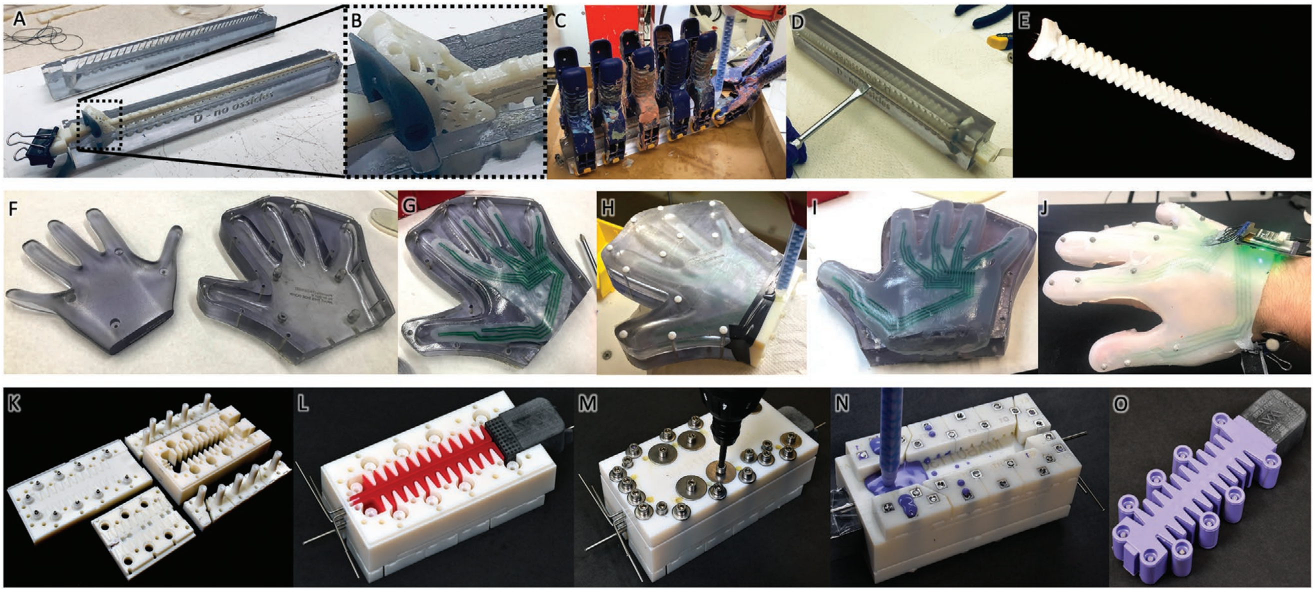

Figure 9. Examples of parts made through injection molding. A–E) Shows a bi-directional sea star-inspired actuator that contains a series of rigid ossicles. A) Mold preparation with all ossicles inserted; B) close-up view of the porosity features for silicone inclusion; C) mold is clamped and injected with True Skin 30; D) mold is pried open; E) completed part. F–J) A wearable glove with an embedded fluidic channel for sensing. F) The mold contains a large core to create the hand cavity; G) the ionic microchannel is inserted; H) the glove mold is injected with Ecoflex 00-30; I) the top mold is removed to reveal the glove; J) the completed glove in use. K–O) A bi-directional actuator with ten magnetic dome actuators that contain a number of embedded components, such as mesh, magnets, tubing, and a rigid 3D printed cap for connection. K) All 13 mold pieces; L) the mold assembled with soft cores (red), cap piece, and rods to hold the mold components in place; M) mold is clamped with M5 fasteners using a torque screw driver; N) injection of Smooth-Sil 945; O) final molded part.

a lab, and we recommend the Optimixer 25 (for cost and mix quality) and the Turbo 0.4×20 (for highest flow rate and mix quality).

6. Injection Molding Steps

6.1. Injection

Once a mold is fully assembled and clamped, the silicone cartridge is loaded into the cartridge gun, using the piston directional control button to retract or actuate (if using a pneumatic gun), while using the trigger to move the piston as labeled in Figure 3C. Next, the cartridge cap is removed, and the cartridge is purged into a cup by actuating the gun forward until parts A and B flow at the same rate. This step is generally only needed on the first use of the cartridge, since the volume of both silicones may not be identical from filling.

Next, air pressure is adjusted (as seen in Figure 3C) depending on the material and mold complexity (up to 827 kPa depending on the injection gun in use), a mixing nozzle is screwed onto the cartridge and material is purged an equal or greater amount relative to the retained volume of the nozzle (see Table 4) to ensure good initial mixing of the material and to remove air in the nozzle. The mold can then be raised on a jack scissor stand (as seen in Figure 3C) until firm contact is made from the tapered mixing nozzle to the tapered injection port. Additional force will be applied to this port once dispensing occurs, as the cartridge is displaced 1–2 mm downward when pressurized.

Material can (and should) then be injected into the mold continuously without stopping to avoid introducing air into the mold. Once material reaches the furthest riser and no bubbles are observed, the injection process can end, and the mold can be removed.

If injecting multiple parts, the mixing nozzle can be left attached so long as it does not exceed the pot life of the material, and no additional purging is required. It is best practice to remove the nozzle from the cartridge when complete, replacing it with a plug, and storing the cartridge on its side. The cartridge should be considered empty if there is less than 5 mm of remaining piston travel, as the last portion of material is likely to contain air bubbles trapped between cartridge uses.

6.2. Cartridge Filling

The technique to filling two-part cartridges is outlined in Section S1, Supporting Information, which discusses the filling, degassing, and capping of the cartridges.

7. Application Examples

This two-part silicone injection molding for laboratory scale production, made possible by re-purposing construction equipment, is a new and useful tool for the development of novel geometries for soft robots. Injection molding has allowed more complex parts to be made, with wall thicknesses down to 0.4 mm, 3D rigid porous networks to transition from soft to hard down to 2 mm grid spacing with 1 mm holes as seen in Figure 9A–E, K–O, and large surface area overmolds 1.5 mm thick as seen in Figure 9F–J. Here, we demonstrate three parts, shown in Figure 9, that would be difficult or impossible to make via traditional casting methods, in addition to the soft fingers seen in Figure 2.

Figure 9A–E demonstrates the injection molding of an actuator inspired by an arm of a brittle star that has a large number of embedded rigid ossicles. These ossicles are 3D printed with breakaway interconnections, baked the same as 3D printed molds, and inserted into the two-part mold. The mold is clamped and injected with True Skin 30. The pressure of the injection allows silicone to infiltrate throughout this entire actuator, flowing into the numerous undercuts and complex pathways that otherwise would trap bubbles via traditional casting methods.

In Figure 9F–J, we show a soft wearable glove being molded with Ecoflex 00-30. The glove has a premade sensing layer with microchannels filled with ionic liquid that are placed and aligned inside the glove cavity. The mold is then clamped, and Ecoflex 00-30 is injected. The glove geometry is challenging for traditional casting due to the large core and thin walls. There are significant undercuts that pressurized silicone excels at reaching. With a casting approach, the two halves of the glove would likely need to be made in separate parts and adhered together subsequently.

In Figure 9K–O, a bi-directional bellow-type actuator that contains ten separate dome actuators is shown. This part requires a significant number of embedded components: 10 magnets, 11 mesh inserts, tubing, a large 3D printed mount cap to transition from soft to hard mounting, and soft cores used for molding the bellow cavities. The mold requires a two-step injection process, with a 13-part mold for the first step, and a two-part mold for the second (not shown). The mold is clamped with a number of fasteners, and injected with Smooth-Sil 945.

To traditionally cast the bi-directional bellow with integrated dome actuators, most of the pre-assembled inserts would have to be placed into open mold parts filled with silicone and then quickly assembled, making the alignment challenging. All the mesh inserts would also need to be pre-dipped into silicone to ensure adequate penetration before being placed into the mold. The thin domes walls (0.65 mm) are also prone to bubble defects using casting methods.

8. Conclusion

Our method of injection molding soft actuators is a logical step to increase part resolution, increase actuator complexity, decrease manufacturing time, reduce defects, and does not require large industrial injection molding equipment. Our method allows for high part repeatability by replacing the traditional (artisanal) casting process, instead making the manufacturing process a science. In addition to guidelines for injection mold design (injection ports, vents, and runners), we introduce three mold making techniques that make assembly (poka-yoke), alignment (elastic averaged kinematic coupling), and clamping (cone of influence) robust and repeatable.

By adapting caulking and epoxy dispensers intended for building construction to low-volume prototype molding of soft actuators, we have identified affordable, off-the-shelf components to facilitate laboratory-scale, two-part liquid silicone injection molding. Using cartridge-based injection has the benefit of minimal upfront cost (at $67 for a manual injection gun, $2.20 per cartridge, and $2.07 per static mixing nozzle). Labs can quickly switch out materials loaded in the cartridges, without having to open buckets, measure, mix, and degas before use. By having cartridges degassed and with injection metered in the correct ratio, the overhead of molding is greatly reduced. Further, injection molding allows for significantly faster curing materials, since once the part is injected, there is no additional clamping or inserts required. Materials with cure times less than a minute can routinely be used, and the process of prototyping can therefore be accelerated. We have even found that users who have traditional molds use the injection molding setup to just dispense mixed materials into their existing poured molds, since the material is readily available and already prepared. Overall, the injection molding process we developed has increased the quality and throughput of our soft robot actuators by reducing user errors, defects, and enabling more complex parts to be produced.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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hydraulic/pneumatic actuators, soft actuator design, soft robot materials, soft sensors and actuators

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[1] F. Schmitt, O. Piccin, L. Barbé, B. Bayle, *Front. Robot. A.* **2018**, *5*, 84.
[2] M. T. Tolley, R. F. Shepherd, B. Mosadegh, K. C. Galloway, M. Wehner, M. Karpelson, R. J. Wood, G. M. Whitesides, *Soft Rob.* **2014**, *1*, 213.
[3] C. D. Onal, D. Rus, in *2012 4th IEEE RAS & EMBS Int. Conf. on Biomedical Robotics and Biomechatronics (BioRob)*, IEEE, Piscataway, NJ **2012**.

[4] A. D. Marchese, R. K. Katzschmann, D. Rus, *Soft Rob.* **2015**, *2*, 7.
[5] C. M. Schumacher, M. Loepfe, R. Fuhrer, R. N. Grass, W. J. Stark, *RSC Adv.* **2014**, *4*, 16039.
[6] A. B. Lawrence, A. N. Alspach, D. C. Bentivegna, in *2016 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, IEEE, Piscataway, NJ **2016**.
[7] K. C. Galloway, K. P. Becker, B. Phillips, J. Kirby, S. Licht, D. Tchernov, R. J. Wood, D. F. Gruber, *Soft Rob.* **2016**, *3*, 23.
[8] H. Zhao, Y. Li, A. Elsamadisi, R. Shepherd, *Extreme Mech. Lett.* **2015**, *3*, 89.
[9] K. P. Becker, Y. Chen, R. J. Wood, *Adv. Funct. Mater.* **2020**, *30*, 12.
[10] B. Mosadegh, P. Polygerinos, C. Keplinger, S. Wennstedt, R. F. Shepherd, U. Gupta, J. Shim, K. Bertoldi, C. J. Walsh, G. M. Whitesides, *Adv. Funct. Mater.* **2014**, *24*, 15.
[11] Y. Sun, Y. S. Song, J. Paik, in *2013 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, IEEE, Piscataway, NJ **2013**.
[12] M. Bell, I. Pestovski, W. Scott, K. Kumar, M. Jawed, D. Paley, C. Majidi, J. Weaver, R. Wood, *IEEE Rob. Autom. Lett.* **2018**, *3*, 3.
[13] M. A. Bell, L. Cattani, B. Gorissen, K. Bertoldi, J. C. Weaver, R. J. Wood, in *IROS 2020*, IEEE, Piscataway, NJ **2020**.
[14] D. S. Garcia Morales, S. Ibrahim, B.-H. Cao, A. Raatz, in,*New Trends in Mechanism and Machine Science*, Mechanisms and Machine Science, Springer International Publishing, Cham, **2020**, pp. 488–495.
[15] A. Zolfagharian, A. Z. Kouzani, S. Y. Khoo, A. A. A. Moghadam, I. Gibson, A. Kaynak, *Sens. Actuators, A* **2016**, *250*, 258.
[16] S. Seok, C. D. Onal, R. Wood, D. Rus, S. Kim, in *2010 IEEE Int. Conf. on Robotics and Automation*, IEEE, Piscataway, NJ **2010**.
[17] M. Wehner, R. L. Truby, D. J. Fitzgerald, B. Mosadegh, G. M. Whitesides, J. A. Lewis, R. J. Wood, *Nature* **2016**, *536*, 451.
[18] S. Abondance, C. B. Teeple, R. J. Wood, *A Dexterous Soft Robotic Hand for Delicate In-Hand Manipulation*, IEEE, Piscataway, NJ **2020**.
[19] F. Johannaber, *Injection Molding Machines: A User's Guide*, Hanser, München **2016**.
[20] M. Bont, C. Barry, S. Johnston, *Polym Eng Sci.* **2021**, *61*, 331.
[21] E. B. V. Goodship, *Practical Guide to Injection Moulding*, Rapra Technology, Shropshire, UK **2004**.
[22] N. Patel, *Master of Science in Plastics Engineering*, University of Massachusetts Lowell **2002**.
[23] L. Matysiak, P. Saj, R. Sekula, in *V European Conf. on Computational Fluid Dynamics (ECCOMAS CFD)* **2010**.
[24] Healthcare liquid silicone rubber - injection molding guide, Technical report, Bluestar Silicones **2014**, http://www.silbione.com/wp-content/uploads/2014/02/LSR-Users-Guide.pdf.
[25] Liquid injection molding: Processing guide for SILASTICTM Liquid Silicone Rubber (LSR) and SILASTICTM Fluoro Liquid Silicone Rubber (F-LSR), Technical report, The Dow Chemical Company, **2020**.
[26] Y. Zhang, M. Mischkot, H. N. Hansen, H. N. Hansen, P.-E. Hansen, *Replication of Microstructures on Three-Dimensional Geometries by Injection Moulding of Liquid Silicone Rubber*, Technical Report **2010**, https://www.researchgate.net/publication/280223167.
[27] E. Haberstroh, W. Michaeli, E. Henze, *J. Reinf. Plast. Compos.* **2002**, *21*, 5.
[28] M. Barbaroux, G. Stalet, G. Regnier, J.-P. Trotignon, *Int. Polym. Process.* **1997**, *12*, 2.
[29] The Realities of Aluminum Tooling, https://www.moldmakingtechnology.com/articles/the-realities-of-aluminum-tooling
[30] How Long Can I Expect My Injection Mold to Last? https://www.kaso.com/how-long-can-i-expect-my-injection-mold-to-last/
[31] Injection Molding, Casting, and Thermoforming with 3D Printed Molds, https://formlabs.com/blog/low-volume-production-injection-molding-casting-thermoforming/
[32] Nordson EFD 2K Selection Guide, https://azcscxpprodcdn.azureedge.net/-/media/Files/Nordson/efd/Products/Manuals/2K-Products/Nordson_EFD_2K_Selection_Guide.PDF
[33] Two-Component Dispensing Systems Guide, Technical report, Nordson EFD, East Providence, RI, **2019**, https://www.nordson.com/en/divisions/efd/products/mixers/optimixer.
[34] B. Stritzke, *Custom Molding of Thermoset Elastomers: A Comprehensive Approach to Materials, Mold Design, and Processing*, Carl Hanser, Munich **2009**.
[35] N. W. Bartlett, K. P. Becker, R. J. Wood, *Soft Matter* **2020**, *16*, 5871.
[36] Technical Guide to Cure Inhibition, https://www.techsil.co.uk/resource-centre/technical-guide-to-cure-inhibition/.
[37] P. Preechayasomboon, E. Rombokas, *PLoS ONE* **2020**, *15*, e0234354.
[38] F. Connolly, P. Polygerinos, C. J. Walsh, K. Bertoldi, *Soft Rob.* **2015**, *2*, 1.
[39] M. Bell, T. Paschal, J. Sperry, S. Sieniewicz, R. Wood, J. Weaver, *IEEE Rob. Autom. Lett.* **2019**, *4*, 4.
[40] M. A. Bell, J. Weaver, R. J. Wood, *[In Review] Soft Rob.* **2021**.
[41] Back to Basics on Mold Venting https://www.ptonline.com/articles/back-to-basics-on-mold-venting
[42] A. Slocum, J. Hart, P. Willoughby **2001**.
[43] A. Slocum, *Precision Machine Design: Design of Joints and Bearing Rails* **1994**.

