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Elastomeric Origami: Programmable Paper-Elastomer Composites as Pneumatic Actuators

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Abstract

This paper describes the development of soft pneumatic actuators based on composites consisting of elastomers with embedded sheet or fiber structures (e.g., paper or fabric) that are flexible but not extensible. On pneumatic inflation, these actuators move anisotropically, based on the motions accessible by their composite structures. They are inexpensive, simple to fabricate, light in weight, and easy to actuate. This class of structure is versatile: the same principles of design lead to actuators that respond to pressurization with a wide range of motions (bending, extension, contraction, twisting, and others). Paper, when used to introduce anisotropy into elastomers, can be readily folded into three-dimensional structures following the principles of origami; these folded structures increase the stiffness and anisotropy of the elastomeric actuators, while keeping them light in weight. These soft actuators can manipulate objects with moderate performance (for example, they can lift loads up to 120 times their weight). They can also be combined with other (for example, electrical) components to increase their functionality.

1. Introduction

So-called "hard" robots—robots based on rigid structural elements, typically of metal and conventional mechanical joint bearings, and actuators—are highly evolved for operations in controlled environments (e.g., in manufacturing). They are, however, often heavy and not well adapted for unstructured, unstable, or fluid environments (e.g., lose gravel, sand, or mud). Robots used for performing delicate tasks (e.g., surgery[1, 2]) can be flexible in their movement, but are quite specialized. Airborne robots (e.g., unmanned and autonomous air vehicles) are highly evolved, but do not have to deal with the vagaries of rough terrain.[3]

"Soft" robots—robots fabricated using flexible or elastomeric structural elements—offer potentially useful approaches to problems in robotics. They can be designed to have low centers of gravity. They can also distribute pressure evenly on the ground, or with the objects with which they interact. They can use their often highly non-linear responses to actuation to accomplish, relatively simply, types of motions and tasks (e.g., grasping soft objects[4]) that would be very difficult to accomplish with hard robots and conventional controllers.[5, 6]

Pneumatic soft robots—such as those driven by micro-pneumatic actuators embedded in elastomeric materials—offer an underexploited entry into the family of soft robots and soft machines. For pneumatic actuation to be most useful, it must satisfy three conditions: i) It should be flexibly controllable in direction and force. ii) It should take advantage of its non-linearities to simplify the accomplishment of functions that are difficult with linear actuators. iii) It must be easily incorporated into designs that are practical to fabricate, inexpensive, and functional.

New materials and structures that are easy to control, inexpensive, and compatible with soft actuation and soft robotic applications would expand the capabilities of this area of functional materials. Elastomeric polymers will be an important class of materials for soft robotics. Unless intrinsically anisotropic in structure (e.g., liquid crystals) or processed (e.g., by stress orientation) to generate anisotropy, organic polymers are usually approximately isotropic in their response to stress, and thus constrained in the range of motion they can generate on actuation. We wished to introduce controlled anisotropy into the response of elastomers to stress (especially that caused by pressure in pneumatic actuation) by design. This paper demonstrates a method of doing so by the fabrication of composite structures comprising elastomers and flexible sheets (especially paper, but also a range of other sheet and fiber materials). Using composites of paper and a highly elastomeric siloxane (Ecoflex ©), we demonstrate the range of motions that can be generated by pressurization (including extension, contraction, twisting, bending, and combinations of them).

2. Background

The emphasis of much of robotic development has been on structures intended for durability, to apply force, to operate in human-unfriendly or constrained environments, and to move at high speed. Many of the structures of hard robots are based on structures derived from the body plans of mammals (or parts of them).[1, 7, 8] Their skeletons are typically rigid, and electric motors (or sometimes hydraulic or pneumatic systems) provide actuation.[9, 10]

Muscle—a structure ubiquitous in nature—still has no real counterpart in materials science, robotics, or actuation, although there are examples of electromagnetic actuators and other useful structures (for example “air muscles”) which have some muscle-like properties.[11] There are a number of approaches exploring muscle-like structures as new types of components for soft robotic, but few have been widely developed or deployed.[12-14]

Many biologically inspired soft robots have been built using electroactive polymers (EAPs) actuators.[15] For example, Nie et al. (2007) developed a tortoise-like flexible micro robot that can crawl and swim underwater by using legs actuated by an ionic conducting polymer film (ICPF).[16] The response of systems based on EAPs to control signals are typically slow (unless they are very small) since they require the diffusion of ions for their function. Ionic polymer-metal composites have been used to fabricate robots that use undulatory locomotion to generate forward impelling force, and move in ways that resemble worms[17] or fish.[18] EAP gels have been used to fabricate gel robots that changes shape under the influence of an external electric field. For example Otake et al. (2002) developed a robot in the shape of a starfish that used an EAP gel to turn over on application of electric fields.[19] Both EAPs and ICPF suffer, however, from shortcomings that make their extensive use in soft robots unlikely: For example, many ionic EAPs work only in aqueous media,[20] conjugated polymers and ionic polymer-metal composites have short lifecycles due to creep and material degradation,[21] and EAP gels require very high voltage for maximum actuation (up to 150 MV/m).[22]

Our initial work in soft robotics has demonstrated the usefulness of pneumatic networks (PneuNets)—fabricated in PDMS elastomer, using soft lithographic techniques highly developed in microfluidics—to actuate soft structures.[4] In the research described in this paper, we were interested in increasing the range of motions available for soft robots, while keeping a high ratio of performance to cost. Our soft robotic actuators use networks of pneumatic channels (PneuNets) fabricated in Ecoflex or Ecoflex/PDMS composites that include flexible but inelastomeric structures (paper, cotton cloth, fiber, nylon mesh, thin polymer films, polyester tulle, or metallic mesh), to control the motion resulting from pneumatic actuation.

3. Results and Discussion

3.1. Choice of Materials

We used a silicone elastomer (Ecoflex 00-30, Smooth-on, http://www.smooth-on.com) and a polyester/cellulose blend paper (VWR, West Chester, PA) for most demonstrations of actuators, but a number of other polymers, fabrics, films, tapes, threads, and other elastomeric and flexible structures also work. Ecoflex is commercially available, as are many sheet, strip, tube, and fiber structures. They are easy to work with and relatively inexpensive.

Ecoflex is a translucent, soft elastomer (00-30 Shore hardness) that can withstand repeated bending, and fractures only above a maximum strain of 900%.[23] We used Ecoflex where high extension is necessary (e.g., the pneumatic channel). Polyester/cellulose blend paper has a high tensile strength (~50 N/mm^2), is light-weight (~68 g/m^2), and is easily shaped by cutting. Paper structures can be easily embedded into elastomers (paper absorbs Ecoflex to a level of ~300 mL/m^2 for polyester/cellulose blend paper).[23] Because of its high tensile strength, paper limits extension of structures in which it is embedded (to <5% in Ecoflex), but allows bending without significant increase in bending modulus.

Figure 1 describes the fabrication process. The choice of materials and the design of the channels determine the response of the device to applied pressure. **Figure 2** shows how a homogeneous elastomeric matrix expands isotropically upon pressurization of its PneuNet. When the PneuNet is embedded in a paper-elastomer composite, however, pressurization of the structure results in anisotropic deformation.

3.2. Fabrication

Soft lithography is widely used to form channels in silicones and other elastomers.[24, 25] We have applied these methods to the fabrication of soft PneuNets inside paper-Ecoflex composites. The molds used in the construction of the PneuNets were designed using computer-aided design (CAD, Airlibre Inc.) and generated by three-dimensional (3D) printing (StrataSys Dimension Elite) with acrylonitrile butadiene styrene (ABS) plastic.[26] Ecoflex releases readily from these molds; we have used them over a hundred times with no damage or degradation in performance. We formed the PneuNets by first casting Ecoflex prepolymer in the mold and curing it at 60 ˚C for 15 min. Right after the unmolding, the resulting open-channel structure was placed in contact with a piece of paper that had been completely filled with Ecoflex by spreading the elastomer on it, followed by degassing to remove air bubbles in a desiccator at 36 Torr for 3 min. After baking the ensemble at 60 ˚C for 3 h, it cured fully, and generated the final composite device with channels. We connected these channels to 1.57 mm O.D. polyethylene tubing using a 1.65 mm I.D. cannula (see Supplemental Material). Finally, we trimmed the excess paper and polymer with scissors.

3.3. Proof of Concept: Bending Contractor

Figure 3 provides an illustration of the motion resulting from pneumatic actuation of an elastomeric structure with a central pneumatic channel having stripes of paper embedded in its top and the bottom. When this structure is pressurized (50–200 mbar), the pneumatic channel expands in the regions that are most compliant (that is, that have the lowest stiffness). Since the embedded strips of paper constrain the deformation of the channel, the asymmetric elongation induced on the device makes it bend. After releasing the pressure of the pneumatic channel the system fully recovers its original shape.

3.4. Linear Contractor

Paper is a versatile material. Sheets of paper are easily patterned, rolled, or folded into three-dimensional structures.[27, 28] The range of structures that can be fabricated by simple creasing of paper is remarkable, and is the basis of origami. Embedding paper structures into elastomeric matrixes offer many possibilities for programming the mechanical properties of the resulting composites, and their response to pneumatic actuation.

Pneumatic artificial muscles (PAMs) – based on the pressurization of a thin, flexible, tubular membrane with fiber reinforcement – enhance strength and mobility when implemented in precision robotic tasks, and have also been used in other technologies such as those used in human exoskeletons.[29, 30] To characterize the relative change of length of the actuators upon pressurization, we used ε, a coefficient that can be defined by Eq. 1. Here l_{Patm} is the length of the device when no external pressure is applied to the PneuNet

(P_{atm}= atmospheric pressure) and l_P is the length of the device upon application of a pressure (P). A positive sign for ε indicates extension on pressurization; a negative sign indicates shortening.

$$\varepsilon = \frac{l_P - l_{Patm}}{l_{Patm}} \tag{1}$$

Figure 4 shows a soft actuator with its design based on a PAM, which contracts on pressurization (ε= -0.27 at P= 200 mbar). To fabricate this device, we trimmed and cut a single sheet of paper (~200 µm thick) with a laser cutter (Fig. 4A). Then we rolled and glued the patterned piece of paper into a cylinder, and placed the structure in a tube-shaped mold with a gap of 1mm. The mold was filled with Ecoflex, and the ensemble was degassed in a desiccator (36 Torr) for 3 min to allow the liquid Ecoflex to permeate the paper completely. The paper-elastomer composite was cured at 60 ˚C for 15 min. After removing the composite structure from the mold, gluing both ends of the tube against paper-Ecoflex caps using Ecoflex limited their deformation upon pressurization.

3.5. Soft Robotic Actuators Based on Pleated Structures

3.5.1. Extensor

Origami is an art[27] (and a science[28]) that guides the fabrication of three-dimensional paper structures by folding. Embedding folded paper structures in elastomeric polymers makes it possible to fabricate soft pneumatic actuators in which motion on pressurization is determined by the pattern of folds in the paper. For example, the embedded paper structures can reinforce the elastomeric matrix, and generate actuators that can withstand pressures up to 300 mbar, and therefore manipulate heavy loads (up to 0.3 kg/cm^2 of supporting surface). Moreover, since the actuation depends on the number of pleats that are unfolded, large extension (large positive values of ε, Eq. 1) can be easily achieved by increasing the number of folds in the paper.

To demonstrate this strategy, we fabricated an accordion-like structure from a single, rectangular piece of paper (**Fig. S3** describes the origami design). The origami structure was unfolded, placed in the tube-like mold described before (Fig. 4), covered with Ecoflex prepolymer, and degassed at 36 Torr for 3 min. Once the origami structure was saturated with liquid polymer, we removed it from the mold and partially cured it at 100 ˚C for 1 min (extended, in vertical position) to obtain a uniform coating of the paper. Then we completely folded the partially cured paper-elastomer composite, held it with paper clips, and fully cured it at 60 ˚C for 15 min. The paper-elastomer pleated structure was then glued (using Ecoflex) to paper caps, leaving an internal sealed chamber for pneumatic activation. The actuator, which remains contracted in unpressurized state, extends as the pleated structure unfolds upon pressurization.

Figure 5 shows a bellows structure with ten creases; this structure extends (up to $\varepsilon = 3.61$) when pressurized at 170 mbar. The activation time of this actuator depends on how fast the air can be introduced into the device. By feeding the actuator with a compressed air source (600 mbar; 1.14 mm I.D. inlet tube with a length between pressure source and device of 25 cm) the actuator reached full extension in 352 ms (an average velocity during extension of 0.23 m/s; for reference, the speed of sound in dry air at 20 ˚C is 343.2 m/s). When the pressure in the pneumatic chamber decreased, the actuator folded up and recovered its resting shape (Fig. 5D); the hysteresis between the curves describing pressurization and depressurization was modest (Fig. 5C).

Counteracting the mechanical resistance of the paper can decrease this hysteresis. A simple method to built a restoring force into the actuator is to connect both of its caps with an internal elastomeric Ecoflex strip. In this structure, when the internal pressure is reduced, the elastic restoring force exerted by the internal Ecoflex strip exceeds the mechanical resistance of the paper-elastomer composite to folding, and effectively eliminates the hysteresis.

Paper-Ecoflex pleated structures are light. For example, the device shown in Figure 5 weighs 8.3 g. These actuators can, however, lift loads 120 times their weight. **Figure 6** shows an origami actuator lifting a mass of 1 kg upon applying a pressure of 238 mbar to its pneumatic chamber.

3.5.2. Angular Extensor and Other Actuators

Pleated structures offer many possibilities for generating complex actuation simply by local modification of the pleats. **Figure 7** demonstrates how the same type of bellows structure shown in Figure 5 can perform a different movement when the pleats of one of its lateral faces are glued together with Ecoflex. When the internal chamber of the actuator is pressurized, glued pleats are unable to open; this constraint forces an angular elongation of the actuator.

Similarly, **Figure 8**A and 8B shows how structures like the ones shown in Figures 5, 6, and 7 can perform different types of actuation by gluing together different pleats. Figure 8C shows the case in which the expansion of the pleats is partially constrained by the attachment of a paper strip soaked in Ecoflex with a length shorter than the length of the actuator at full extension. In this case, the actuator expands linearly until the paper-elastomer strip extends to its maximum, and thereafter in a curve. The length of the strip attached to the pleats of the bellows structure controls the radius of curvature of the actuator upon pressurization.

3.6. Twisting Actuator

Embedding a helical strip of paper into an Ecoflex tube results in a motion that combines twisting and extension. The pressurization of the central channel both elongates the tube and causes it to twist around its long axis. **Figure 9** shows an actuator that can twist up to 420 ° upon pressurization. It weighs 7.9 g and is able to apply a torque of 0.015 N·m at a pressure of 120 mbar. The actuator recovers its original shape without significant hysteresis when the internal pressure returns to ambient. We made another type of twisting actuator by embedding a helical thread into an Ecoflex tube (see **Fig. S2**).

3.7. Controlling Light Emission with Soft Material Composites

The procedure used to embed paper structures in Ecoflex can be used to provide functions other than mechanical actuation. We demonstrate this functional flexibility by controlling emission of light.

Figure 10 shows a pneumatic actuator that acts like a lantern by opening translucent windows hiding a blue light-emitting diode (LED) that is housed in the pneumatic chamber. This actuator embedded aluminum foil in a multilayer structure to make a bendable shield that blocks the light (Fig. 10A). The aluminum foil was also used to make the electrical contacts between the LED and the external voltage source (see Fig. 10C). We have characterized both the contraction and the normalized intensity emitted by this actuator upon pressurization (see Fig. 10G, 10H, and supporting information for details). In this demonstration, regulating the pressure inside the actuator easily controls both light emission and mechanics (in this instance, using coupled actuation). This type of coupling may be useful in connecting light emission to motion, and in control strategies that involve sensing actuators at a distance optically.

4. Conclusions

We demonstrated the feasibility of combining a highly stretchable elastomer (Ecoflex) with a non-stretchable but easily bendable sheet (patterned paper, fabric, string, polyester or metallic meshes, and polymer films) to prototype components useful in soft actuators, machines, and robots. These actuators show a range of complex motions (extension, contraction, bending, extension plus torsion) on pressurization; the corresponding motions would be difficult to achieve as simply with hard robots.

We believe that this technique for fabricating soft actuators, when more highly developed, has the potential to generate structures with applications in a range of uses, from biomedical devices to tools for disaster relief (for example, soft motile robots able to navigate tight spaces in complex environments such as the rubble of a collapsed building).

Actuation of composite Ecoflex/paper structures using PneuNets has five useful characteristics: i) It represents a flexible and relatively inexpensive solution to the problem of constructing simple, low-cost, light-weight soft actuators. ii) Paper, as the material that defines the motion of the actuator, is light-weight, readily available, and easy to manufacture (there are highly developed technologies for cutting and folding it). Paper can also incorporate a number of other functions (for example, electrical conductivity, by including flexible metal or graphite wires). iii) Following the principles of origami, paper can be folded and rolled into a range of complex three-dimensional structures with high stiffness, anisotropic responses, and light weight. iv) Fabrication of prototypes of soft actuators based on paper-elastomer composites requires only low-cost tooling and handwork. v) Paper can also be used as a substrate for laying out sensors[31] and electromechanical systems[32] that would improve the adaptive interaction between a soft robot or actuator and its environment or task.

The fabrication of soft actuators activated by PneuNets has two limitations: i) The particular set of composite materials described here (paper and Ecoflex) are not suitable for manipulating heavy objects, and (especially when stretched) are fragile and susceptible to damage by puncture or cutting. Straightforward engineering using tougher elastomers and higher pressures will allow them to generate higher forces. ii) These actuators require a source of compressed air for continuous operation (the tether required to connect the actuator to the gas, however, can be small and flexible). Although the requirement for a tether is not a limitation for a robot that is fixed in place, or restricted to a limited range of operations, it can restrict mobility, and makes completely autonomous operation impractical. It also makes difficult the miniaturization of the actuators below the cm scale. We describe alternatives to tethering in other papers.[33]

5. Experimental

Fabrication of Micropneumatic Soft Robotic Actuators by Casting of Elastomers: We designed a mold with the negative of the micropneumatic network of the soft actuator using computer-aided-design (CAD) software (Alibre, Inc.). A three-dimensional (3D) printer (StrataSys Dimension Elite, Eden Prairie, MN) printed the CAD design and formed a negative mold of the micropneumatic network on acrylonitrile butadiene styrene (ABS). We used a two-part silicone rubber (Ecoflex, Smooth-On Inc., Easton PA) to replicate the fabricated mold. This formulation mixed Ecoflex 00-30 part A and part B, 1:1 v/v ratio. After curing the elastomer at room temperature for 1 hour, we unmolded the elastomeric slab incorporating the pneumatic network, and contacted it with a polyester/cellulose blend paper (VWR, West Chester PA) that had previously been impregnated with uncured Ecoflex 00-30 by immersion and degassing in a desiccator at 36 Torr for 3 min. During the curing process, the elastomer that permeated the paper also cured and welded that structure to the slab of elastomer that contained the pneumatic network; after curing, the two are impossible to differentiate. After the composite structure is formed, and completely cured, we trimmed excess paper and elastomer with scissors.

Attaching to the Off-board Pressure Source: To connect the micropneumatic network of the soft actuator with the external gas source, we used polyethylene tubing (Intramedic, Sparks MD) with an outer diameter of 1.57 mm. This tubing was easily introduced into the soft actuator through a 1.65 mm cannula (see the snapshots of the process in **Fig. S4**). After removing the cannula, the elastomer conformed to the tubing, and blocked leakage of the low-pressure air. We attached the external gas source to the tubing of the actuator using a regular hypodermic needle (16G, 3.81 cm long) as the connector (process depicted in **Fig. S5**). Full actuation of these systems was achieved when the valve pressure on the gas source was 400-700 mbar (40-70 kPa).

Finite Analysis Simulations: We used COMSOL multiphysics 3.5a to calculate the deformation of a paper-elastomer composite material and a homogeneous elastomer material showed in Figure 1. The elastomeric material is isotropic and hyperelastic—ideally elastic material for which the stress-strain relationship derives from a strain energy density function—and is modeled as a Mooney-Rivlin[34] material with a Poisson's ratio of 0.5 using Eq. 2, where E is the Young's modulus, G the bulk modulus, and ν Poisson's ratio.

$$E = 2G(1 + \nu) \tag{2}$$

Since the material is almost incompressible, the bulk modulus is set to G= 100 kPa. The compression of the confined air is assumed to be adiabatic, giving the pressure-density relation expressed in Eq. 3, where p being the pressure, ρ being the density, and γ the adiabatic index.

$$\frac{p}{p_0} = \left(\frac{p}{p_0}\right)^{\gamma} \tag{3}$$

Paper was simulated as a material with E=1 GPa and G= 330 kPa. The number of elements for each model was 102,659. The value of P was 100 mbar.

Fabrication of Origami Actuators: To fabricate the origami actuators shown in Figures 5, 6, 7, and 8 we folded a rectangular piece of paper as described in **Figure S3**. We completely filled the origami structure with Ecoflex prepolymer by spreading the elastomer on it, followed by degassing to remove air bubbles in a desiccator at 36 Torr for 3 min. After removing the excess of Ecoflex with a plastic stick, we partially cured the elastomer by heating at 100 ˚C for 1min. In order to have the actuator folded at resting state we folded up the origami structure, held it with a clamp, and cured it for 15 min at 60 ˚C. We used two hexagonal pieces of paper-Ecoflex (see Fig. 5d) to seal the top and bottom of the origami structure, using Ecoflex to glue them.

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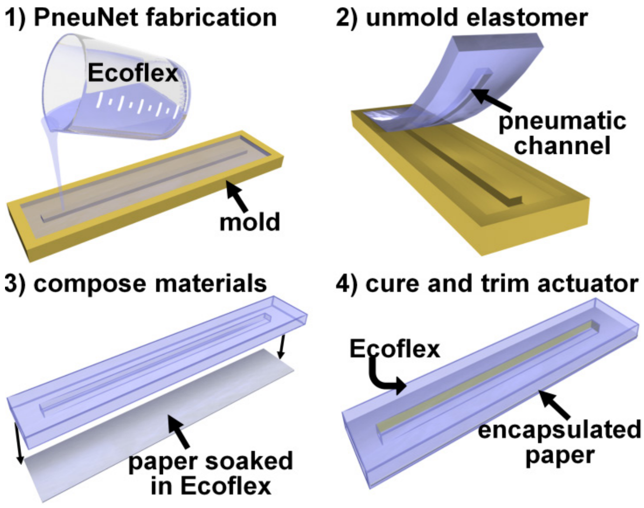

Figure 1. Schematic diagram outlining the fabrication of pneumatic soft actuators based on programmable paper-elastomer composites. a) Fabrication. First, an elastomer pre-mixture is poured over a mold with features designed to form the pneumatic channels. After curing, it is peeled off the mold, and placed in contact with a piece of paper soaked with uncured elastomer pre-mixture. Finally, the assembly is thermally cured to generate a sealed pneumatic channel. The final device is unsymmetrical in its mechanical response, because the top and bottom layers (elastomer and paper soaked with elastomer, respectively) have very different mechanical properties.

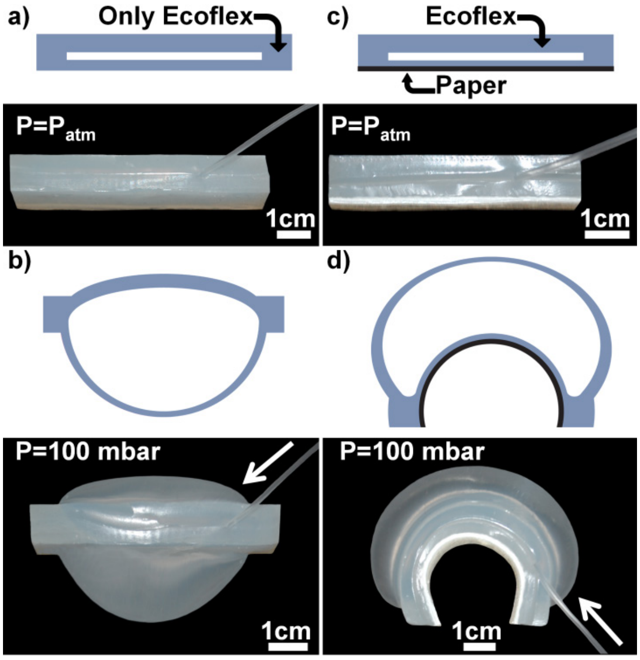

Figure 2. Comparison between the actuation of a pneumatic channel in a homogeneous elastomeric matrix, and in a paper-elastomer composite, under 100 mbar of pressure (1,013.25 mbar = 1 atm). a), b) Finite element analysis, and real device, showing the symmetrical deformation of an actuator fabricated in a single material. c), d) Finite-element analysis, and real device, showing the asymmetrical deformation of a paper-elastomer composite actuator upon pressurization. The schematics are sections along the center of the long axis of the structures. In this example, the higher tensile strength of the paper limits the extension of the elastomeric matrix, and results in bending of the device on pressurization.

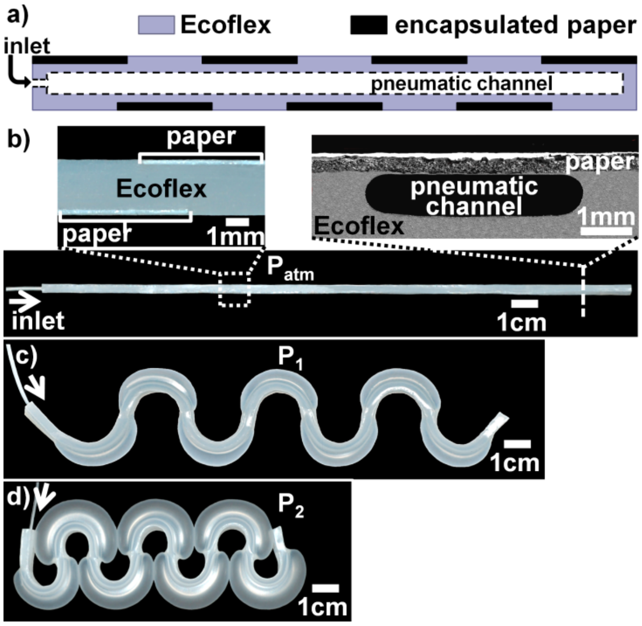

Figure 3. A contracting actuator consisting of multiple stages of bending actuators sharing a single pneumatic channel. a) The schematics of the design showing the layout of the pneumatic channel and the paper. b), c), and d) show the resting state (P_{atm}) and two different actuated states (P_1 and P_2) of such a device, respectively. Left inset in b) correspond to the optical image of the lateral cross section of the device. The right inset in b) corresponds to the SEM image of the perpendicular cross section of the device. P_1= 70 mbar P_2= 220 mbar. The arrows indicate the polyethylene tubes used to supply compressed air for actuation.

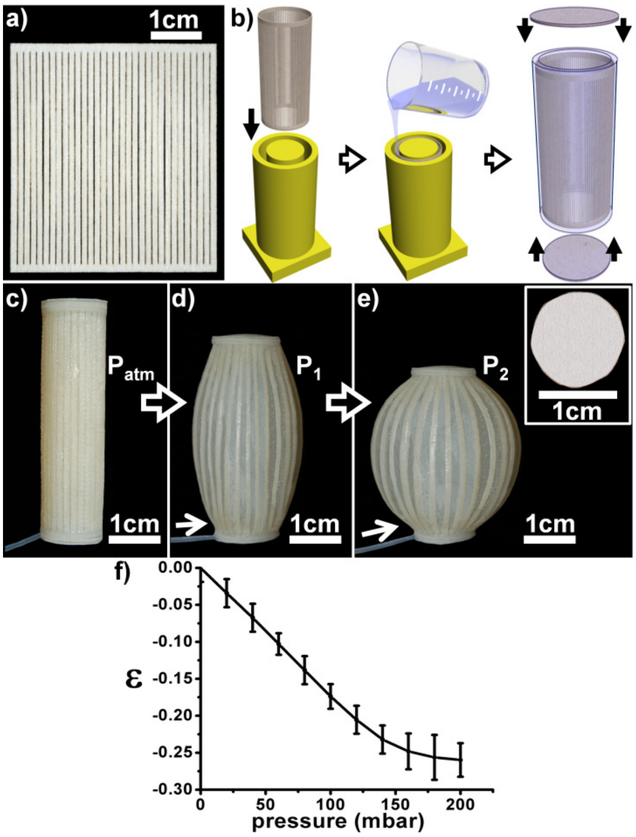

Figure 4. A contracting actuator that is composed of longitudinally patterned paper stripes rolled around a cylindrical pneumatic channel. a) The two-dimensional pattern of the paper. b) Schematic representation of the fabrication process: the paper with the pattern shown in a) is first rolled into a cylinder, and inserted into a cylindrical mold. A pre-mixed elastomer is then poured into the mold, and cured with the patterned paper embedded. The pneumatic chamber is completed by sealing the top and bottom against two circular pieces of paper embedded in elastomer. c), d), and e) show the resting and actuated states of such a device under atmospheric pressure (P_{atm}), P_1= 80 mbar, and P_2= 200 mbar, respectively.

f) Dependence on pressure of the contraction factor (Eq. 1) after 50 pressurization/depressurization cycles. The error bars show the standard deviation from the mean values.

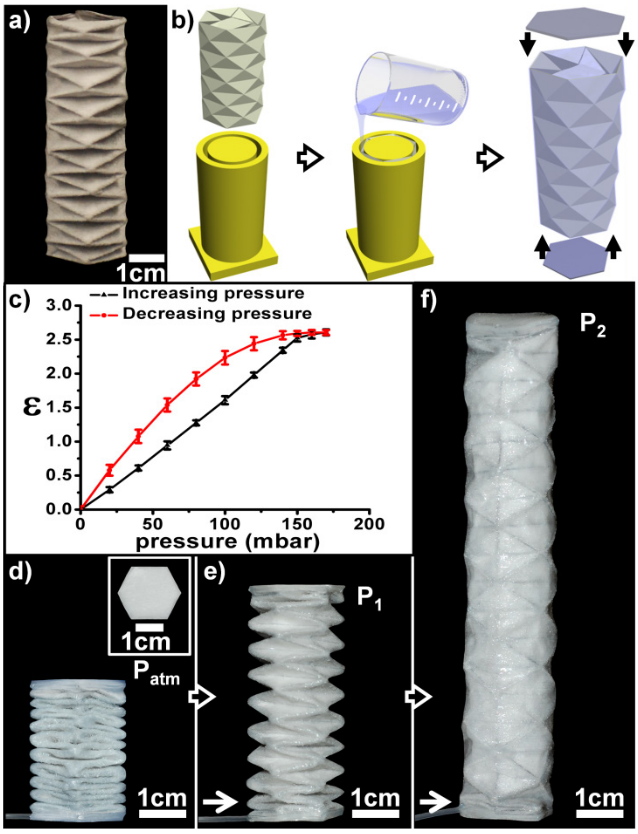

Figure 5. An elongation actuator with paper folded into a bellows-like pattern around a cylindrical pneumatic channel. a) The three-dimensional bellows-like pattern of the paper. b) The fabrication process is similar to the one shown in Figure 3: the paper with the pattern shown in a) is first inserted into a cylindrical mold. An elastomer pre-mixture is then poured into the mold, and cured with the patterned paper embedded. Finally, sealing the top and bottom completes the pneumatic channel. c) Pressure dependence of the extension (relative to its original length in the resting state) after 50 pressurization/depressurization cycles. d), e), and f) show the resting and actuated states of such a device under atmospheric pressure (P_{atm}), P_1= 50 mbar, and P_2= 170 mbar, respectively.

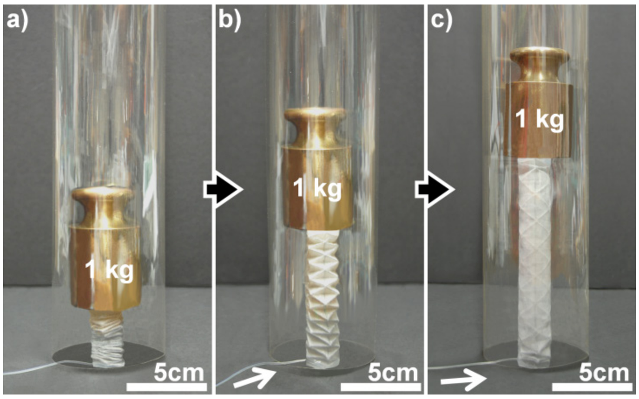

Figure 6. Origami extension actuator lifting a standard weight of 1 kg. A transparent tube was used to constrain the weight and origami actuator to a common vertical axis during the lifting. The pressure inside the pneumatic chamber of the actuator required to lift the weight to maximum extension of the actuator was 238 mbar. The actuator weighed 8.3 g. The arrows indicate the polyethylene tubes used to supply compressed air for actuation.

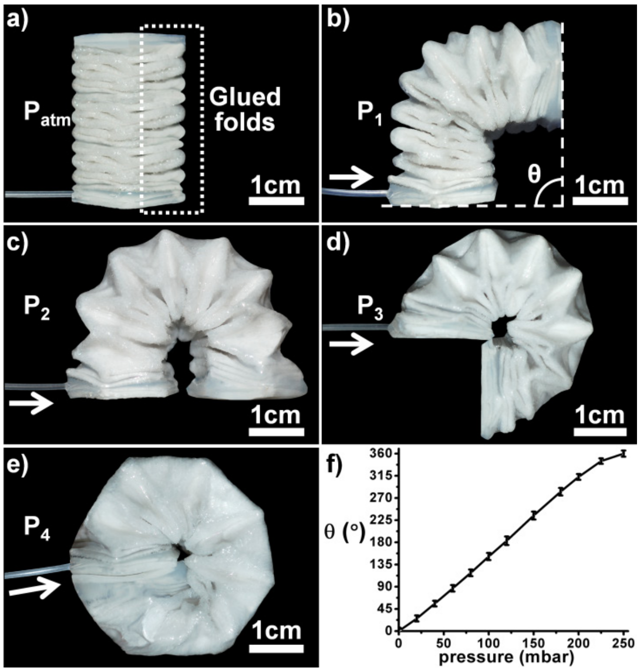

Figure 7. A biased bellows actuator, fabricated by modifying the elongation actuator in Figure 5. a) The three-dimensional bellows-like pattern of the paper, the same design in Figure 5. b) The fabrication process is similar to the one shown in Figure 5 except that the right edges of the paper structure were glued together. The elongation is possible from the left side of the device. c), d), and e) show the resting and actuated states of such a device under P_1= 60 mbar, P_2= 125 mbar, P_3= 175 mbar, and P_4= 250 mbar, respectively. f) Dependence of the angle θ on pressure after 50 cycles of pressurization/depressurization. The small standard deviation (error bars) indicates that θ does not change significantly as a function of the number of cycles.

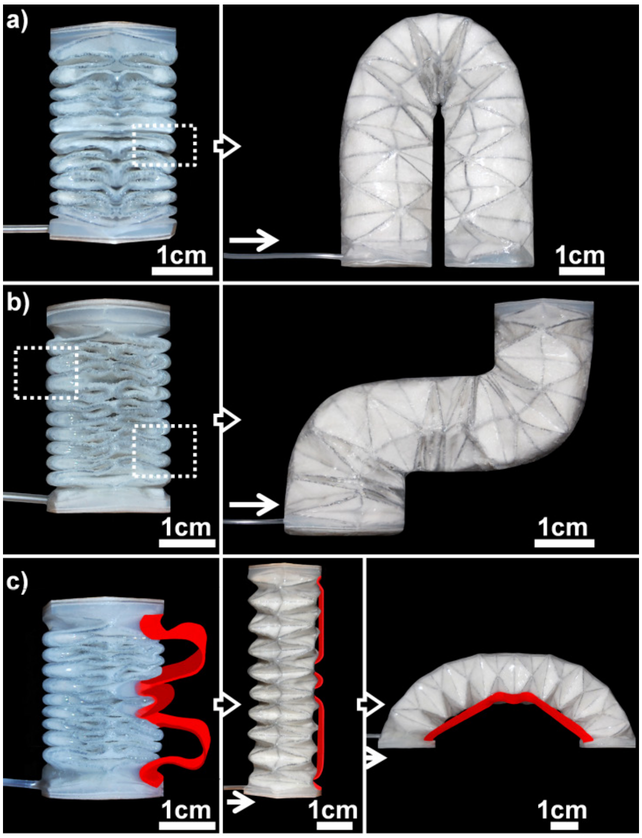

Figure 8. Bellows actuators, fabricated by limiting the elongation of their pleats. a) A bellows actuator that bends in a U-shape. b) A bellows actuator with two bending modes. c) A bellows actuator with a strip (in red) limiting the expansion of the pleats. The strip was built on the outside of the device for the sake of clarity.

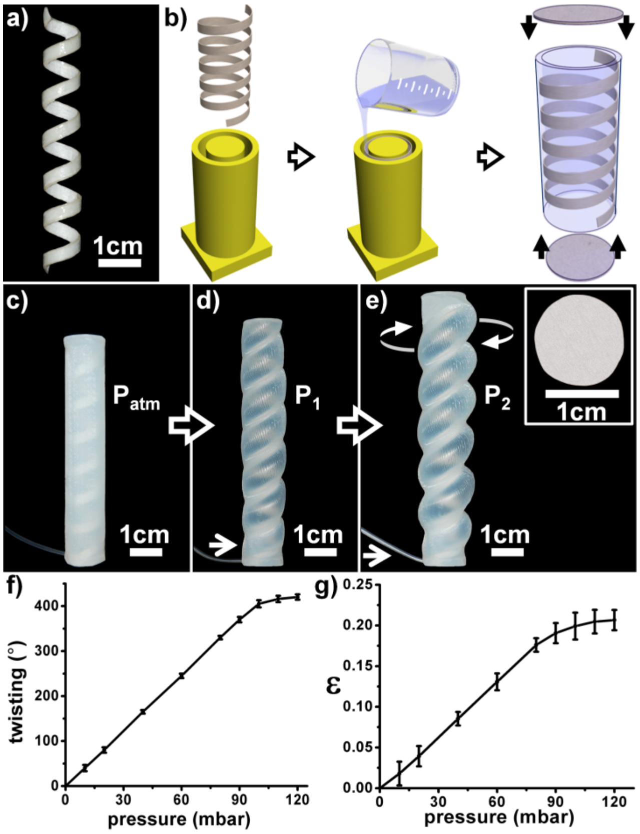

Figure 9. A twisting actuator with a helical patterned paper strip wrapped around a cylindrical pneumatic channel. a) The three-dimensional pattern of the paper. b) The fabrication process is similar to the one shown in Figure 4: the paper with the pattern shown in a) is first inserted into a cylindrical mold. An elastomer pre-mixtured is then poured into the mold, and cured with the patterned paper embedded. Finally, sealing the top and bottom completes the pneumatic channel. c), d), and e) show the resting and actuated states of such a device under an applied pressure of P_1= 50 mbar and P_2= 120 mbar respectively. f) and g) Pressure dependence of the twisting angle and the elongation after 50 pressurization/depressurization cycles.

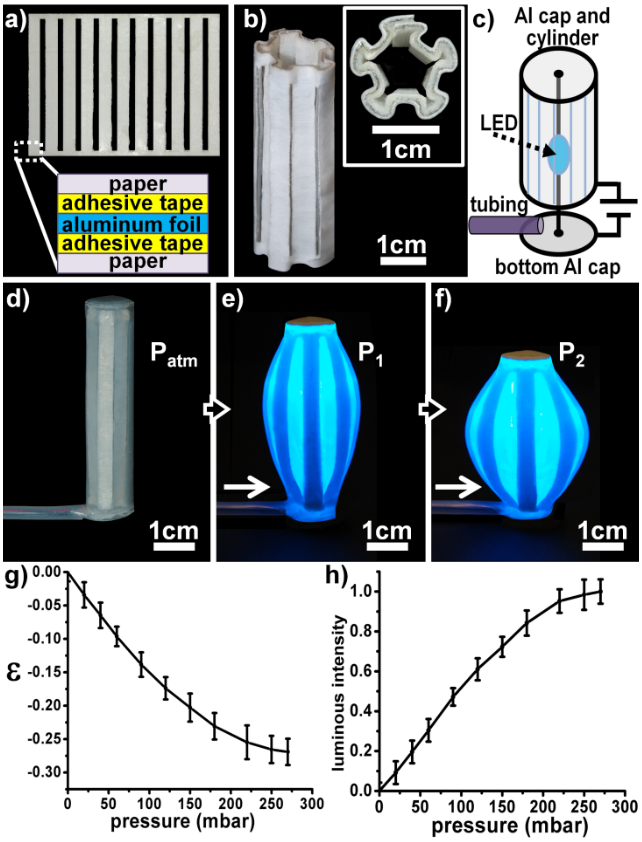

Figure 10. A contraction actuator that couples inflation of an Ecoflex cylindrical shell reinforced with aluminum foil to emission of blue light upon pressurization. a) Two-dimensional pattern of the composite of paper and aluminum foil. b) Folded structure rolled into a cylinder to fabricate the actuator. c) Aluminum foil was used (composed with paper and Ecoflex) to fabricate a bendable structure that allows electrical conduction to a blue LED housed in the internal chamber from the outside. The anode of the LED is connected to the top aluminum cap (electrically connected through the aluminum cylinder). The cathode of the LED is connected to the bottom aluminum cap (isolated from the anode with Ecoflex). d), e), and f) Resting and actuated states of such a device with the LED on. P_{atm}= atmospheric pressure, P_1= 100 mbar, and P_2= 285 mbar, respectively. The exposure time was longer for e) and f) than d). g) Dependence of the contraction with the applied pressure after 50 pressurization/depressurization cycles h) Dependence of the normalized luminous intensity (in the far field) with the internal pressurization of the device.

Table of Contents

Soft pneumatic actuators based on composites consisting of elastomers with embedded sheet or fiber structures that are flexible but no extensible combine soft lithography, for fabrication, with the principles of origami, for structural design. These actuators respond to pressurization with a wide range of motions (bending, extension, contraction, twisting, and others).

Keywords: Soft Robotic, Pneumatic Actuators, Origami, Composites.

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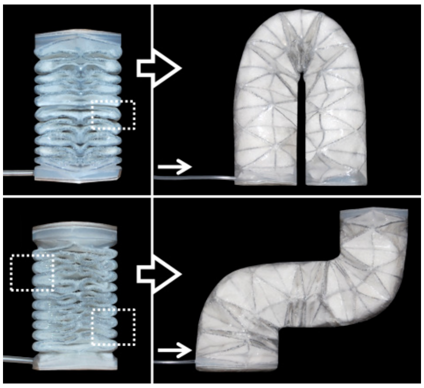

ADVANCED
FUNCTIONAL
MATERIALS

Supporting Information

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“Elastomeric Origami: Programmable Paper-Elastomer Composites as Pneumatic Actuators”

By *Ramses V. Martinez*[1], *Carina R. Fish*[1], *Xin Chen*[1], and *George M. Whitesides*[1,2*]

Supporting Information

Composite Materials to Fabricate Soft Pneumatic Actuators. Flexible but nonstretchable materials can be embedded in Ecoflex can be used to fabricate soft pneumatic actuators as described in this work. **Figure S1**, **S2**, and **S3** show actuators fabricated with these kind of materials. Flexible materials with a bad adhesion to Ecoflex (such us polymer films) can be embedded into the elastomer by punching holes along their surface (Fig. 4E-F). All materials were purchased from McMaster–Carr Inc. (Chicago, IL). We embedded the materials in Ecoflex by pouring the prepolymer on top, degassing to remove air bubbles in a desiccator at 36 Torr for 3 min, and curing at 60 ˚C for 15 min. To connect the pneumatic network of the soft actuators with the external gas source we used polyethylene tubing (Intramedic, Sparks MD) with an outer diameter of 1.57 mm. This tubing was easily introduced into the soft actuator through a 1.65 mm cannula (see **Fig. S4**). We attached the external gas source to the tubing of the actuator using a regular hypodermic needle (16G, 3.81 cm long) as the connector (process depicted in **Fig. S5**).

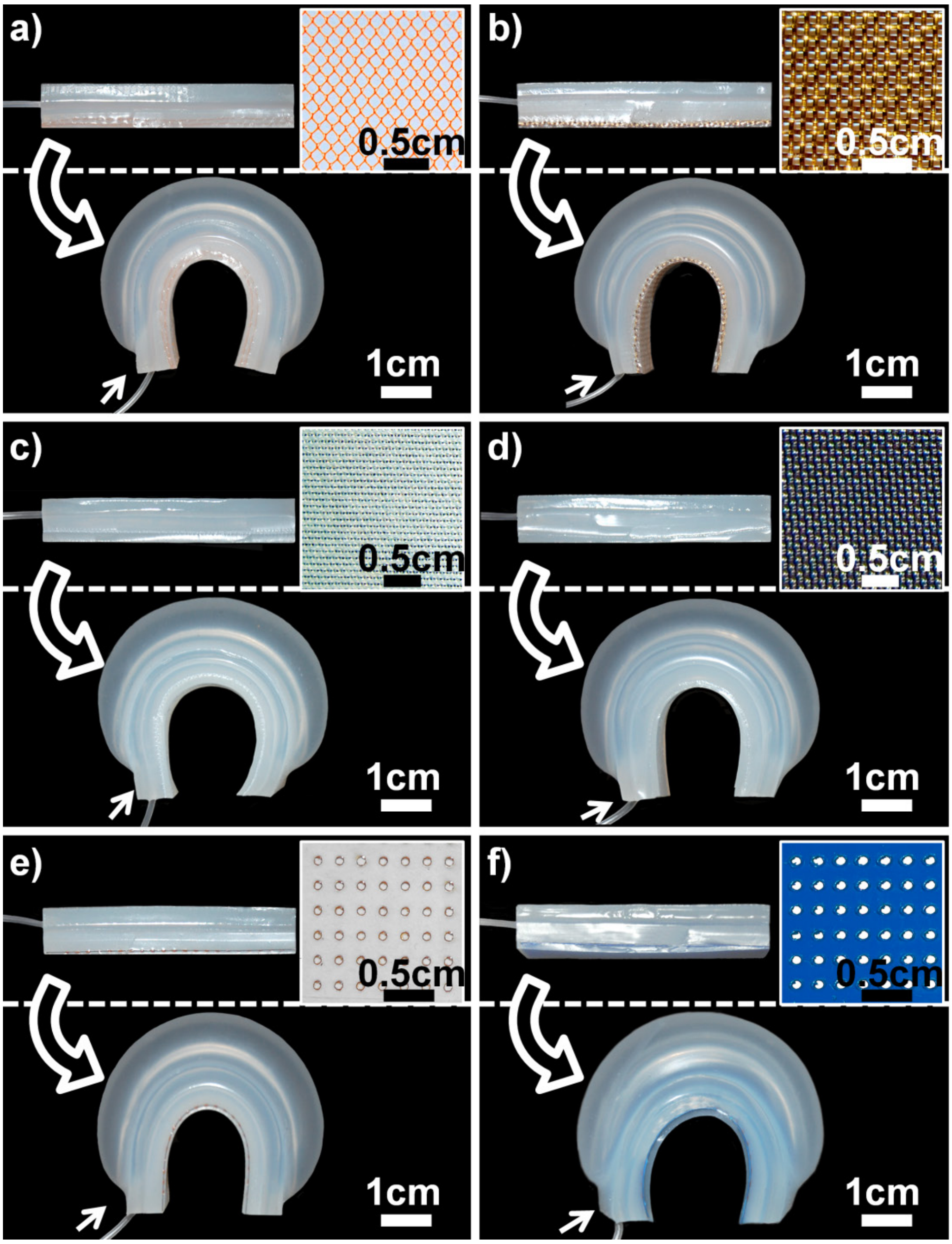

Figure S1. Soft actuators that embed different flexible but nonstretchable materials that make them bend upon pressurization. a) Tulle. b) Cooper mesh. c) Cotton cloth. d) Nylon mesh. e) PET film. f) Polyester tape.

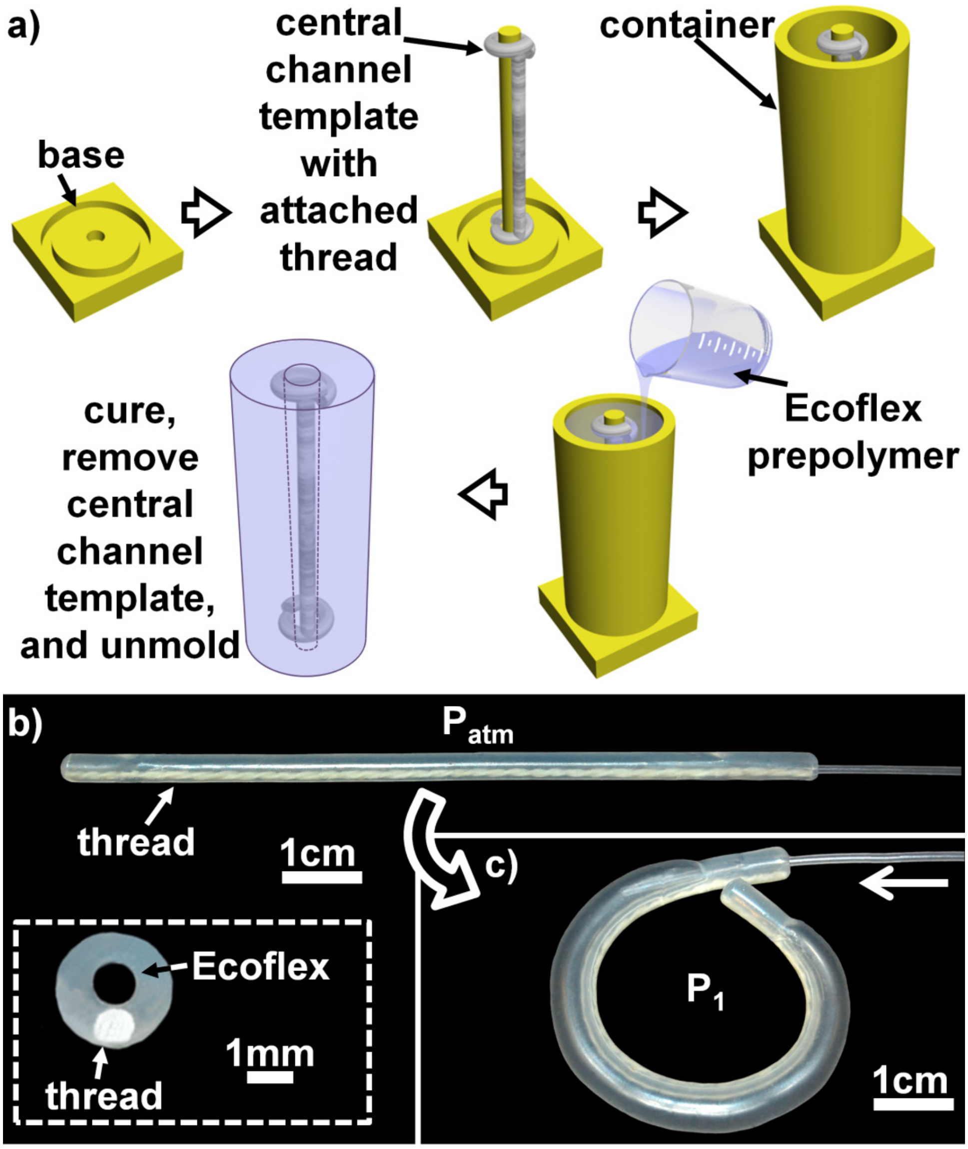

Figure S2. Soft actuator that embeds a thread parallel to the pneumatic channel. a) Schematic representation of the fabrication process. Both ends of this actuator are glued with Ecoflex to seal the pneumatic channel. b) Resting state (P_{atm}) of such a device. Inset in b) correspond to the optical image of the lateral cross section of the device. c) Actuated state (P_1=75 mbar).

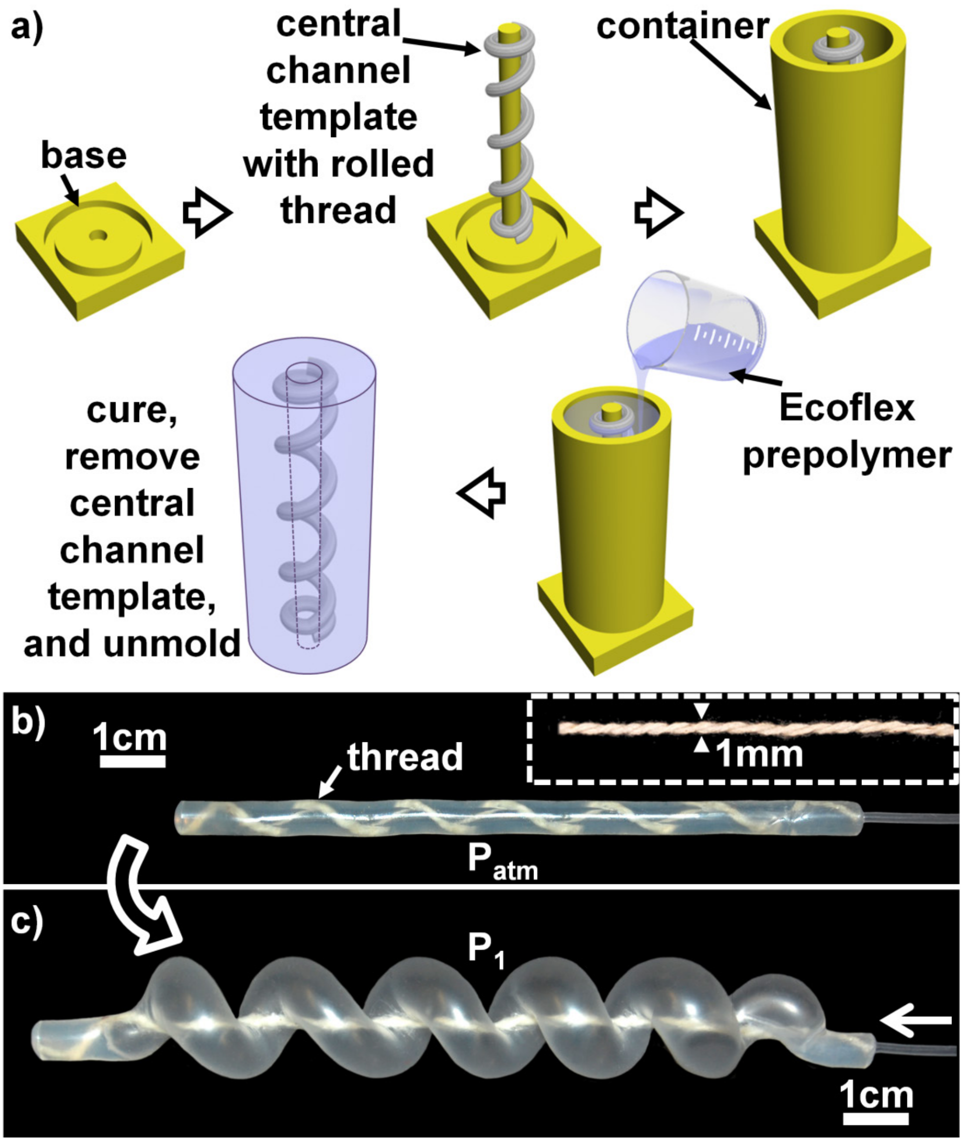

Figure S3. Soft actuator that embeds a thread rolled around the pneumatic channel.

a) Schematic representation of the fabrication process. Both ends of this actuator are glued with Ecoflex to seal the pneumatic channel. b) Resting state (P_{atm}) of such a device. Inset in b) correspond to the optical image of the thread embedded in the actuator. c) Actuated state (P_1=125 mbar).

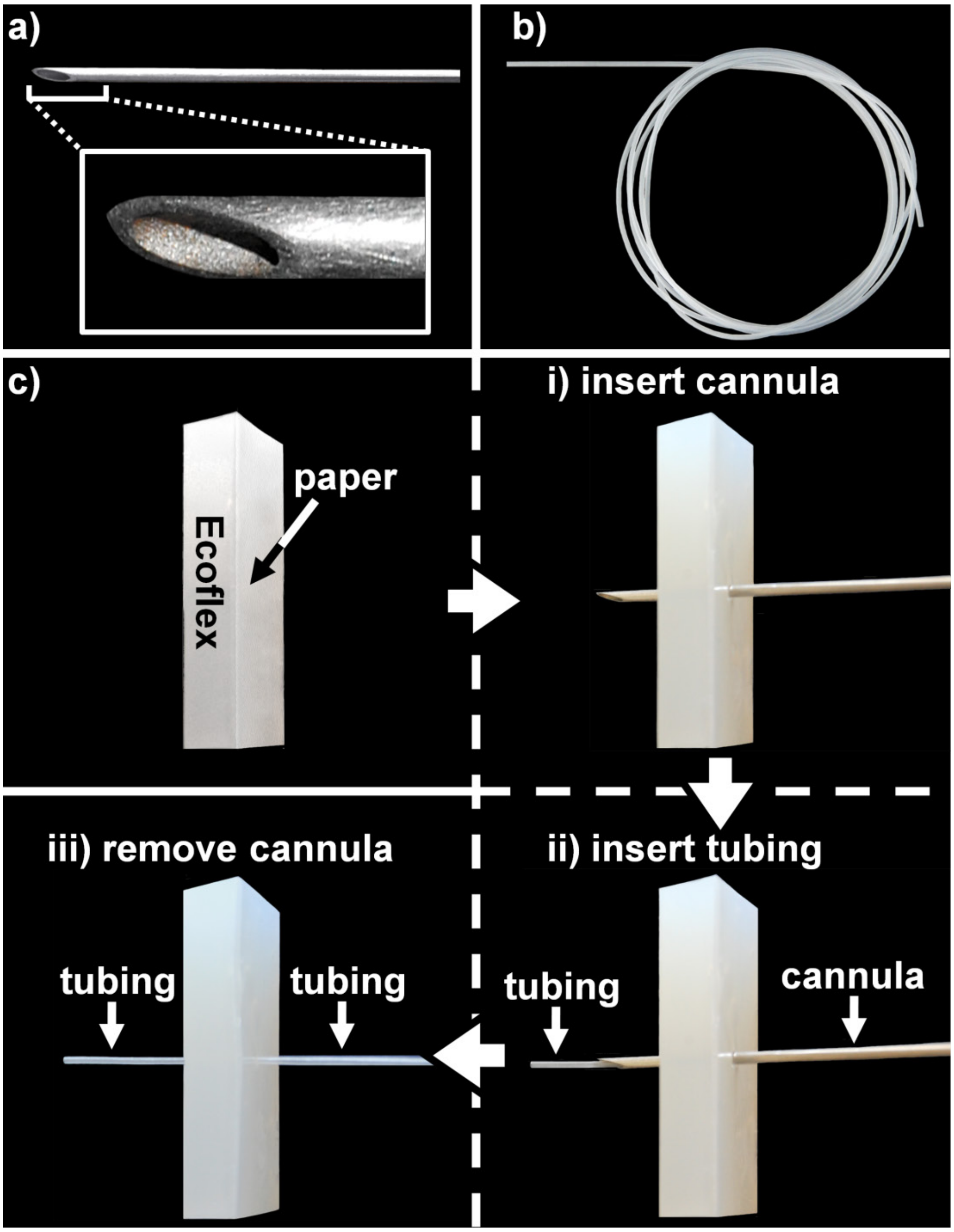

Figure S4. Procedure followed to insert the tubing into a soft paper-Ecoflex actuator.

a) 1.65 mm thick cannula. b) Polyethylene tubing with an outer diameter of 1.57 mm.

c) Ecoflex-paper slab simulating the wall of the actuator that is going to be connected to the gas source by the tubing. The insertion of the tubing requires to perforate the wall of the actuator with the cannula, to both introduce the tubing through and to remove the cannula.

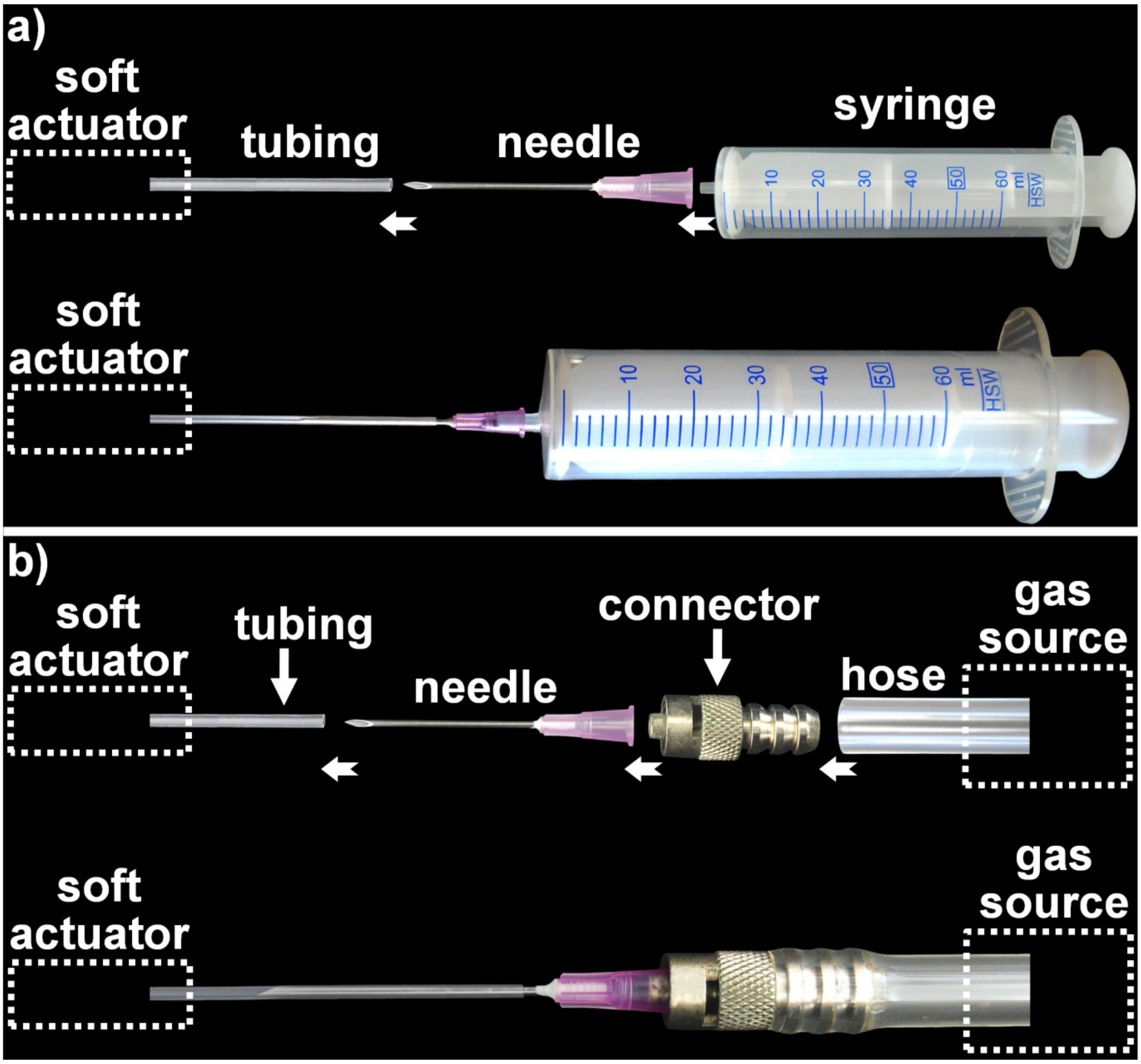

Figure S5. Connection to the external gas source. a) Components used to pressurize the pneumatic actuators with a 60 ml syringe (top). Final connection (bottom) . b) Elements used to pressurize the actuators with a compressed gas bottle (top). Elements after being connected (bottom).

Fabrication of Bellows Structures. Figures S6 and **S7** show the design and mechanical response of a bellows structure with an internal Ecoflex strip that links the top and the bottom caps of the actuator. The elastomeric strip is stretched when the actuator extends upon pressurization. When the internal pressure decreases, the elastic restoring force of the Ecoflex strip causes the device to recover its original shape without significant hysteresis.

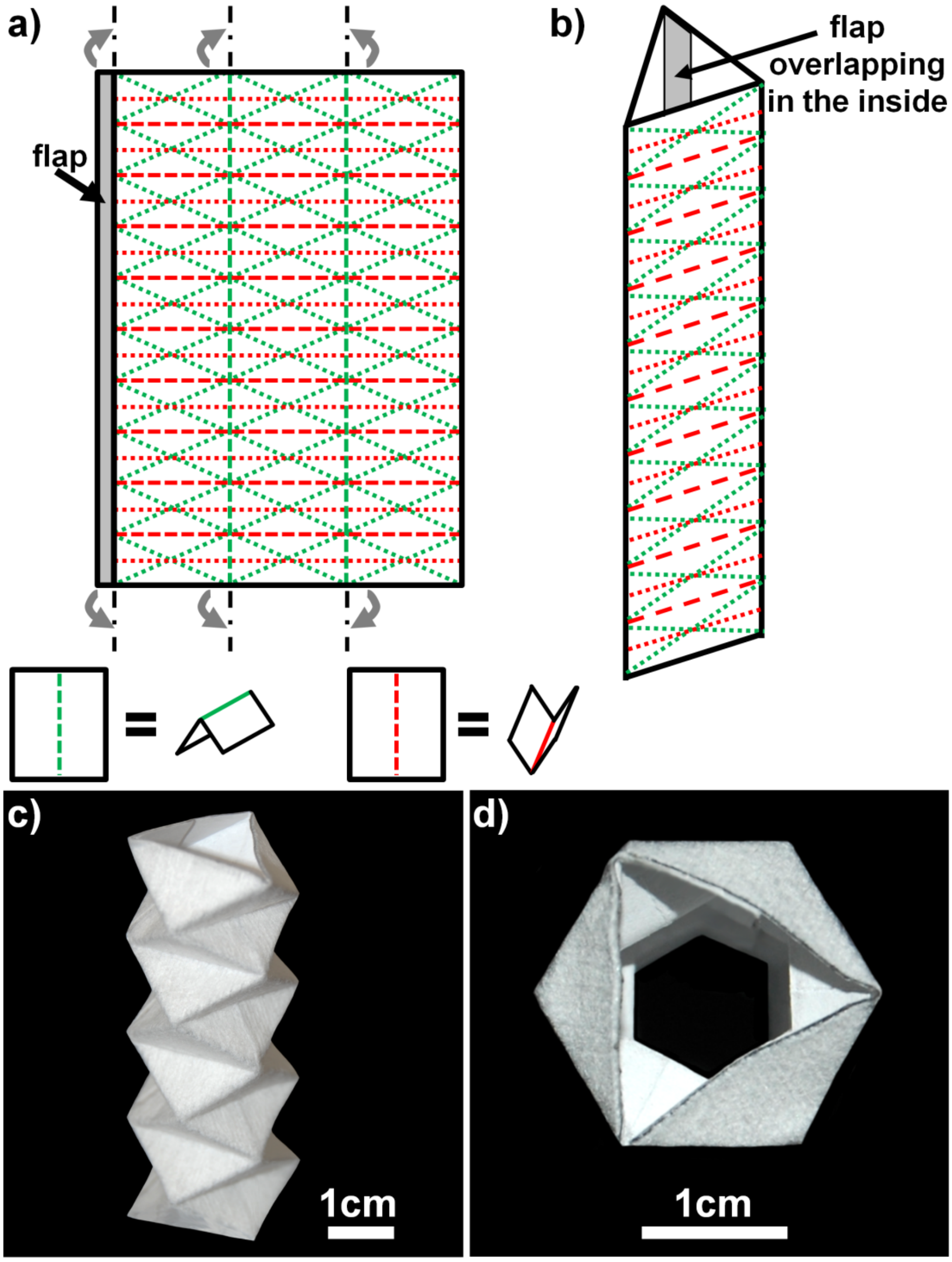

Figure S6. Folding scheme to fabricate origami actuators. a) Folding marks for a rectangular single piece of paper. b) The folded piece of paper is first folded along the three vertical axis shown in a). The flap closes the structure by overlapping. c) Paper origami structure obtained by folding the paper along the creases defined in a). d) top view of the paper structure showed in c).

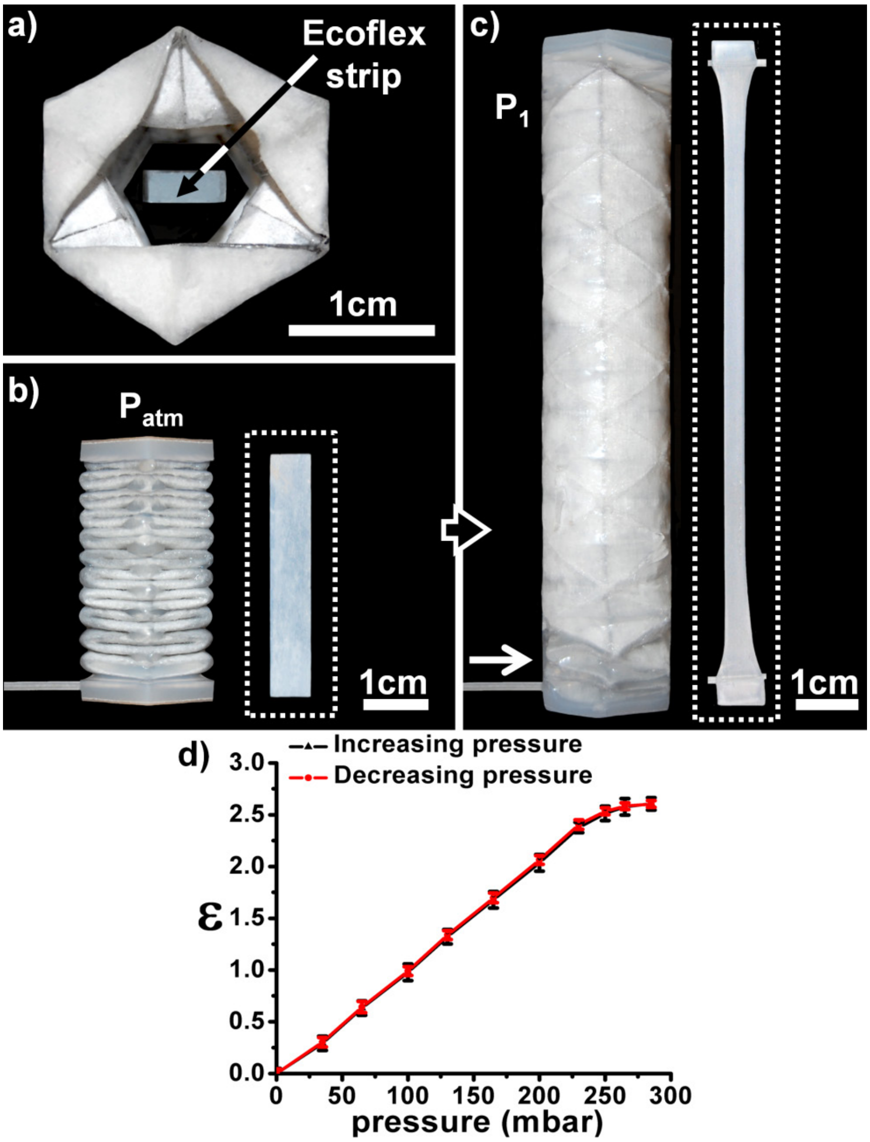

Figure S7. Origami actuator with the hysteresis compensated by the elastic recovery of an Ecoflex strip that joins the top and the bottom of the actuator. a) Top view of the origami structure without the top cap. The Ecoflex strip is glued with more Ecoflex to the bottom cap of the actuator. b) Folded actuator in the resting state (atmospheric pressure inside the pneumatic chamber). The inset shows the relaxed piece of Ecoflex linking the top and the bottom of the actuator. c) Extended actuator when the pressure in the pneumatic chamber is 175 mbar. The inset shows the stretched piece of Ecoflex that is housed in the actuator.
d) Pressure dependence of the extension of the actuator relative to its length at rest. In this case, the Ecoflex strip housed into the actuator helps the actuator to fold up when the pressure decreases minimizing the hysteresis.

Cost. We have not yet considered the issues that would arise in manufacturing. Excluding labor and capital expenses, however, the estimated cost for making any of the actuators described in this communication is less than \$10: i) The estimated cost of the molded material is less than \$1.5 (<15g at \$0.10/g for silicone-based materials). ii) The estimated cost for printing the reusable 3D mold used to fabricate some of the actuator described is less than \$7 (22 g at \$0.30/g for the 3D printed material). iii) The estimated cost of the paper used to make the actuators is less than \$0.01 (<100 cm^2 at \$0.44/m^2).

Scanning electron imaging. Scanning electron microscope (SEM) image (Fig. 5B inset) of the paper-elastomer actuator was acquired with a Zeiss Supra55 VP FESEM at 2 kV at a working distance of 6 mm. Before SEM imaging, the sample was placed on a silicon wafer and sputter coated with Pt/Pd at 60 mA for 15–45 s.

Luminous intensity measurements. We used a high-speed silicon photodetector (Thorlabs DET 10A) to measure the light emission from the soft actuator shown in Figure 10. The output signal from the photodetector (in the 0-10V range) was registered by a digital oscilloscope (Tektronix TDS 2024B). Both soft actuator and photodiode were isolated from any external light and kept at a separation distance of 1 m during the measurements.