

Supporting Information:

Robotic Tentacles with Three-Dimensional Mobility Based on Flexible Elastomers

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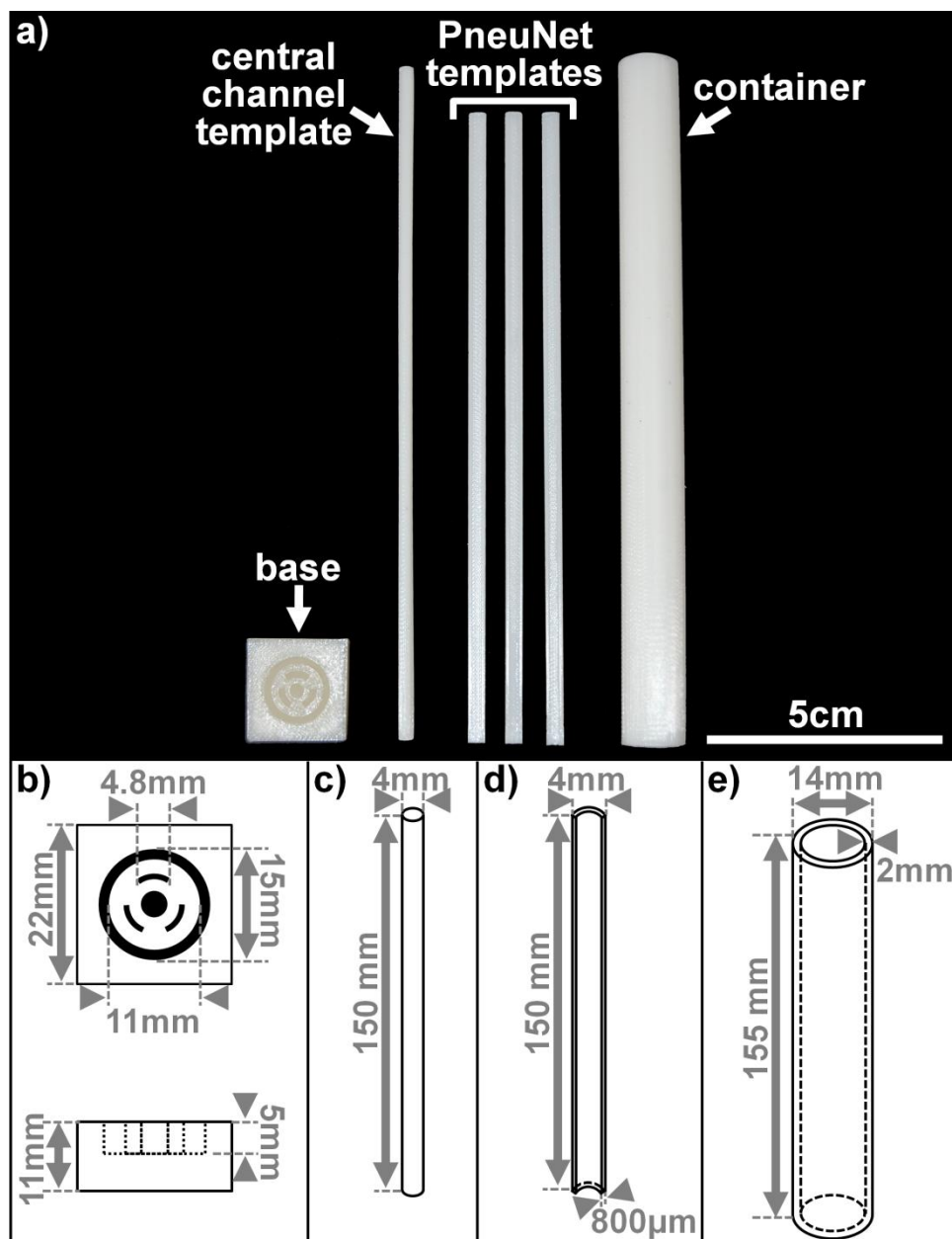


Figure S1. Dimensions of the molds used to fabricate the tentacles. a) Molds built in ABS using a 3D printer. b) Dimensions of the base of the mold. c) Dimensions of the central

channel template. d) Dimensions of the pneumatic channel template. e) Dimensions of the tube used to contain the elastomers during the molding process.

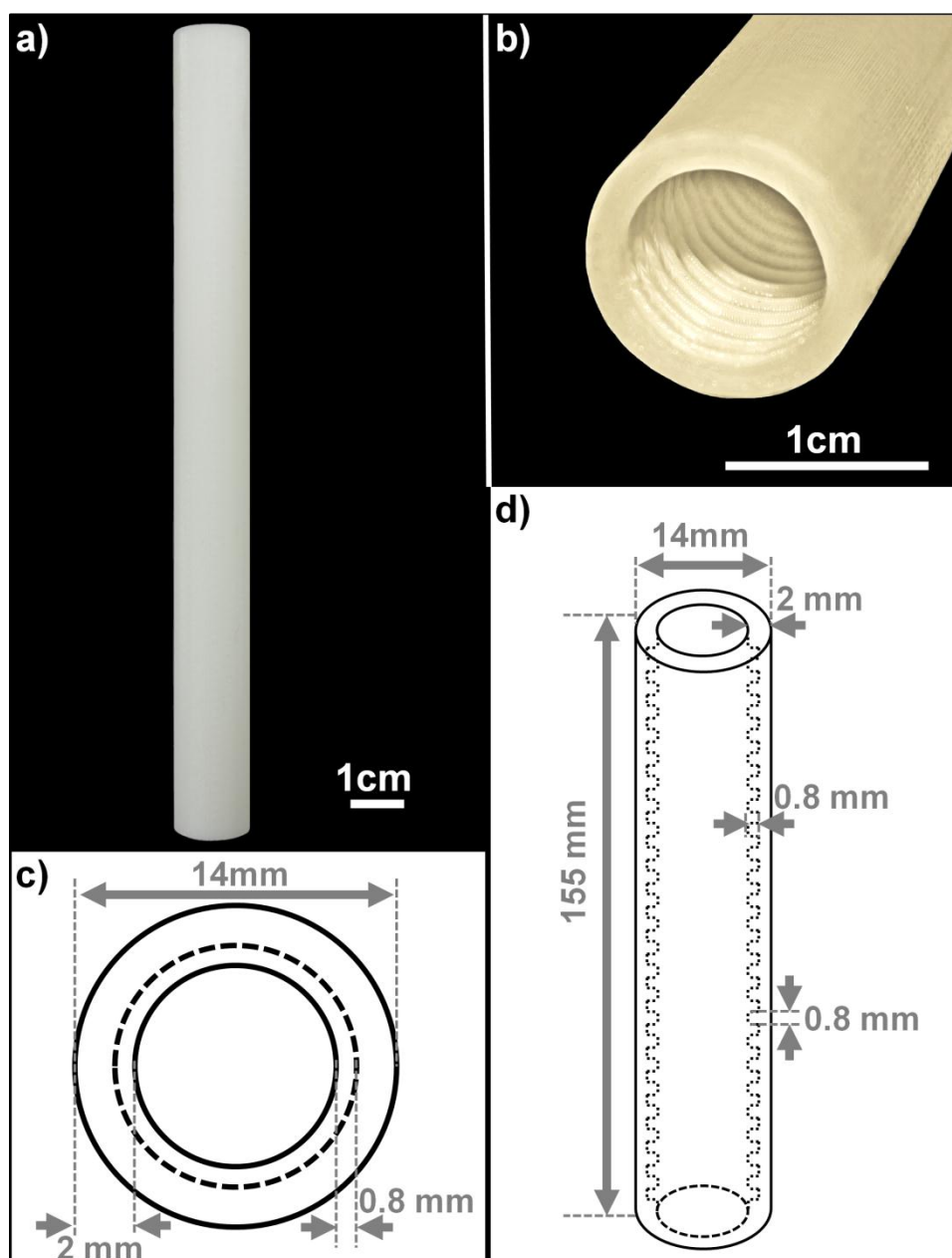


Figure S2. Tube used to mold textured tentacles. a) Lateral view of the tube fabricated in ABS by 3D printing. b) Perspective view of the tentacle showing its internal texture. c) Dimensions of the mold (top view). d) Dimensions of the mold (perspective view).

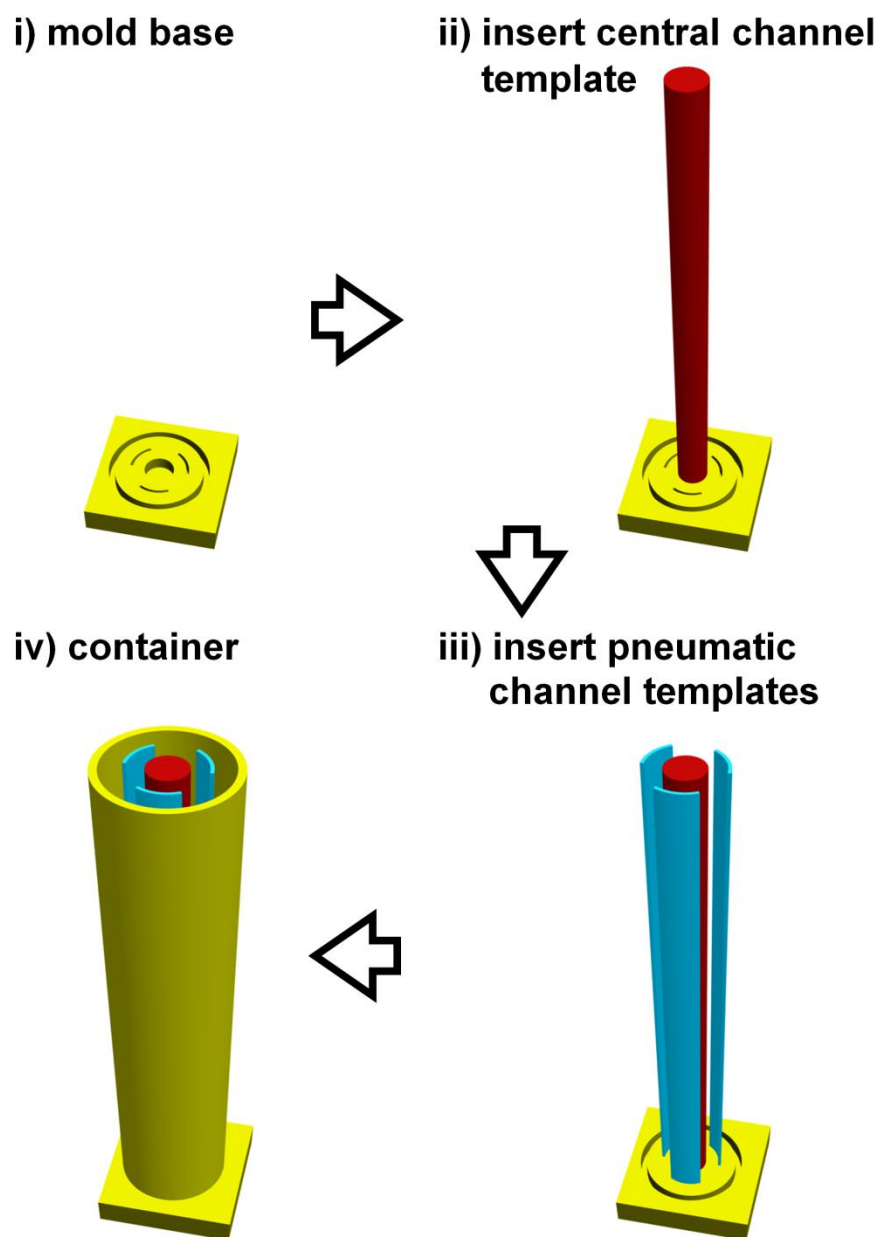


Figure S3. Process followed to ensemble the mold used to fabricate the tentacles.

Attaching to the Off-board Pressure Source. To connect the micropneumatic channels of the tentacles 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 robotic actuator through a 1.65-mm thick cannula following the process described in

Figure 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 (18G, 3.81 cm long) as a connector following the process depicted in **Figure S5.** The range of pressure required to activate the tentacles was 25-300 mbar (2.5-30 kPa).

Integration of optical camera. A 3.7 mm CCD color camera with 240 lines of resolution was purchased from Supercircuits Inc. (<http://www.supercircuits.com>, PC210). The camera and its wires were introduced through the central channel before pouring PDMS into that space. PDMS and Ecoflex bond together after curing for 48 h at 24 °C without affecting the functioning of the camera.

Cost. Excluding labor and capital expenses, we estimated the cost for making any of the tentacles described in this communication to be less than \$10. The estimated cost of the molded material is less than \$2.0 (<20g at \$0.10/g for silicone-based materials). The estimated cost for printing the reusable 3D mold used to fabricate the tentacles is less than \$6.0 (19 g of ABS at \$0.30/g for the material used for 3D printing).

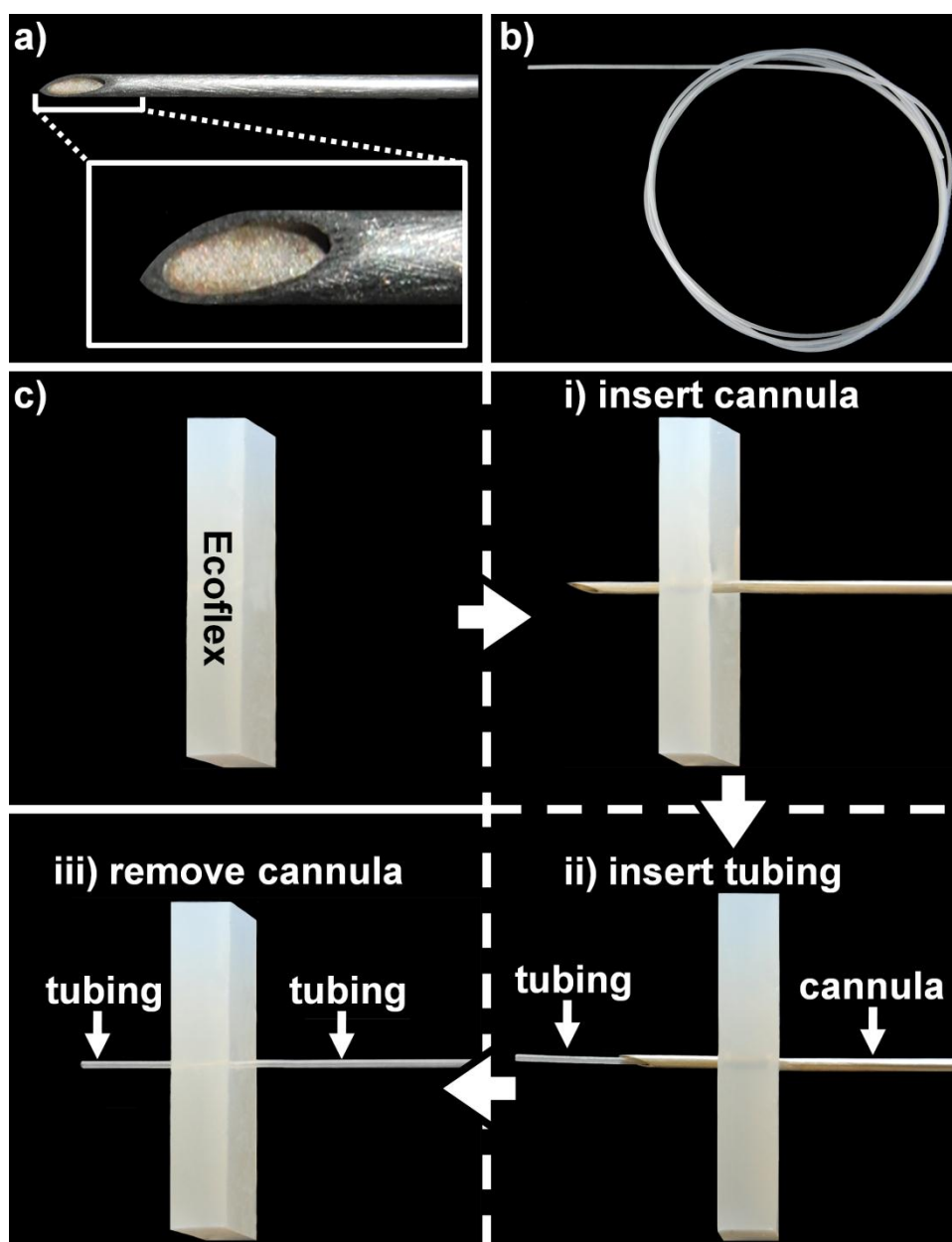


Figure S4. Procedure followed to insert the tubing into a soft Ecoflex-PDMS actuator.

a) 1.65-mm thick cannula. b) Polyethylene tubing with an outer diameter of 1.62 mm.

c) Ecoflex 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 perforation of the elastomeric wall of the actuator with the cannula, to introduce the tubing through the Ecoflex, and to remove the cannula.

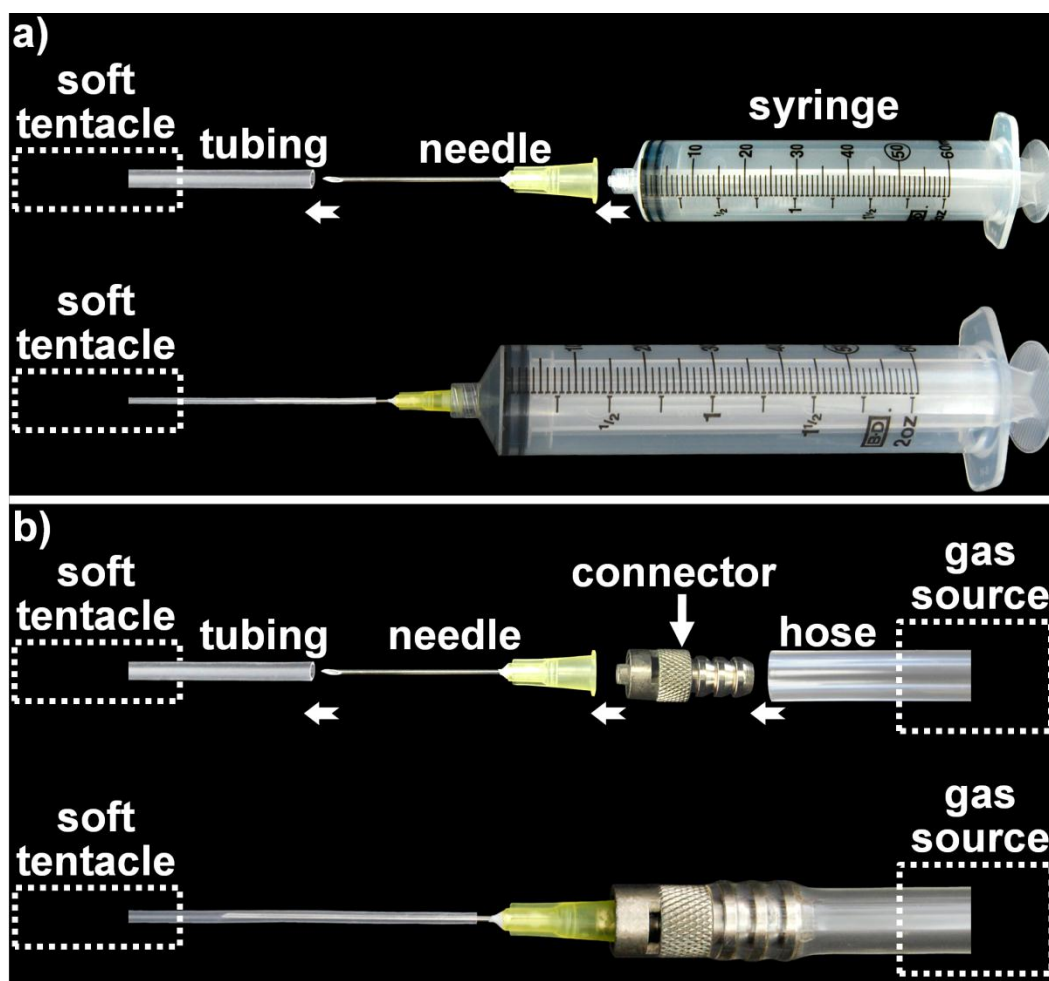


Figure S5. Connection to the external gas source. a) Components used to pressurize the pneumatic actuators with a 60-mL syringe (top). Final connection (bottom). b) Elements used to pressurize the actuators with a compressed gas bottle (top). Elements after being connected (bottom).

Finite Analysis Simulations. We simulated the actuation of a pneumatic soft tentacle using the finite element software ABAQUS. We used a 3D model of the tentacle where pressure is added in one of the pneumatic channels as the loading. In order to capture the process of the snap-through instability, the Riks method is used in the simulation.^[1] Since the expansion and bending of the pneumatic channels initiates at the free end (where the critical condition of the instability is always first satisfied due to the boundary constraint) and steadily propagates along the tentacle, we calculated the curvature of the bending simulating only a length of 25 mm (including 5 mm of the sealing section). We used elements C3D20H for the vicinity of the pressurized pneumatic channel, and elements C3D20RH for the rest of the model.^[2]

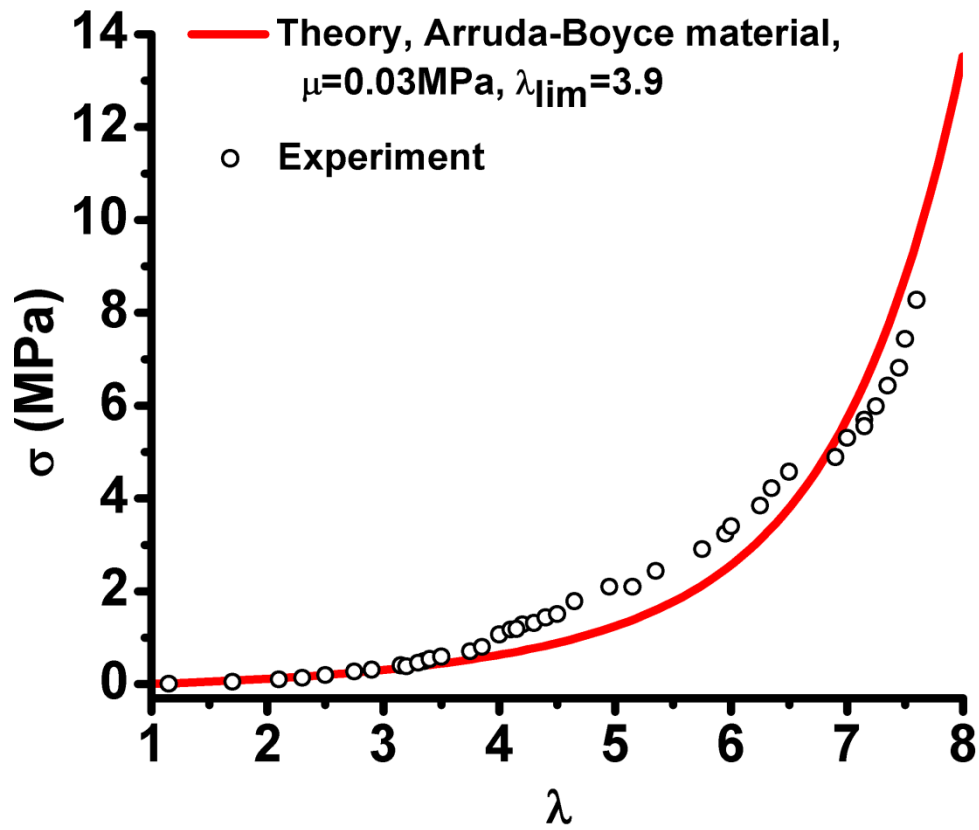


Figure S6. Stress-stretch relation of Ecoflex under uniaxial tension test. Experimental data is shown as empty dots while the fitting by the Arruda-Boyce model is shown as a solid line.^[2] Based on this fitting, we modeled Ecoflex as an incompressible material with shear modulus $G=0.03\text{ MPa}$ and $\lambda_{\text{lim}}=3.9$.

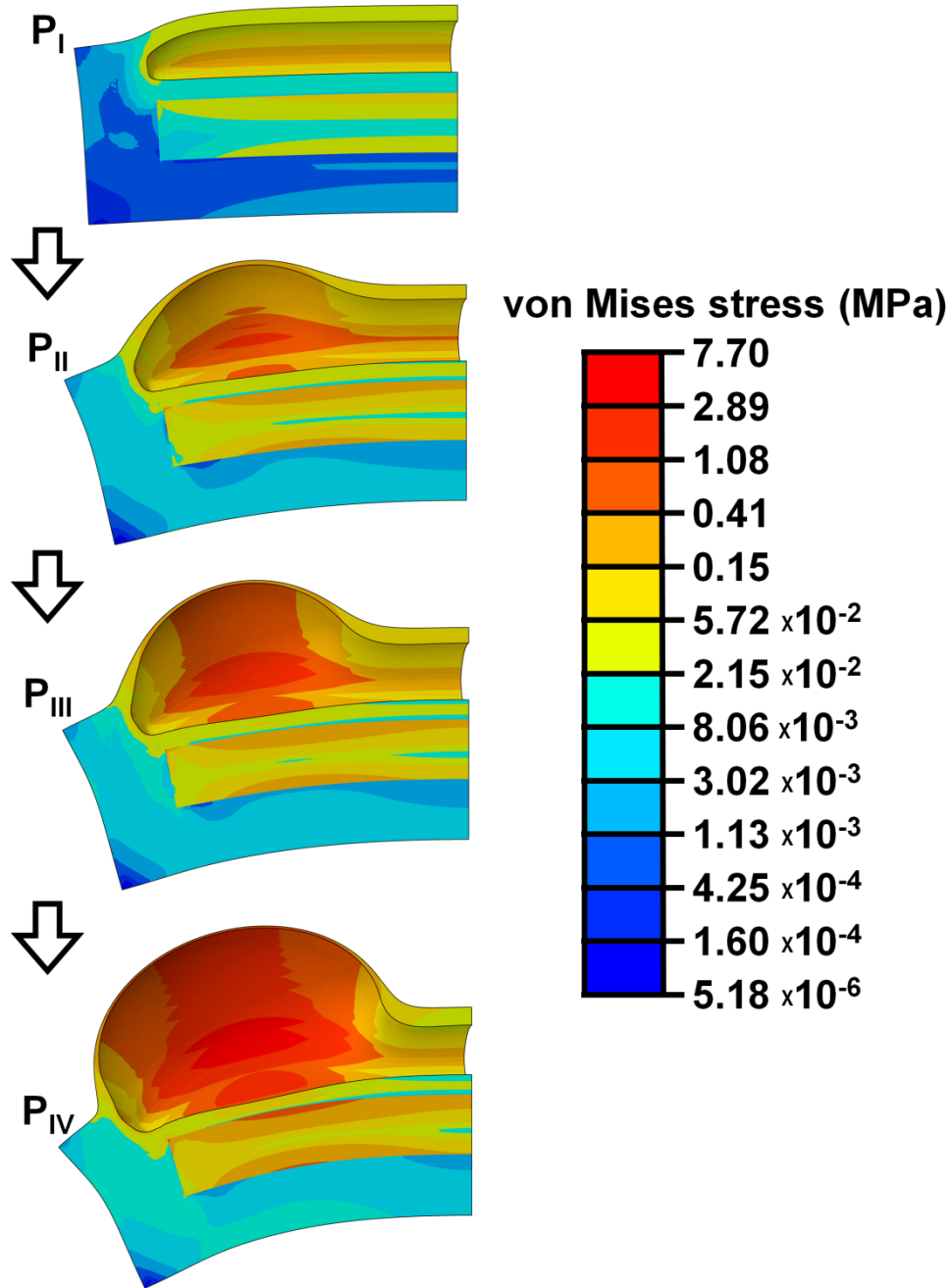


Figure S7. Process of the propagation of the snap-through instability and the bending of the tentacle. The color represents the value of the von Mises stress when the micropneumatic channel is pressurized above atmospheric pressure with $P_I=75$ mbar, $P_{II}=149$ mbar, $P_{III}=P_{IV}=231$ mbar (before and after the snap-through instability). These four increments of pressure correspond to the four dots in Figure 2D.

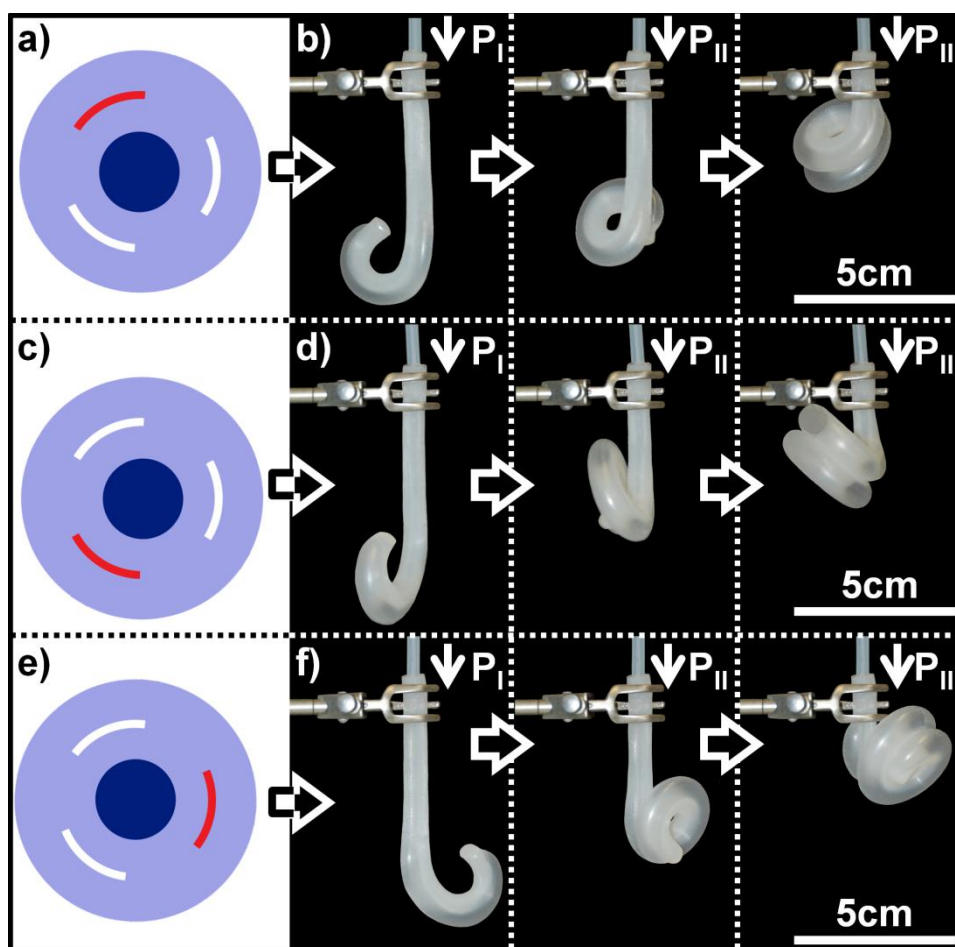


Figure S8. Three-dimensional motion of a tentacle on pressurization of its pneumatic channels. a), b) Channel 1. c), d) Channel 2. e), f) Channel 3. $P_I=75$ mbar, $P_{II}=130$ mbar, and $P_{III}=270$ mbar (all pressures are values above atmospheric).

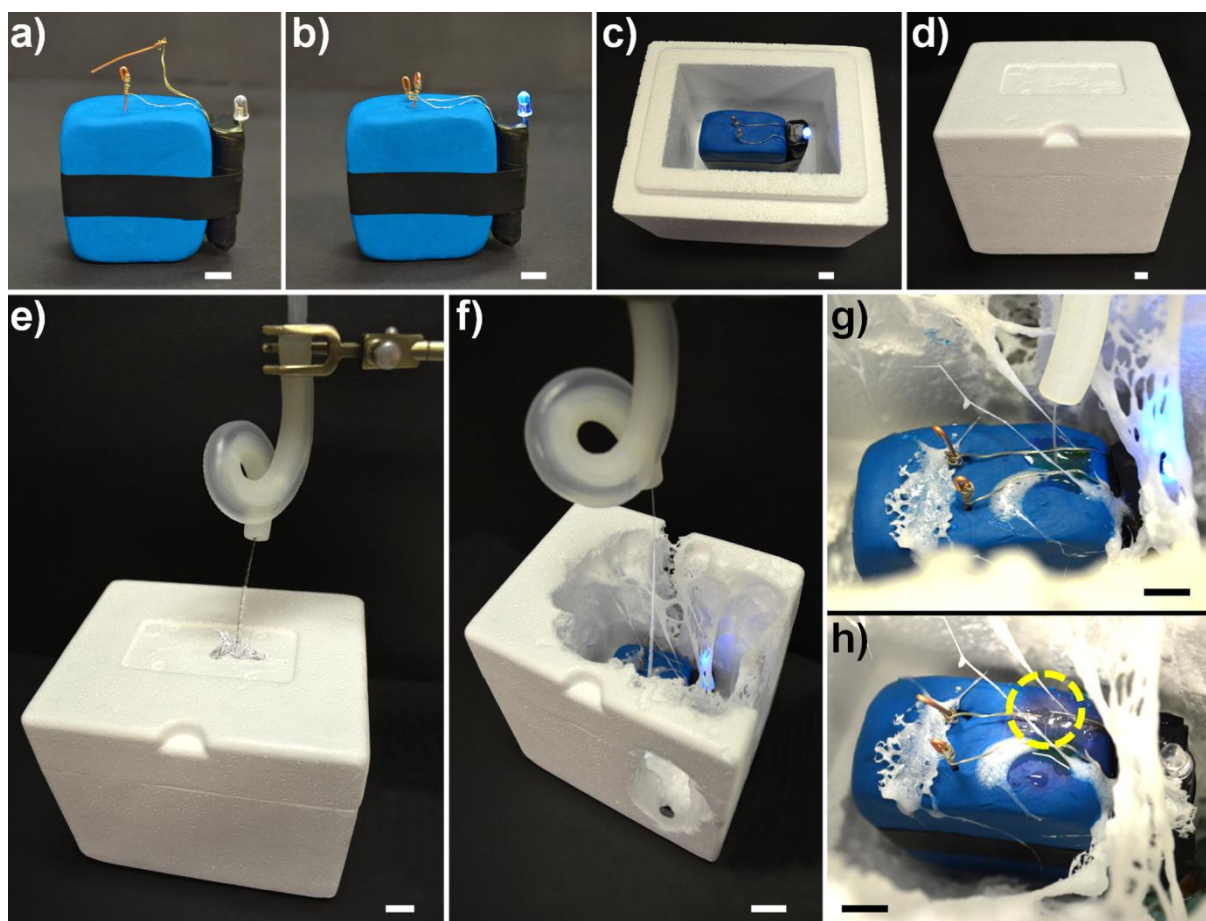


Figure S9. Soft tentacle deactivating a simple circuit enclosed in a polystyrene foam box by local delivery of liquids through a tether embedded in the tentacle. a) Inactive circuit (LED off). b) Active circuit (LED on). The electric current that keeps the LED on comes from two metallic wires linked to a battery. c) The circuit is placed in a thermally insulated polystyrene foam case. d) The box, with the circuit inside, is sealed. e) A soft tentacle with a channel for the delivery of fluids curls so it can get to the top of the box and deliver acetone. f) The soft tentacle directs the stream of acetone over the box to dissolve a hole that provides access to the active circuit. g) The tentacle uncurls, and enters the box through the opened hole; it then pours concentrated HNO_3 on the metallic wires of the circuit. h) The metallic wires dissolve in the acid. The LED goes off, indicating that the circuit is now deactivated. Scale bars are 1 cm.

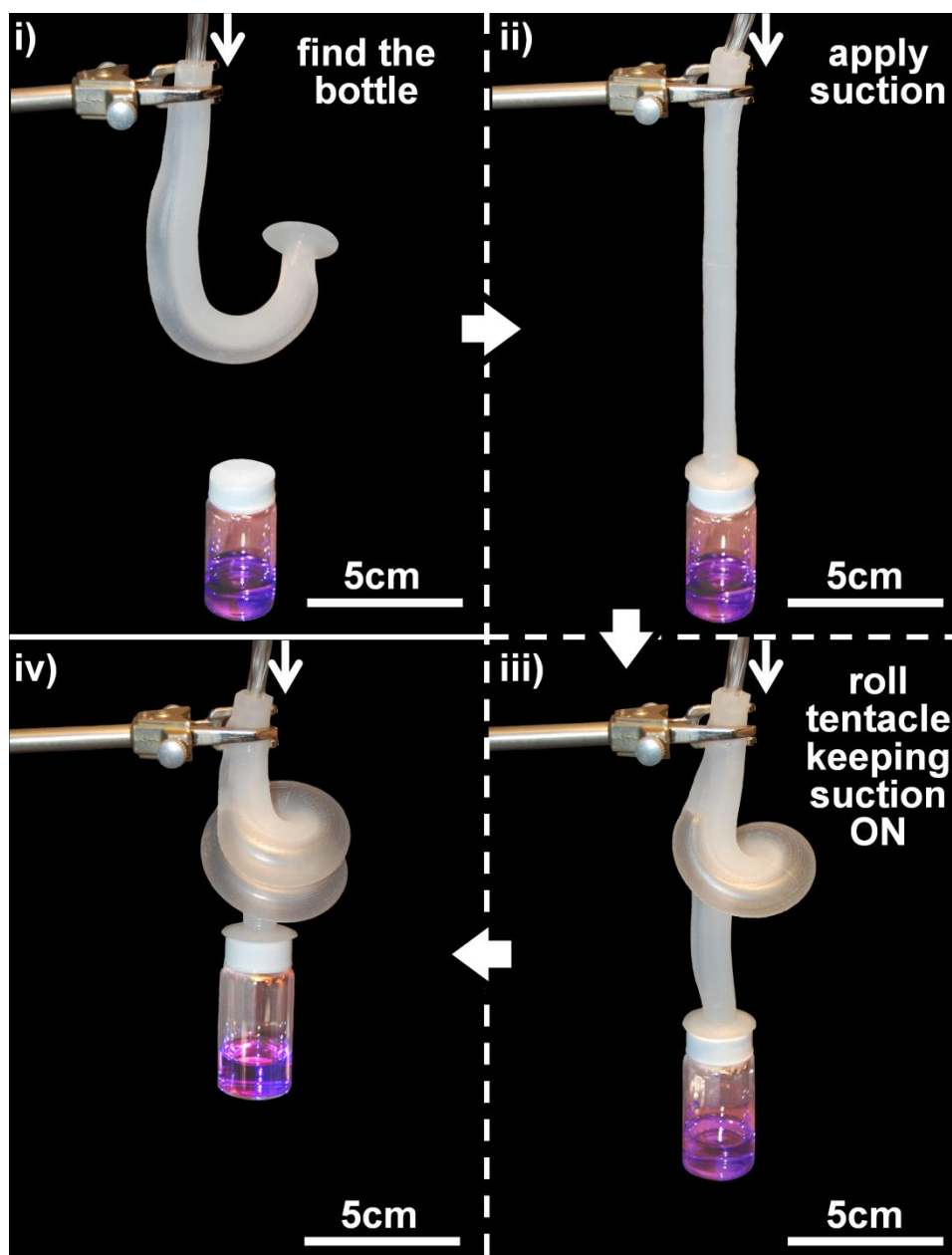


Figure S10. Tentacle showed in Figure 5C lifting a bottle (46 g) by using a suction cup attached to its end. i) The tentacle moves to locate the bottle. ii) The suction channel pumps air out of the suction cup holding the top of the bottle. iii) and iv) The tentacle bends and lifts the bottle.

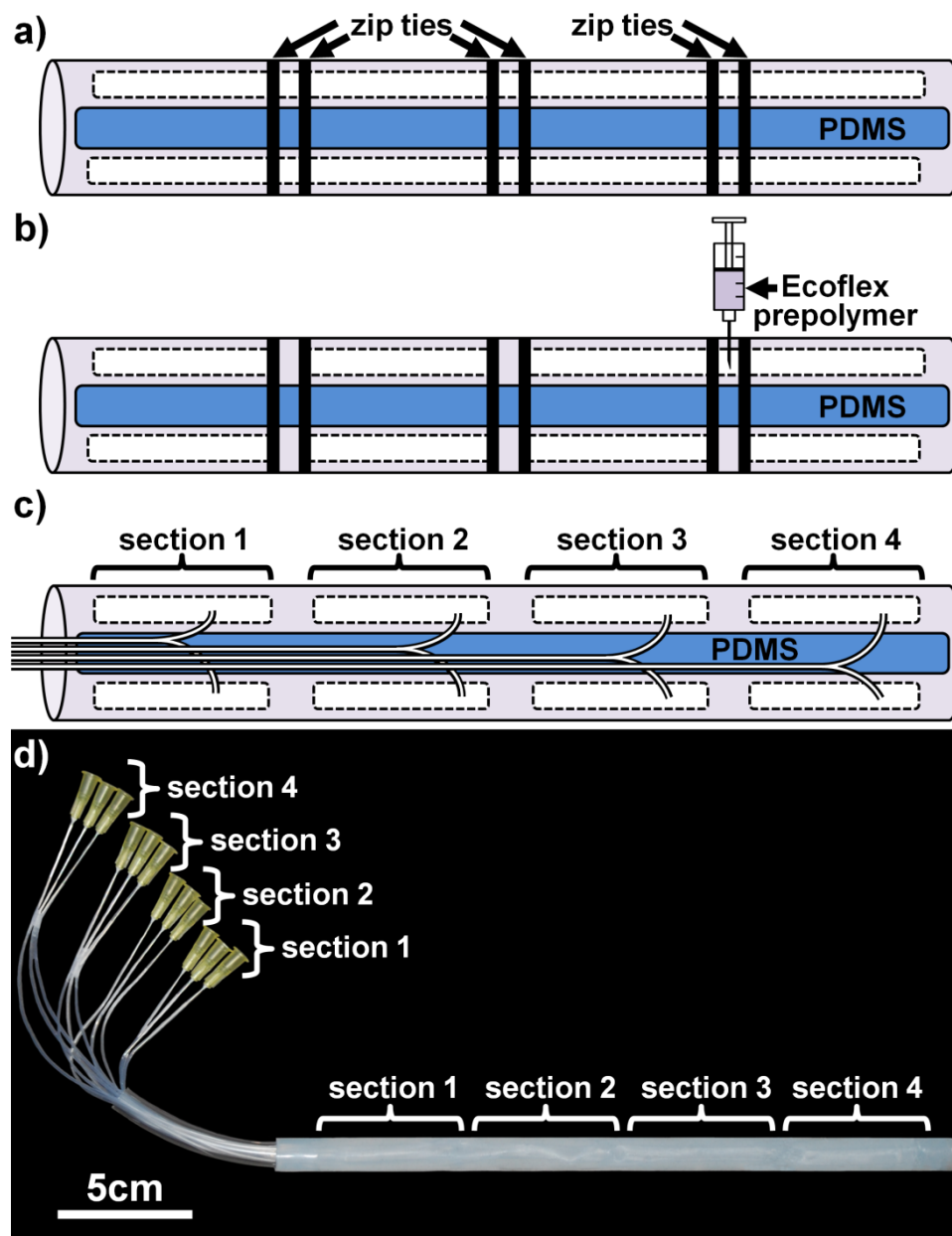


Figure S11. Process to fabricate tentacles with multiple pneumatic sections. a) Zip ties were used to isolate different regions of the pneumatic channels along tentacle. b) The isolated chambers are filled with Ecoflex prepolymer using a syringe and cured at 60°C for 15 min. c) Removing the zip ties allows the tubing to be introduced into the tentacle. d) Tentacle with four sections and 12 independent pneumatic channels (see Figure 3F).

References

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- [2] Abaqus Analysis User's Manual (v6.7):
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