ONLINE SUPPLEMENTAL MATERIALS

Soft Robotics for Chemists

Filip Ilievski[1], Aaron Mazzeo[1], Robert F. Shepherd[1], Xin Chen[1], and George M. Whitesides[1,2,*]

[1] Department of Chemistry and Chemical Biology, Harvard University

12 Oxford Street, Cambridge, MA 02138

[2] Kavli Institute for Bionano Science & Technology,

29 Oxford Street, Cambrdige MA, and

Wyss Institute for Biologically Inspired Engineering, Harvard University

3 Blackfan Circle, Boston, MA 02115

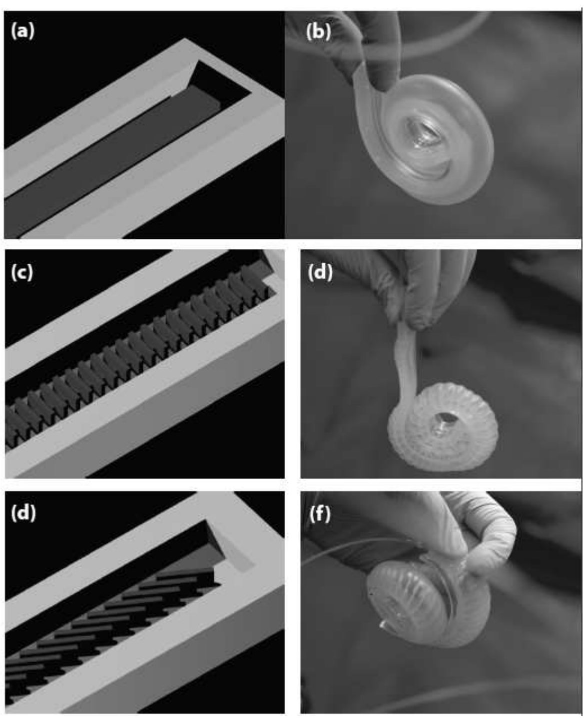
* corresponding author: gwhitesides@gmwgroup.harvard.edu

S1. Design of PneuNets

This paper focuses on the design of networks of pneumatic channels embedded in PDMS. As shown in Figure S 1, it is also possible to design an embedded network of channels, which only consists of a single cavity. In some cases, this may prove to be advantageous. Preliminary tests show that the components shown in Figure S 1(a) and (b) attained similar bending to the structure shown in Figure S 1(c) and (d) but with less applied pressure.

Figure S 1: a) Computer-generated image of a mold with a single channel (width 7.5 mm and height 3.5 mm). b) Pneumatically actuated structure cast from the mold shown in (a). c) Computer-generated image of a mold with a narrow channel (width 7.5 mm, height 3.5 mm, channel thickness of 1.5 mm, and gap between channels 2.5 mm) traveling the length of the mold with a series of cross-channels. d) Pneumatically actuated structure cast from the mold shown in (c). In (b) and (d), a flat piece of PDMS covered and sealed the molded pneumatic networks cast in Ecoflex. e) A design for a finger, which, when actuated, curls in a helix. f) The fabricated device molded from (e). The handedness of the structure is determined by the angle of the channels with respect to the long axis.

Figure S 1

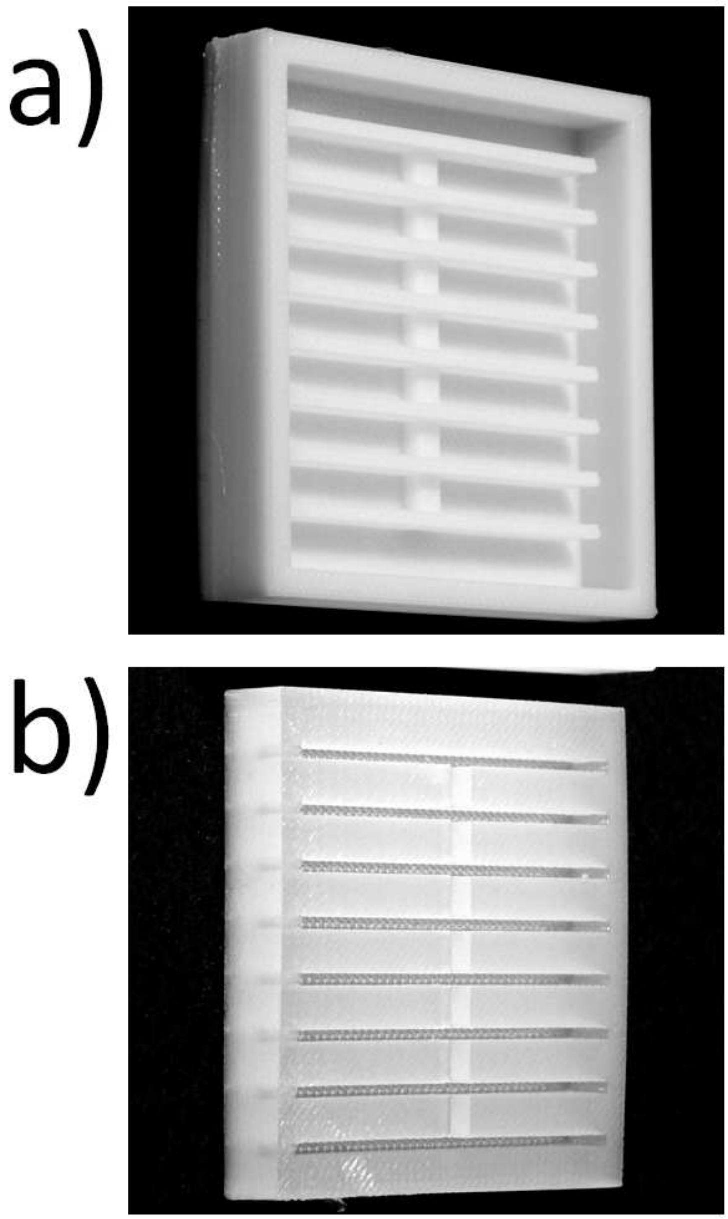


S2. 3D Molding

We fabricated channels in flexible silicone elastomers using established techniques from soft lithography.

A 3D printer (StrataSys Dimension Elite) produced the molds for casting Ecoflex. Depending on the size and complexity of the master, the time for printing ranged from a few hours to a day. For fabrication of the PneuNets we selected two silicone elastomers (polydimethylsiloxane (PDMS, Dow Corning Sylgard 184) and Ecoflex 00-30 (a siloxane produced by Smooth-On; http://www.smooth-on.com)) because they are easily accessible, are easy to work with, bond well to each other to form multilayer structures, and are relatively inexpensive.

Figure S 2: a) 3D printed molds used to fabricate portions of PneuNets. The material used for printing the mold is a thermoplastic polymer (acrylonitrile butadiene styrene). b) Part of a device made of Ecoflex, which has been molded against the master shown in a).



S3. 3D CAD

For the molds designed in this work, we used software for solid modeling from Alibre Inc. (http://www.alibre.com).

S4. Preparation of Ecoflex

Ecoflex 00-30 was purchased from Smooth-On (http://www.smooth-on.com). We mixed Ecoflex 00-30 precursors using the ratio of 1:1 by volume. Curing times ranged from 15 to 30 minutes at 60 °C or up to 12 hours at room temperature. After bonding Ecoflex to PDMS, we post-baked the assembly at ~60 °C for at least 2 hours to assure a good bond.

S5. Preparation of PDMS

Polydimethylsiloxane (PDMS, Sylgard 184) was purchased from Dow Corning. We mixed the precursors of base to cross-linking agent at the ratio of 10:1 by weight. Curing times at 60 °C ranged from 45 minutes to 6 hours.

S6. Bonding Ecoflex and PDMS

We assembled PneuNets from a molded part and a flat membrane. The flat membrane had a typical thickness of 1 mm and sealed the channels in the molded part. We joined partially cured pieces and glued them together with a thin layer of uncured polymer (either PDMS or Ecoflex, depending on the material of the membrane). After bonding the membrane to the molded piece, we cut away excess, unbonded portions of the membrane.

S7. Inlets

To enable pneumatic activation, we delivered compressed air (1-4 psi) through polyethylene tubing inserted and glued into the PneuNets.

S8. Supplied air

The compressed air supplied for actuation of the PneuNets came from plastic syringes or sources of compressed air.

S9. Mode of failure for actuated PneuNets

Large variations in the thickness of the walls can lead to local failure (i.e., an "aneurysm," which could burst before complete inflation of the entire PneuNet) as channels first expand at the most compliant sections where walls are thinnest.

S10. Cost

Excluding labor and capital expenses, the estimated cost for the molded material in a gripper is less than $10 (100 g @ $0.10/g for silicone-based materials), and the estimated cost for printing a reusable 3D mold is less than $60 (200 g @ $0.30/g for the 3D printed material).

S11. Video of gripper in action

A video showing the gripper picking up a uncooked chicken egg can be found under: http://www.youtube.com/watch?v=m3gCPiek0kE

Table 1. Loading capacity of the starfish grippers when gripping smooth polypropylene (PP) spheres. Four three-layer grippers (Ecoflex-PDMS-Ecoflex) picked up polypropylene spheres: two grippers were with an overall diameter of 9 cm (twice the length of an individual leg) when laying flat and two grippers were with an overall diameter of 14 cm. We examined two types of gripping surfaces based on Ecoflex: a smooth surface and a textured surface (texture shown in **Error! Reference source not found.**). All grippers had a thickness of 1 cm. Missing data points are combinations where the gripper was not able to pick up or maintain the grip on the object.

Maximum loading weight sustained by grippers based on PneuNets.				
Diameter of PP spheres (cm)	9 cm diameter gripper, smooth surface	9 cm diameter gripper, textured surface	14 cm diameter gripper, smooth surface	14 cm diameter gripper, textured surface
2.5	230 g	80 g	100 g	300 g
5	-	120 g	300 g	300 g
7.5	-	90 g	300 g	300 g
10	-	-	100 g	300 g