Supplemental Information

Soft Machines That are Resistant to Puncture, and That Self Seal

Robert F. Shepherd[1], Adam A. Stokes[1], Rui M.D. Nunes[1], George M. Whitesides[1,2]*

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

12 Oxford Street, Cambridge, Massachusetts 02138

[2] Wyss Institute for Biologically Inspired Engineering

60 Oxford Street, Cambridge, Massachusetts 02138

*Corresponding author, email: gwhitesides@gmwgroup.harvard.edu

Actuator & Gripper fabrication

We first blended the fibers (5 grams, ~50 ml dry volume) into Ecoflex 0030 (30 grams). The result of blending was a spongy paste that we then pressed between the two part mold (printed using a 3D printer; Dimension Elite) sketched in Fig. 1a. After 15 minutes in an oven at 70^{o} C, we pulled the mold apart and removed the pleated actuator (active layer; Fig. 1b) and sealed it to a flat sheet (strain limiting layer; Fig 1c) of the fibers impregnated with uncured silicone. After another heat treatment in the oven (15 minutes at 70^{o} C), we inserted the pneumatic tether (a silicone tube). To fabricate the gripper, we arrayed three of these actuators 120^{o} to one another and glued them together using silicone elastomer (Sylgard 184; Dow Corning, Inc.) in a mold cut to hold each of the three actuators.

Calculating the adhesive energy for a crack created by a puncture from a 14 gauge needle

The #14 needle (diameter = 2.1 mm) that punctured the actuator has a circumference of 0.66 cm and it penetrates a thickness of 0.5 cm (the membrane thickness). The surface area created (0.33 cm^2) and the work of adhesion, W~45 erg/cm^2, of a typical silicone[1] causes a self-adhesive energy of 9 erg (0.9 μJ).

Self-sealing gripper using elastomeric Pneu-Nets and hydraulic actuation

We also demonstrated a self-sealing gripper using elastomeric actuators (Fig. S4). This system works by using hydraulic actuation, where the liquid medium (in our case a commercially available tire sealant; Slime™) is filled with high aspect ratio fibers. When a puncture occurs in the in the Pneu-Net, while actuated, the pressure difference from the inside of the Pneu-Net to the outside ($\Delta P = +$) causes the hydraulic fluid to squeeze through the hole. The fibers jam as they squeeze through this puncture, sealing it (Fig. S5).

References

1. Chaudhury MK, Whitesides GM, Langmuir **1991**, *7*, 1013

Figure 1. (a) Two part mold for soft lithography of a pleated, bellows-like actuator. Ecoflex™/ Kevlar™ (composite, yellow) is pressed into the mold and (b) replicated, then pressed against and bonded to a composite flat. The arrows indicate the direction in which the (b) mold or (c) active layer is applied. (d) Fabricated composite bellows actuator with internal pneumatic network at ambient pressure ($\Delta P = 0$), (e) positive pressure (~15psi; $\Delta P = +$), and (f) negative pressure (house vacuum; $\Delta P = -$). Bellows actuators with (g,h) ~0.5 pleats cm^{-1} and (i,j) ~1.3 pleats cm^{-1}. Scalebars are 2 cm.

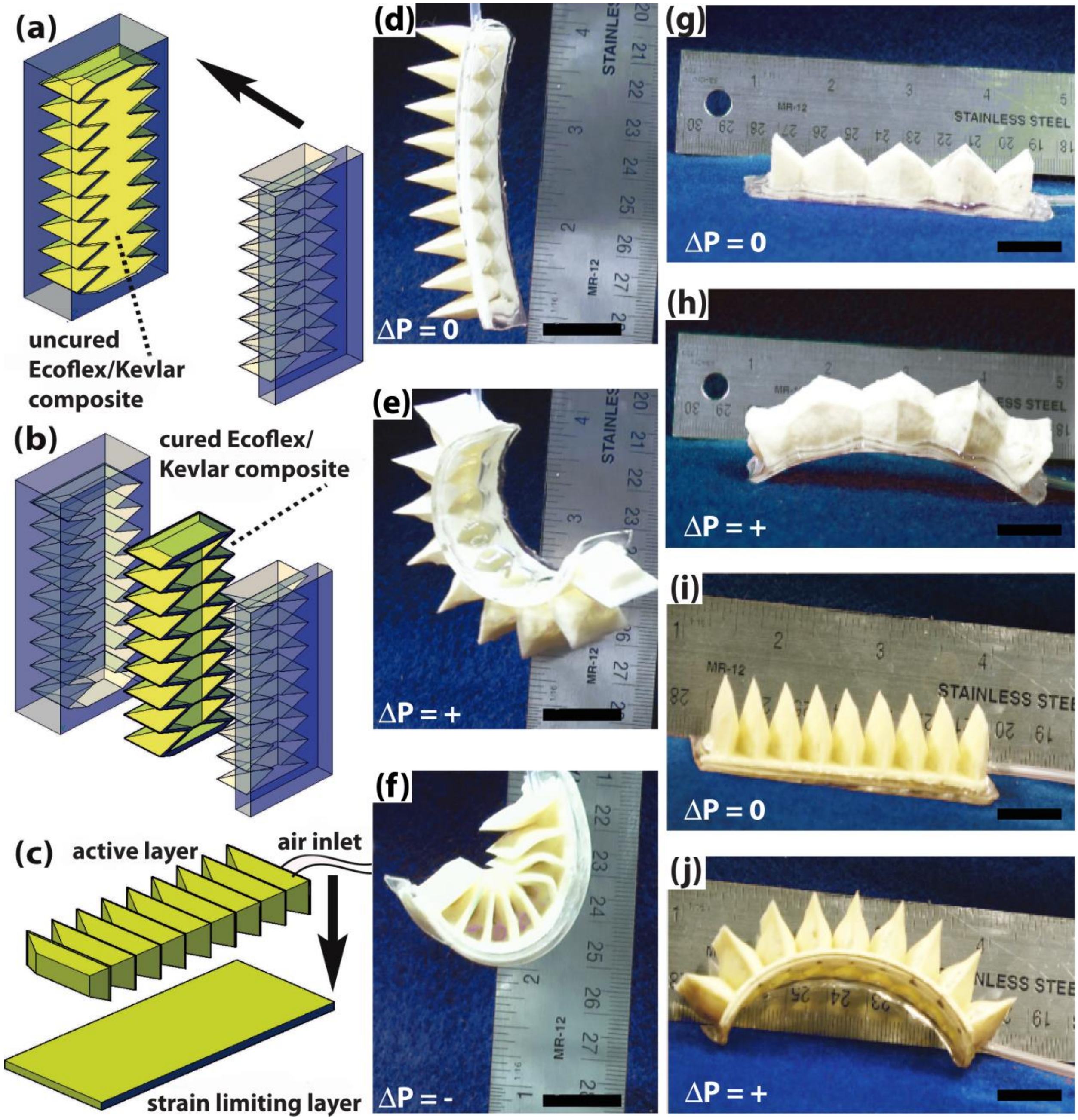

(a)
uncured
Ecoflex/Kevlar
composite
(b)
cured Ecoflex/
Kevlar composite
(c)
active layer
air inlet
strain limiting layer
(d)
ΔP = 0
(e)
ΔP = +
(f)
ΔP = -
(g)
ΔP = 0
(h)
ΔP = +
(i)
ΔP = 0
(j)
ΔP = +

Figure 2. A gripper picks up a wine glass by gripping the (**a-d**) exterior surface or (**e-h**) interior surface.

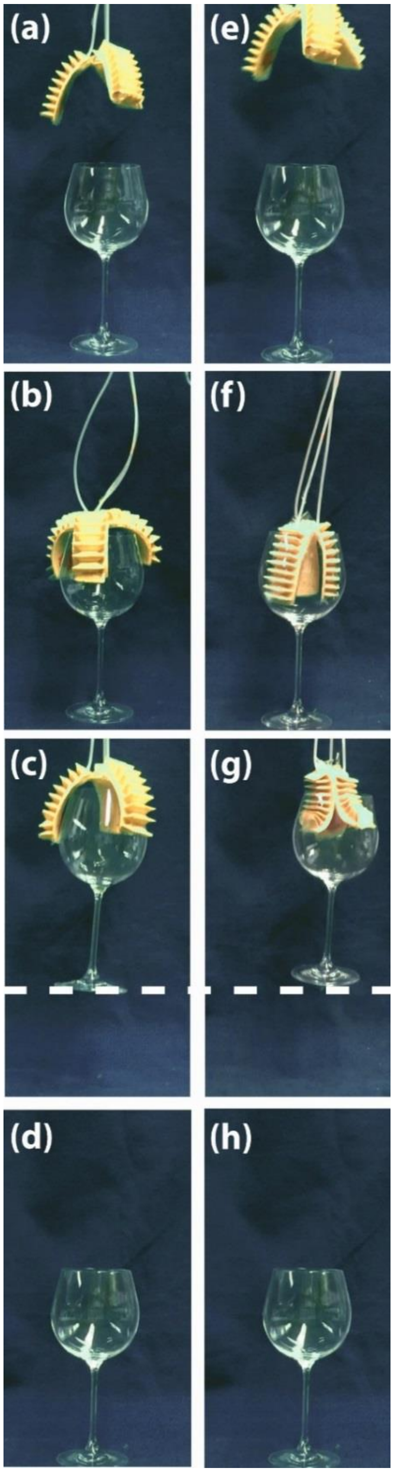


Figure 3. (a) A composite material, bellows-like actuator that (b) bends when pressurized. (c) The material seals around a puncture and the actuator continues to function, (d) even when the source of puncture (a 14 gauge needle) is removed. Scalebar is 2 cm.

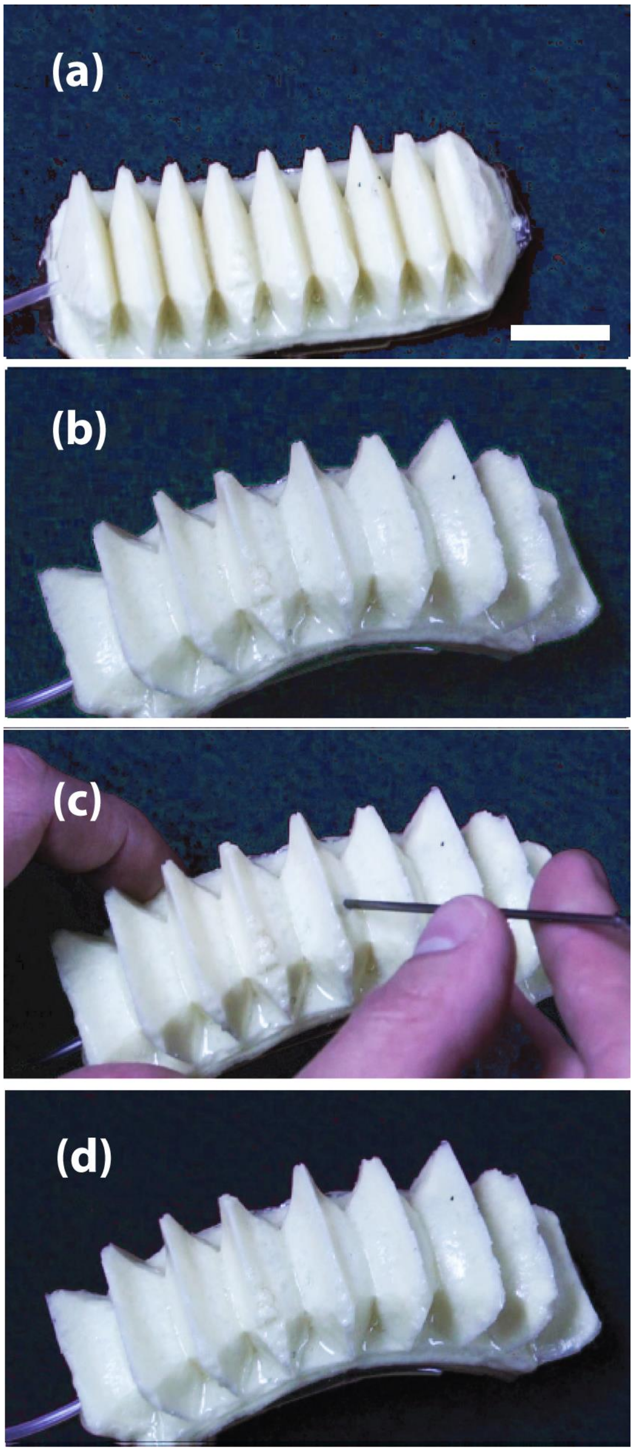


Figure S1. Sress vs. strain curves for a Kevlar/Ecoflex composite (black) and Ecoflex (gray) strip. Both materials were unloaded at 100% strain for one cycle to measure their resilience at that strain—there is no visible hysteresis in the graph. The loading was then reapplied until failure.

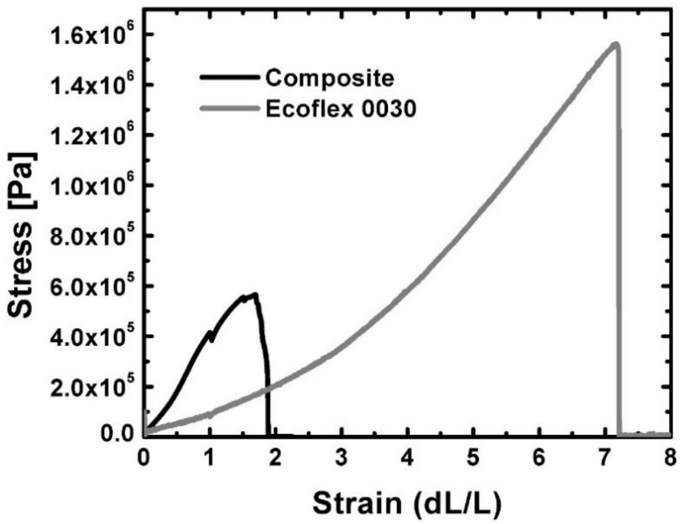


Figure S2. Optical microscopy images of (a) polyaramid fiber bundle and (b) individual fiber. Scalebar is 100 microns.

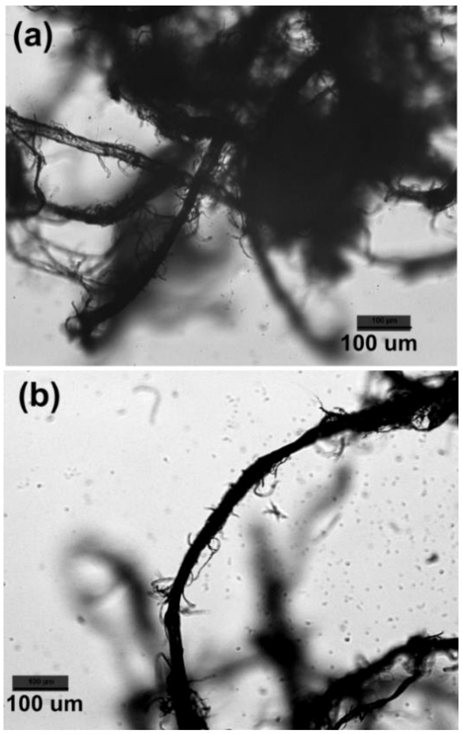
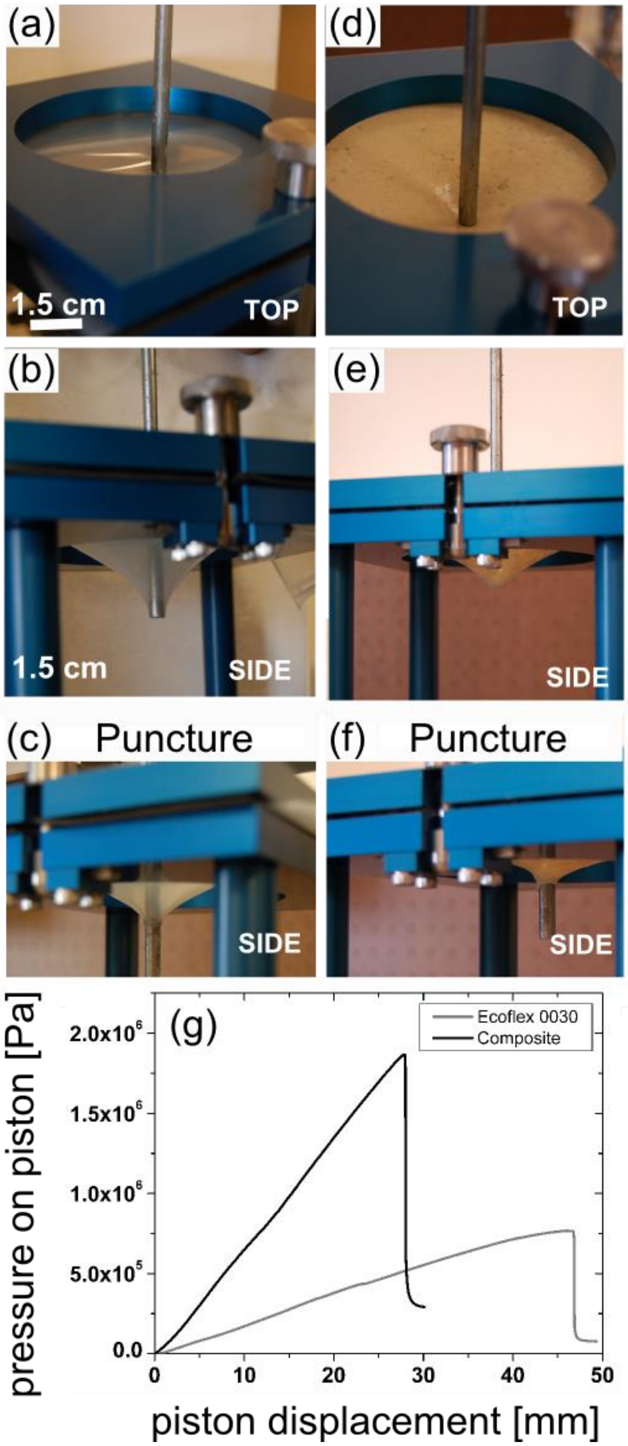


Figure S3. A 5 mm cylinder is pressed onto 5 mm thick sheets of **(a-c)** Ecoflex 0030 silicone elastomer and **(d-f)** a composite of polyaramid fibers and silicone elastomer until they are punctured. **(g)** The pressure applied to the sheets as the cylinder punctures the samples is shown for ecoflex (gray) and the fiber-silicone composite (black).



(a)
1.5 cm
TOP
(d)
TOP
(b)
1.5 cm
SIDE
(e)
SIDE
(c) Puncture
SIDE
(f) Puncture
SIDE
(g)
Ecoflex 0030
Composite
pressure on piston [Pa]
piston displacement [mm]
0.0
5.0x10^5
1.0x10^6
1.5x10^6
2.0x10^6
0
10
20
30
40
50

Figure S4. a) Schematic diagram of soft gripper assembly. b) Top face view of a gripper with a channel filled with slime™. c) Profile scheme of a gripper arm.

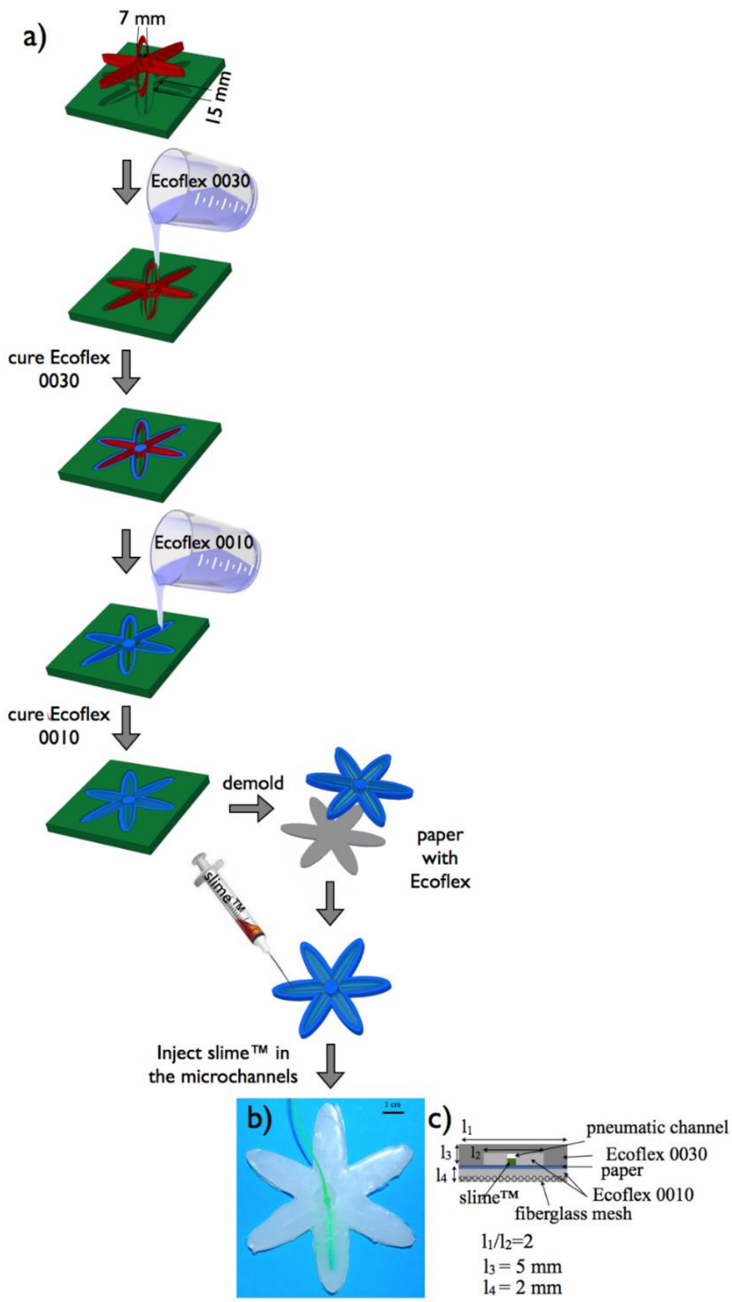


Figure S5. Photos of the hydraulic actuation of an elastomeric gripper and its puncture and self-sealing.a) non-actuated gripper, b) actuated gripper, c) puncturing the inflated side of the gripper with 3.76 mm diameter nail, d) punctured gripper maintains actuation, e) gripper still functions after the nail is removed.