Soft Machines That are Resistant to Puncture and That Self Seal

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We are developing a new class of actuators, machines, and robots–fabricated largely in organic elastomers–that are soft and compliant.[1–5] These systems require fewer components than hard robots, and can generate surprisingly complex motions based on their ability to deform at low stresses.[4,6–12] While our machines[1–5] are built from materials with elastic moduli less than $G' \approx 1$ MPa (for comparison, the elastic modulus of human skin has been measured at $G'_{skin} \approx 30-100$ MPa),[13,14] there are several other classes of soft robots that are built from higher elastic modulus materials (low glass transition plastics like polyethylene,[15,16] metal shape memory alloys,[17,18] or even coffee grounds)[19]-these systems have architectures that allow them to deform at stresses potentially compatible with safe human interactions, a characteristic of soft robots (the strength to rupture and strain to failure of human skin, from cadavers, has been measured at ≈10–30 MPa, and ≈1.25–2.0, respectively).[13,14] These machines are simple to operate, are light weight, can have a low center of gravity, and are low cost (relative to more familiar hard machines–that is those fabricated in metals).[1–5,12,15–20] We anticipate one application of these machines to be in operations involving environments too dangerous for humans (e.g., search and rescue, or the exploration of sites that may be toxic, dangerous, unstable, or radioactive).

We use pneumatic actuation, based on the anisotropic expansion of elastomeric chambers connected by networks of mm-scale channels (Pneu-Nets).[1,3,4] These polymeric structures are highly strained during actuation; at these strains, certain designs for the polymeric structures thin, and tear easily. When punctured, they fail; and even without external damage, repeated actuation of purely elastomeric Pneu-Nets eventually leads to weakening, bulging of the pneumatic channel, and rupture of the internal walls–what we call an "aneurysm"–and to pressure-driven tearing and failure. To build tougher (the material property that describes how much energy our device can absorb without mechanical damage)[21] soft robots, we need new materials and mechanical designs for our actuators.

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Fibrous materials of both natural (e.g., cellulosic) and synthetic (e.g., polyaramid) origin can have elastic moduli in the range of gigaPascals; these materials are, however, typically not highly extensible, and not immediately compatible with the designs we have used for elastomeric Pneu-Nets. There are a number of designs that circumvent this limitation to Pneu-Net-based actuation. For example, by manually folding paper, we developed bellows-like actuators (e.g., pleated structures, as in the folds of an accordion) composed of intrinsically inextensible material to form extrinsically extensible structures.[20] Folding has also been used as a route for actuation in other soft machines.[22–25]

The folds in the inextensible, fibrous material that comprise bellows are typically sewn and they prescribe the controlled collapse and expansion of the system; at the laboratory scale, however, sewing or other forms of joining are too labor-intensive for rapidly iterating soft robot designs. To mold an exact replica of a bellows in a single step (one that is folded on all sides) would require sacrificing a piece of our mold for each actuator.

This paper describes a bellows-like structure that can be fabricated by molding, without sacrificing parts of the mold; unlike true bellows architectures, the materials we use must have some intrinsic extensibility (≈100% strain before failure to achieve actuation amplitudes similar to those of the Pneu-Nets described previously;[1,4] Figure S1, Supporting Information).

We fabricated these actuators from a composite material: polyaramid fibers (Figure S2 shows a representative fiber bundle) embedded in an elastomeric matrix. They operate, in part, by the folding and unfolding of a quasi-bellows arrangement of pleats. This design brings four advantages over our unpleated, purely elastomeric Pneu-Nets:[1] i) These actuators can both fold and unfold; that is, they have positive curvature upon pressurization, and negative curvature under vacuum. ii) The texture at their gripping surface, from the fibers, gives them the ability to handle certain smooth materials[26] (e.g., glass) that would be difficult to manipulate with smooth surfaced grippers. iii) The bellows-like actuators do not require materials that are highly extensible (i.e., capable of hundreds of percent strains); they thus increase our range in materials choices for the design and fabrication of soft robots. (iv) They do not develop aneurysms over approximately two thousand cycles (we did not test to failure).

The material system we chose was polyaramid fibers (Kevlar Pulp, FibreGlast Inc.; 15 wt%; Figure S2) with lengths > 1.0 mm, and average diameters, d≈100 μm, blended into an uncured silicone matrix (Ecoflex 0030, Smooth-On Inc.; 85 wt%). Though cellulose would have also been a good choice, the polyaramid fiber was readily available in a size range that blended well (via mixing with an impeller blade for 15 minutes; see

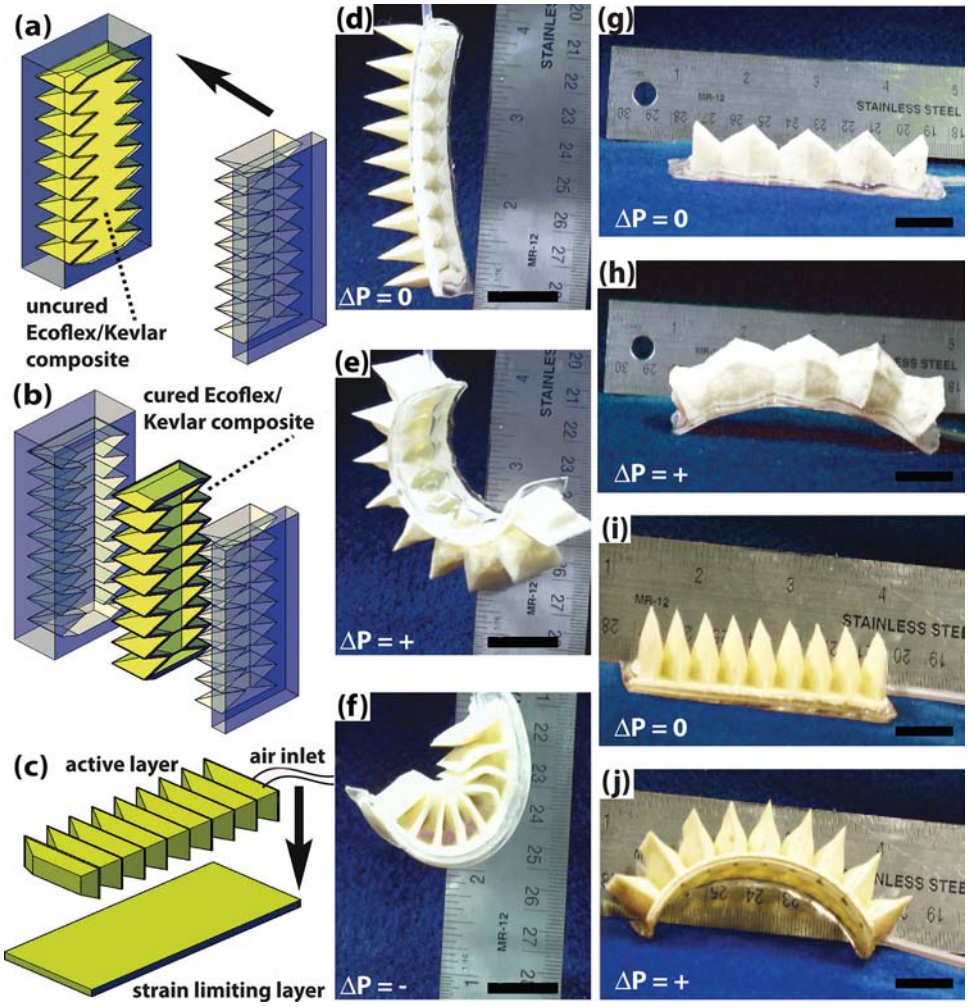

Figure 1. (a) Two part mold for soft lithography of a pleated, bellows-like actuator. Ecoflex/ Kevlar (composite, yellow) is pressed into the mold and (b) replicated, then pressed against and bonded to a composite flat. The arrows indicate the direction in which the (b) mold or (c) active layer is applied. (d) Fabricated composite bellows actuator with internal pneumatic network at ambient pressure (ΔP = 0), (e) positive pressure (≈15psi; ≈100 kPa, ΔP = +), and (f) negative pressure (house vacuum; ΔP = –). Bellows actuators with (g,h) ≈0.5 pleats cm^{-1} and (i,j) ≈1.3 pleats cm^{-1}. Scalebars are 2 cm.

Supporting Information, SI, for more detail) with the uncured silicone. After blending, the mixture was a paste, but one that we could still pour into the molds. We cured the mixture (60 °C for 30 minutes), and then bonded the resulting bellows to an inextensible flat composed of the same material (see SI for more details). These blended composites are not as puncture resistant as woven Kevlar, or as extensible as Ecoflex. As actuators, they have, instead, intermediate properties–resistance to puncture from many mundane hazards (e.g., broken glass, thorns on plants, and sharp rocks), and extensibility sufficient to achieve significant ranges of motion.

Materials with large elastic moduli (G') are difficult to puncture (e.g., diamond has an elastic stiffness modulus of ≈124 GPa)[27] and the composite material we used has four times the elastic modulus ($G'_{comp} \approx 400$ kPa; Figure S1, Supporting Information) of the Ecoflex 0030 ($G'_{Eco} \approx 100$ kPa; Figure S1) used in our prior publications.[1,4] Also, the inclusion of fibers in rubber composites increases the surface area created during crack formation,[26] and thus energy required to propagate the crack. In combination, these properties–high elastic modulus, large strain to failure (≈200%; Figure S1), and disruption of crack propagation–make the composite material actuators less sensitive to puncture than purely elastomeric ones. To compare the puncture resistance of the composite material and the pure elastomer, we pressed a steel cylinder (5.0 mm diameter) into sheets (5.0 mm thick) of the fiber-Ecoflex 00–30 composite, as well as pure Ecoflex 00–30 and found that it required ≈2 MPa of pressure to puncture the fiber composite, and ≈0.75 MPa to puncture the unreinforced elastomer (Figure S3).

The pleats increase the volume of material that can participate in actuation; although each section of the composite expands to a smaller degree than the unreinforced elastomer, the folds increase the number of elements that actuate, and allow large amplitudes of motion (**Figure 1**). To achieve the greatest possible range of motion, we maximized the number

of "folds" per actuator, within the limits set by the resolution of our 3D printed molds: ≈200 microns; Dimension Elite, Stratasys, Inc.) and used this design for all actuators in this paper (Figure 1a–c). The final pleating design we used (Figure 1c,d) allowed us to achieve similar radii of curvature with the fiber-reinforced Pneu-Nets using both positive and negative (with respect to atmospheric) pressure (Figure 1d–f; the acute angles at the tips of the actuator allowed it to collapse into a semicircle under vacuum).

To demonstrate the utility of the pleated Pneu-Net design, we oriented three of the actuators at 120° to one another (**Figure 2**a), and glued them together to build a gripper that is capable of motion in two directions (SI provides fabrication details). We used this gripper to pick up a wine glass (Figure 2a–d) using positive pressure (≈15 psi; ≈100 kPa): the convex curvature on the interior of the gripper surface conformed to the convex exterior of the smooth glass. We also used the manipulator with negative pressure to pick up the wine glass by contact with its interior surface (Figure 2e–h).

In cases where a sharp object punctured an actuator, a soft seal formed spontaneously around the hole and this seal maintained the functionality of the Pneu-Net (**Figure 3**a–c). Even when the object was removed, the actuator continued to function (Figure 3c-d). The fibers probably prevent crack propagation[28] from expanding the damage due to the piercing object, and thus limit the extent of the crack to that of the piercing object itself.

We believe there are three primary mechanisms that cause the self-sealing phenomenon: (i) When a crack is created by an object, it pushes against and strains the bulk elastomer. Due to silicone's high resilience (Figure S1), when the object is removed the silicone returns to its original shape and presses the fresh crack surfaces against themselves–thus sealing the hole. (ii) The crack surfaces are deformable and conform to one another. Chaudhury and Whitesides[29] measured the self-adhesion of PDMS (Sylgard 170; Dow Corning, Inc.), and found a work of adhesion, W, to be ≈45 erg cm^{-2} (4.5 μJ cm^{-2}) for that particular silicone elastomer; using that value of W, we calculate an adhesive energy of ≈9 erg (0.9 μJ) for the hole created from the needle in Figure 3 (see SI for more detail). (iii) While actuated, the internally pressurized Pneu-Net pushes the self-adhered crack inward and applies compressive force to seal the edges of the hole.

By using a stretchable composite of fibers and elastomer in a quasi-bellows geometry, and using soft lithography, we fabricated pleated, pneumatic actuators. These actuators could move in two directions using a single pneumatic control input, and were both soft and resistant to puncture; If punctured, they sealed around the piercing object, and also sealed the hole left behind when the object was removed. We used these actuators to fabricate a gripper that was delicate enough to pick up a wine glass from either its inner or exterior surfaces.

The practicality of soft robots as assistants to humans in search and rescue, as aids in rehabilitation, assisted living, or other tasks that require they be insensitive to sharp objects such as glass, barbed wire, thorns, and sharp rubble. These pleated actuators–composites that are both puncture resistant and flexible–are potential components in such systems. The addition of fibers to the elastomeric matrix also prevented

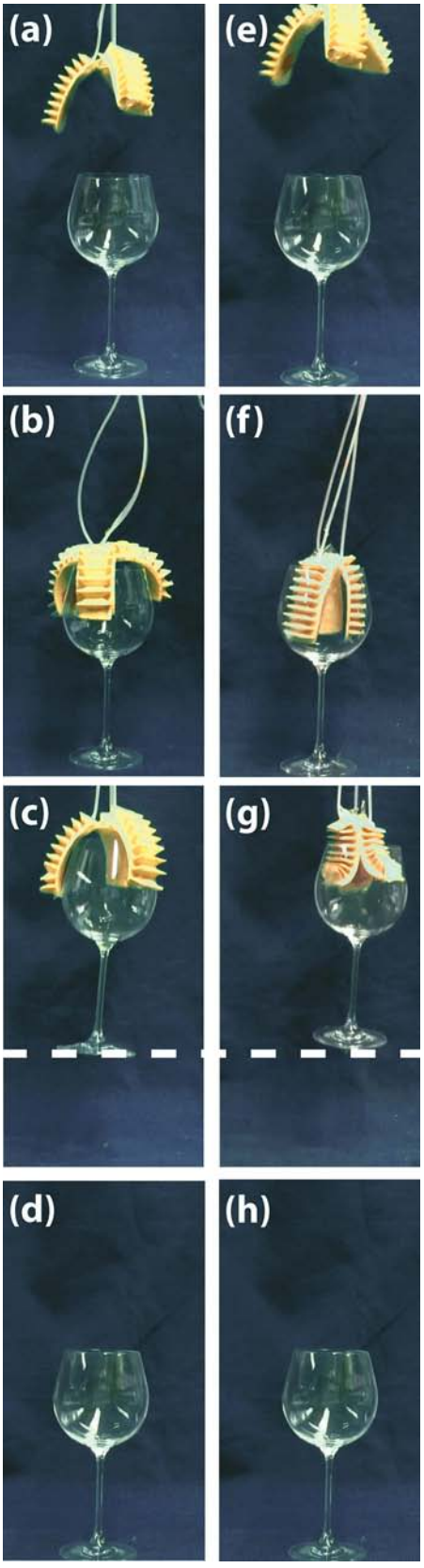

Figure 2. A gripper picks up a wine glass by gripping the (a–d) exterior surface or (e-h) interior surface.

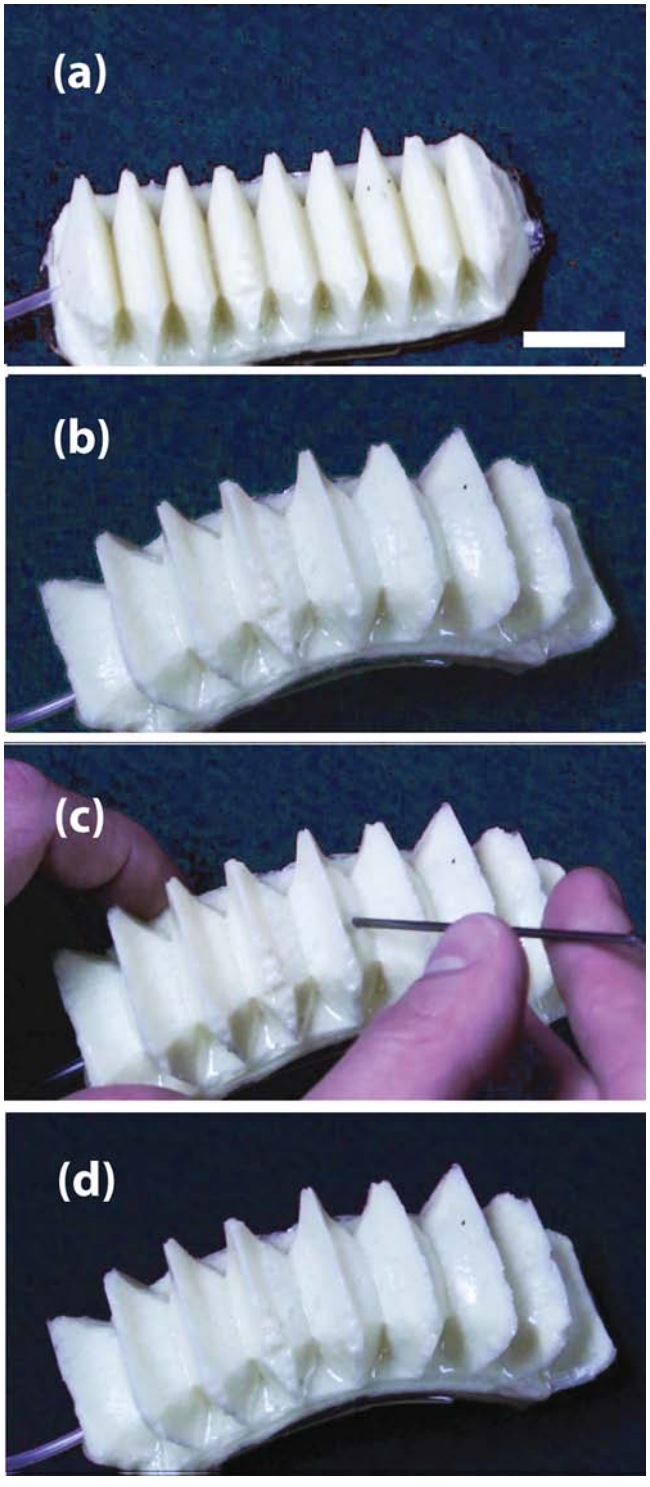

Figure 3. (a) A composite material, bellows-like actuator that (b) bends when pressurized. (c) The material seals around a puncture and the actuator continues to function, (d) even when the source of puncture (a 14 gauge needle) is removed. Scalebar is 2 cm.

failure via the occurrence of aneurysms over the thousands of cycles we tested; this feature, combined with their reduced sensitivity to puncture, will make them useful choices for soft machines in areas that demand reliability in hazardous environments.

Finally, the bellows design we chose is a platform for using fibers and less extensible materials in soft actuators. For example, the use of carbon fiber would add electrical conductivity, and potentially even higher strength-to-weight ratios than the current choice of materials. Glass fibers ($G'_{SiO2} \approx 70$ GPa)[30] may improve their resistance to slashes, abrasion, and tearing (modes of failure we did not explore). In addition, this design allows us to use less extensible rubbers, such as the styrene-butadiene (SBR) formulations in tire rubber;[31] by using these high elastic modulus rubbers ($G'_{SBR} \approx 80$ MPa),[32] it should be possible to actuate pneumatically to higher pressures, and thus to exert greater forces (semi-truck tires are routinely pressurized to >100 PSI; 690 kPa) than is possible in silicone-based soft machines.

Supporting Information

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

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