Supporting Information

"Soft Robotic Actuators and Robots that Are Resistant to Mechanical Damage"

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Fabrication of Quadrupeds and Starfish Grippers by Casting of Elastomers. Figure S1 and **Figure S2** describe the molds used to fabricate quadrupeds and starfish grippers, respectively, according to the method described before.[1, 2] We cast the pneumatic network of the actuators using a two-part silicone rubber (Ecoflex 00-30, Smooth-On Inc., Easton PA.) We mixed equal volumes of Ecoflex 00-30 prepolymer part A and part B, poured it in the negative molds, and cured the mixture at room temperature for 2 hours. After unmolding the elastomeric slab, we layer a compliant, relatively inextensible sheet on the top of the channels that form the pneumatic network in order to seal them. These relatively inextensible sheets served as strain-limiting layers and were fabricated from: i) [poly(dimethyl siloxane) (PDMS); Sylgard 184, Dow Corning]; ii) Nylon mesh (Wear-Resistant Nylon Mesh, Product Code 9318T74, McMasters Carr Supply Company, Dayton NJ) impregnated with uncured Ecoflex 00-30 prepolymer, degassed in a desiccator at 36 Torr for 3 min and cured for 2 hours at room temperature; or a iii) polyester/cellulose blend paper (VWR, West Chester PA) impregnated with uncured Ecoflex 00-30 prepolymer, degassed in a desiccator at 36 Torr for 3 min, and cured for 2 hours at room temperature. A thin film of Ecoflex 00-30 prepolymer was applied at the interface between the inextensible sheet and the slab of elastomer; as the elastomer cures, the two parts weld together, and in so doing, seal the pneumatic network. After the composite structure was formed, and completely cured, we trimmed the excess of strain-limiting sheet with scissors.

Fabrication of Soft Robotic Tentacles. Figure S3 illustrates the design of the molds we used to fabricate soft tentacles, according to the method described before.[3] We filled the negative mold with Ecoflex 00-30 prepolymer and cured the elastomer by heating at 60 ˚C for 15 min. We removed the central template channel and filled the central canal with i) PDMS prepolymer (Sylgard 184, Dow Corning, Midland, MI), ii) rope (100% Natural Jute 3-ply Twine, 1/8 inches diameter, Nassco, Lombard, IL), or iii) bungee cord (Nylon Bungee cord, 3 mm (1/8 inches diameter), The Original Bungee Company, Harbor City, CA). After unmolding, we filled 5 mm-thick sections at both ends of the tentacle with Ecoflex 00-30 prepolymer and cured the elastomer at 60 °C for 15 min to seal the pneumatic channels.

Attaching to the Off-board Pressure Source. We used polyethylene tubing (Intramedic, Sparks MD) with an outer diameter of 1.57 mm to connect the pneumatic network of the soft actuators with the external gas source. The insertion of the flexible tubing was facilitated by the use of a 1.65 mm stainless steel cannula. All our soft machines were fully actuated when the valve pressure on the external gas source was 400-700 mbar (40-70 kPa).

Estimation of the Terminal Velocity of a Soft Tentacle in Free Fall. When dropped from a high altitude, objects reach their terminal velocity when the drag (air resistance force) on the actuator equals the force of gravity.[4] Then, the terminal velocity is defined by Eq. 1S. Here m (kg) is the mass of the soft actuator, g (m/s^2) is the gravity, ρ_{air} (kg/m^3) is the density of air, A (m^2) is the cross section of the soft actuator and C_d (dimensionless) is the drag coefficient.

$$V_T = \sqrt{\frac{2mg}{\rho_{air} A C_d}} \tag{1S}$$

We approximate the value of C_d for the fall of a tentacle from the fall of a long circular rod the atmosphere, assuming that the circular rod falls with the lateral area facing down, and that the flow in the boundary layer is entirely laminar. Under these assumptions, $C_d = 1.2$ [5] The other parameters in the equation are: $\rho_{air} = 1.225$ kg/m^3 (assuming that the fall happens at 15 °C), $m_{tentacle} = 0.018$ kg, $g = 9.81$ m/s^2, $A = 0.0015$ m^2 (longitudinal cross sectional area of the tentacle).

Substituting these values on Eq. 1S we get a $V_T = 12.7$ m/s, or 45.6 km/h. The momentum on impact is mv, and we assume a time Δt of impact of 5 ms. The force is:

$$F \sim \frac{m\Delta v}{\Delta t} \quad (2S)$$

The transient pressure is given by Eq. 3S; substituting the values, we obtain P=30 kPa.

$$P = \frac{m\Delta v}{A\Delta t} \quad (3S)$$

Figure S8 and Movie_M5 show the impact of a soft tentacle being thrown at a speed higher than its terminal velocity (~27 m/s; 97 km/h) against concrete. The tentacle is still functional after the impact (see Fig. S8b)

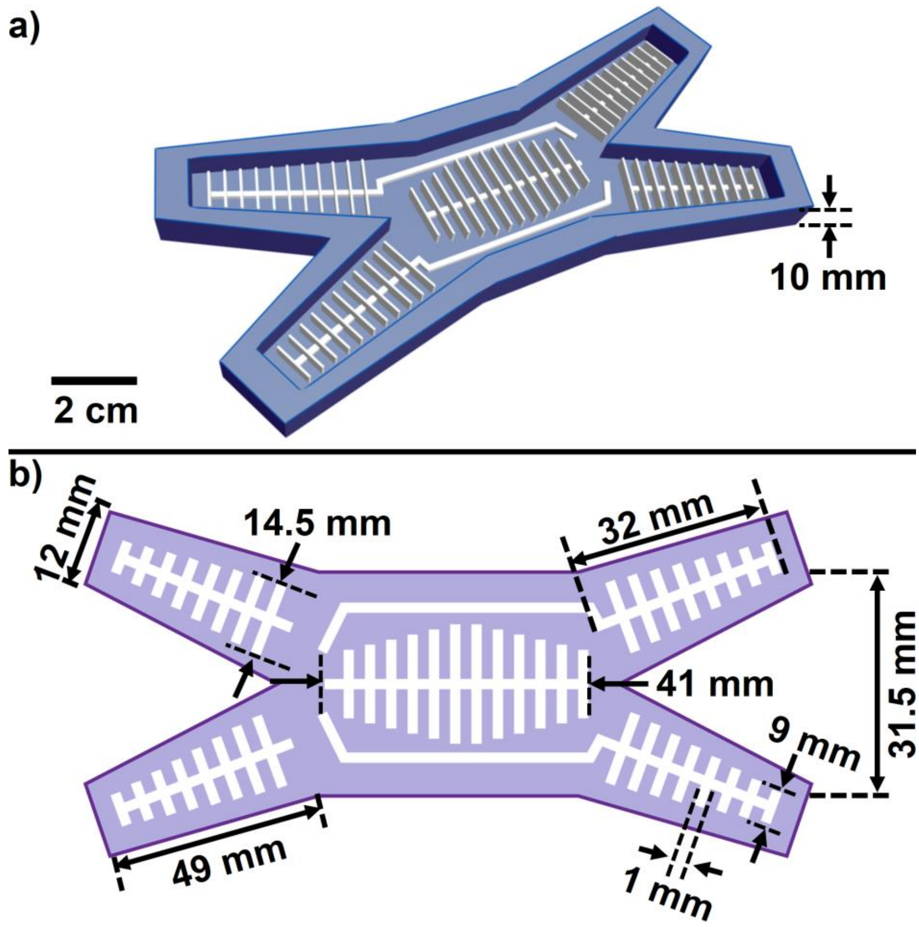

Figure S1. a) Schematic representation of the plastic (ABS) mold used to fabricate the pneumatic layer of the quadrupeds using soft lithography. b) Top view of the pneumatic network of a soft quadruped, showing the relevant dimensions.

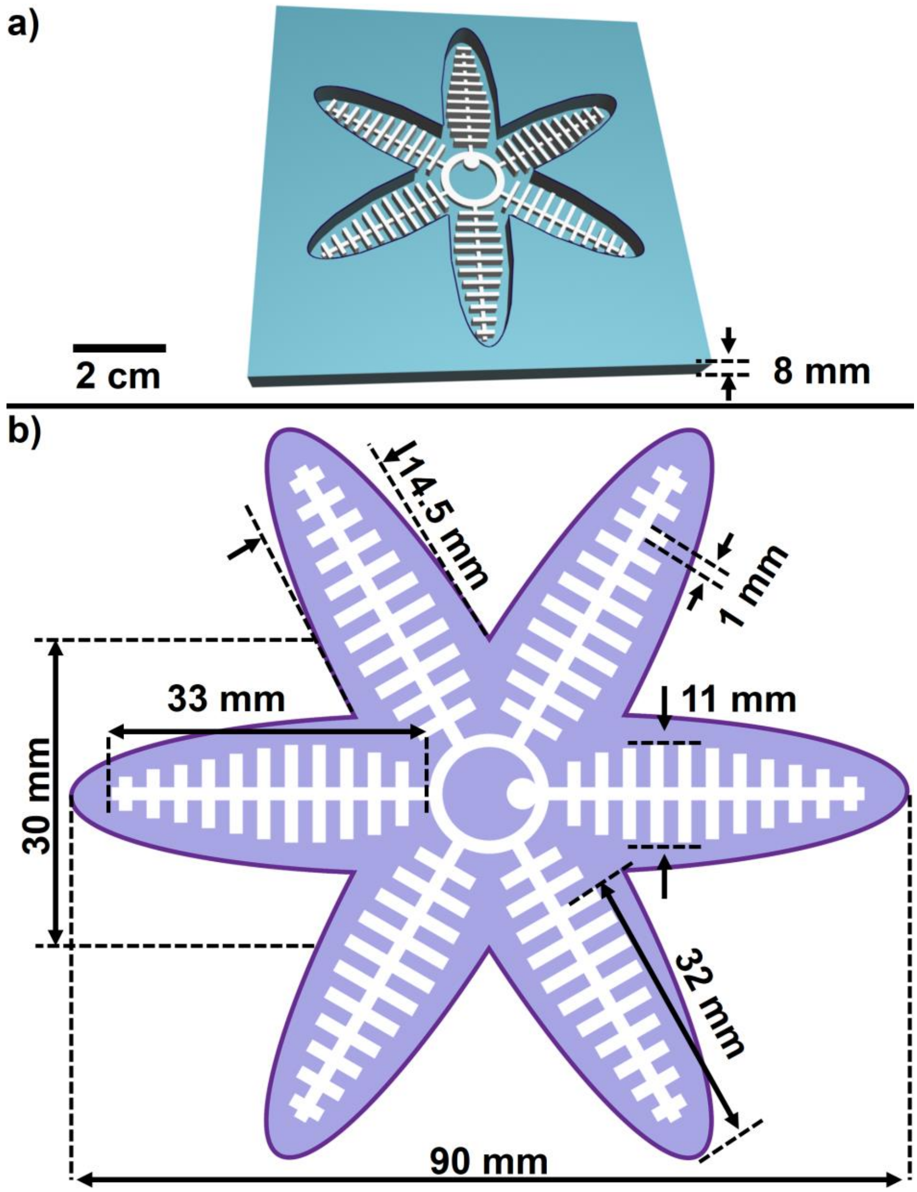

Figure S2. a) Schematic representation of the plastic (ABS) mold used to fabricate the pneumatic network of the starfish grippers using soft lithography. b) Top view of the pneumatic network of a starfish gripper, showing the relevant dimensions.

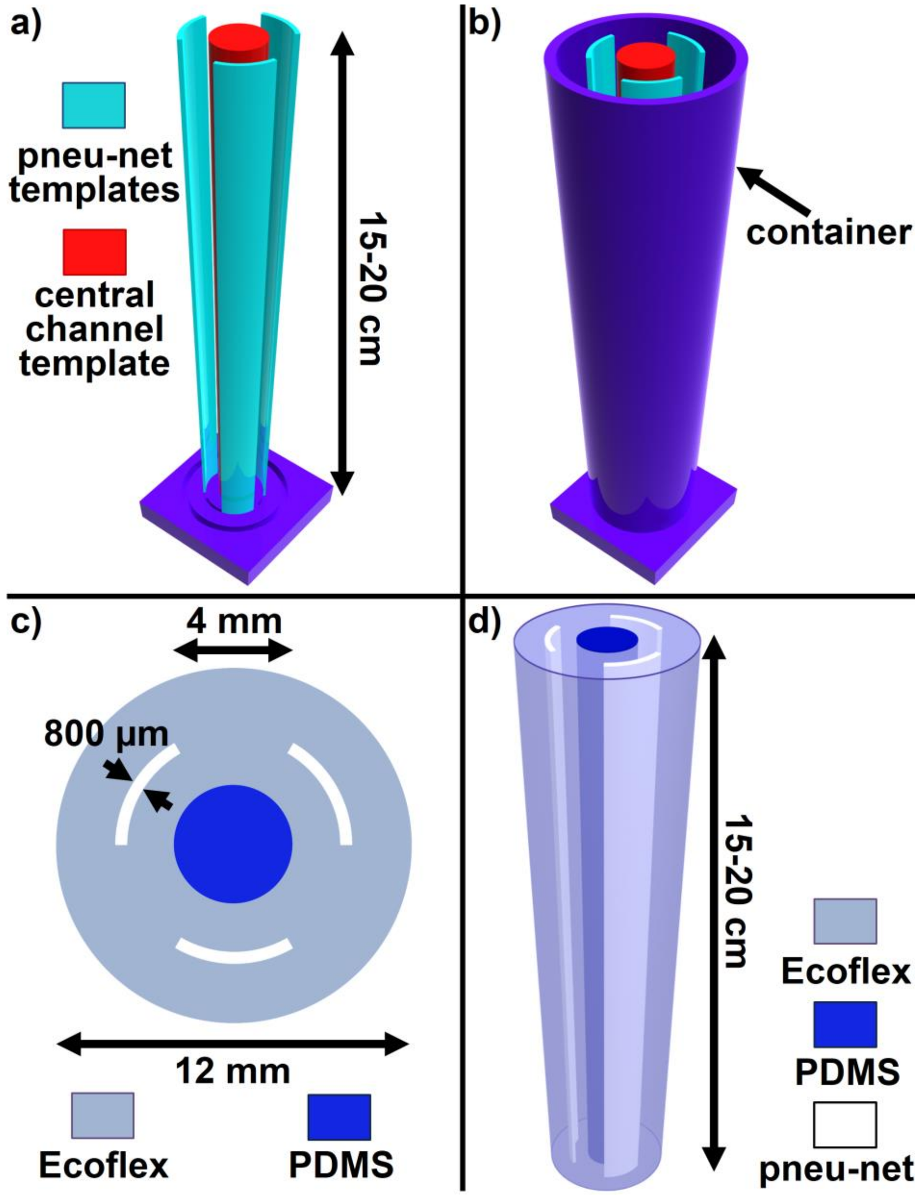

Figure S3. Fabrication of 3D tentacles. a) Mold with the templates for the pneu-nets and the central channel. b) The mold is enclosed in a container having the final outer diameter of the tentacle. The templates for the pneumatic channels are parallel to the walls of the container. Ecoflex 00-30 is poured inside the mold and allowed to cure. After the template for the central channel is removed, PDMS is poured into the void formed and allowed to cure, forming a strain-limiting core. c) Cross-section of the tentacle showing the relevant dimensions.
d) Schematic view of a tentacle with a strain-limiting core made of PDMS and three pneumatic channels parallel to the core.

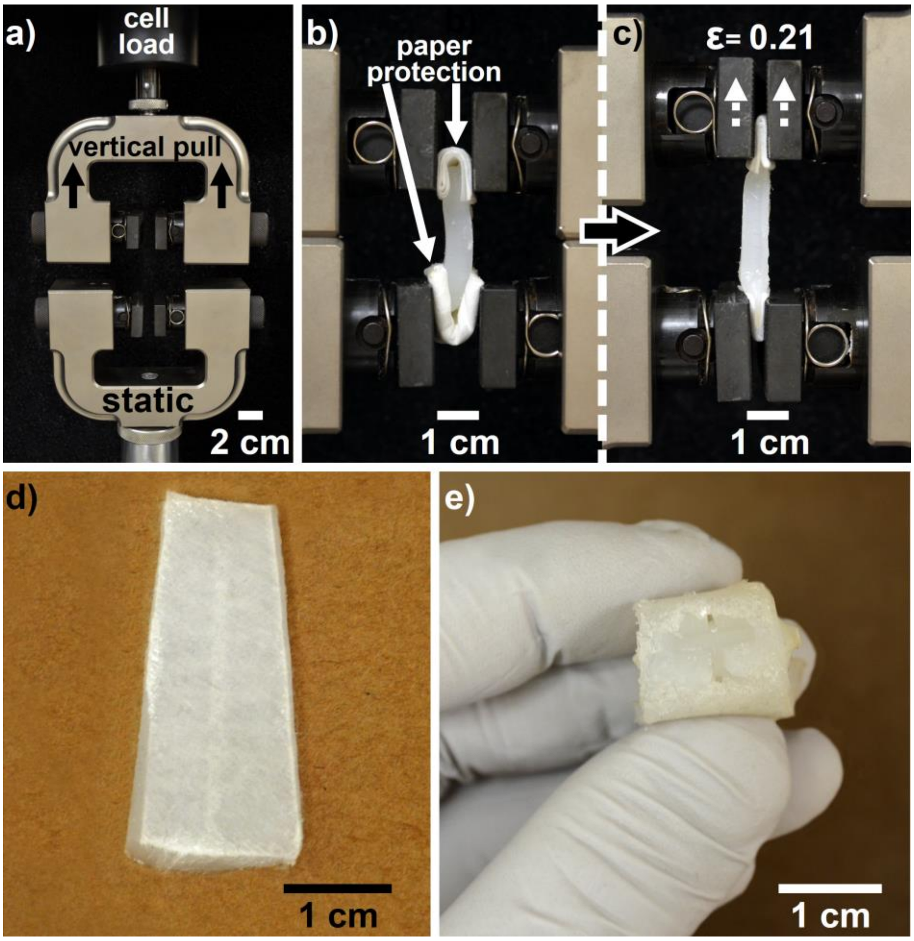

Figure S4. a) Screw side action grips used for holding test specimens that undergo tensile testing using an electromechanical test frame. b) Test specimens are protected with four layers of polyester-cellulose paper to minimize damage by the grips. c) The electromechanical test frame starts applying tension while the values for the load (N) and extension (mm) are recorded. d) A test specimen (here, the leg of one quadruped) is used to estimate the tensile strength of this soft actuator. e) When the strain of the sample reaches 0.21, the strain-limiting layer (here, a paper-elastomer composite) tears, exposing the underlying pneumatic channel.

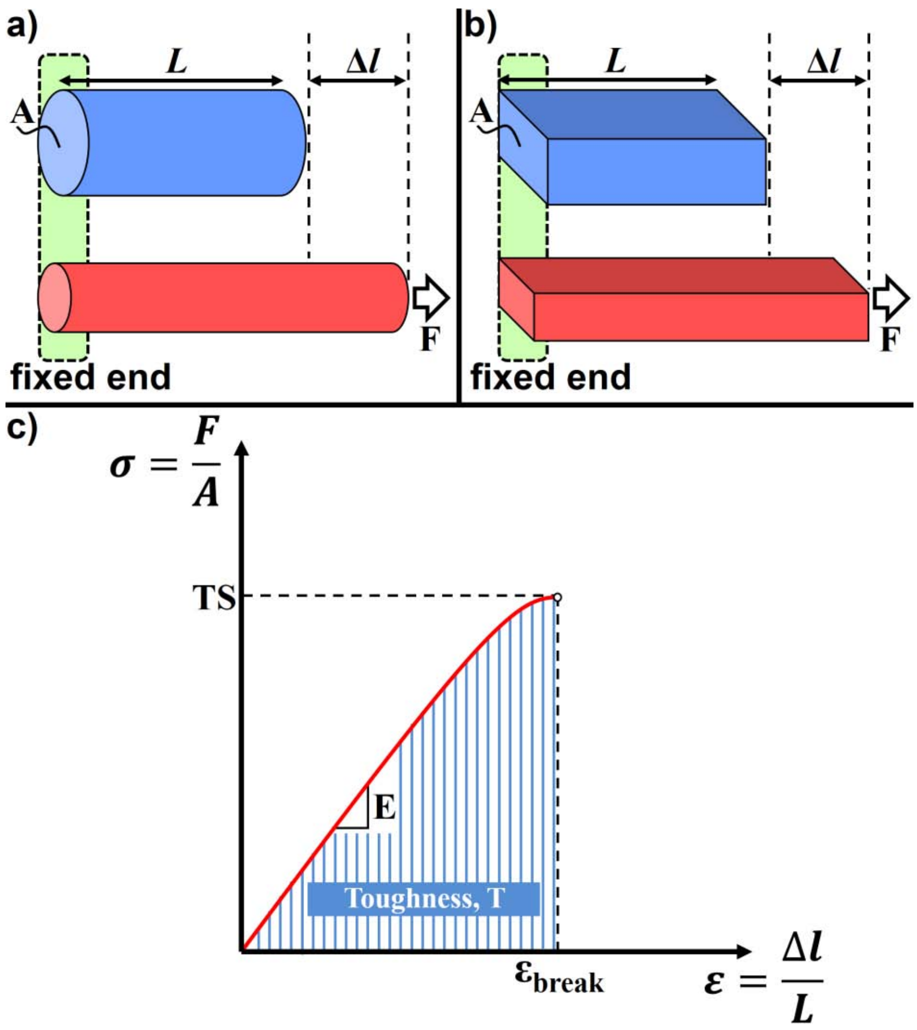

Figure S5. Parameters used to determine the tensile strength of the soft actuators. a) Scheme showing the tensile testing of cylindrical samples (sections of soft tentacles). b) Scheme showing the tensile testing of parallelepipedic samples (fragments of soft quadrupeds or starfish). c) Scheme showing the different parameters used to describe the stress-strain curve.

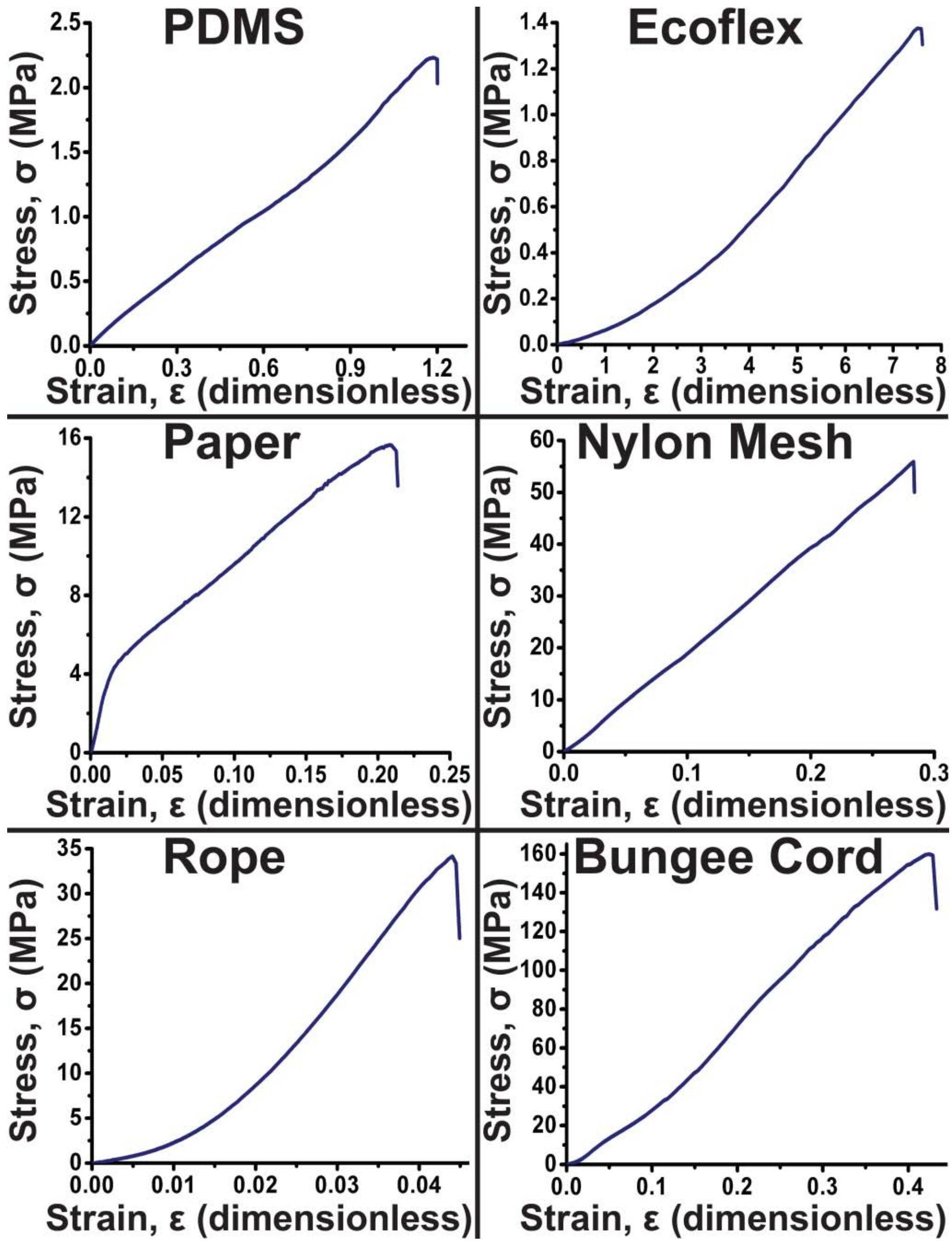

Figure S6. Representative stress-strain curves for the materials used for the fabrication of the soft actuators presented in this study.

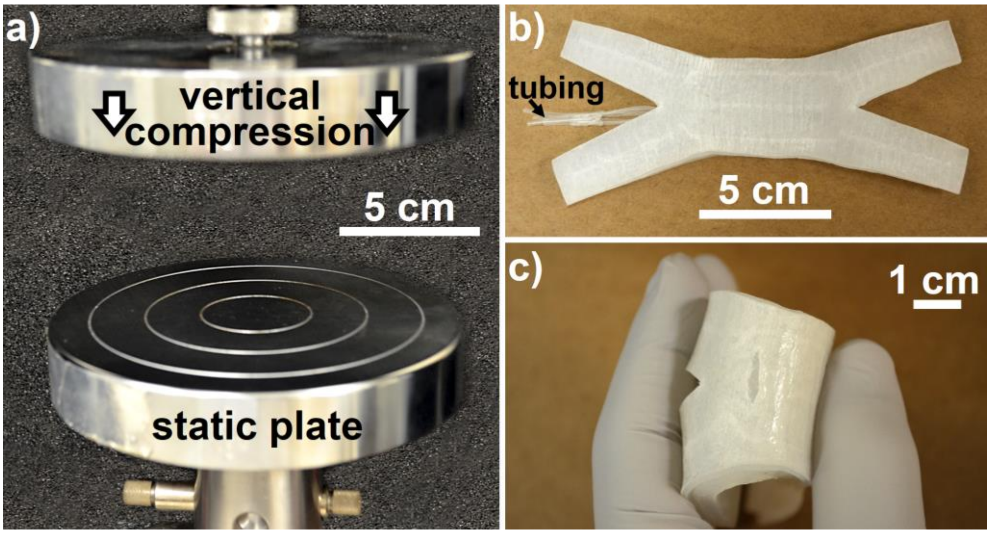

Figure S7. a) Compression platens provide a hardened surface for uniform stress distribution in compression tests. b) A quadruped with a paper strain-limiting layer undergoes compression testing to characterize its compressive strength (see Fig. 8f). c) After applying a compressive load of 1.3 kN the paper of the strain-limiting layer tears and prevents the actuator from functioning normally.

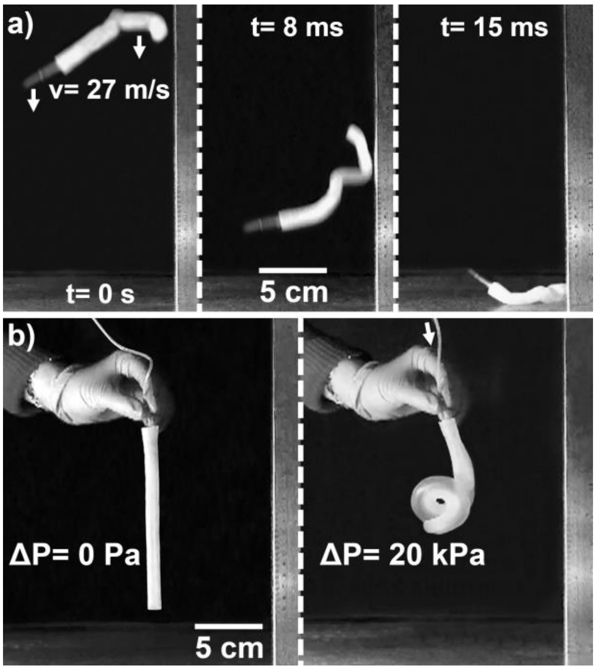

Figure S8. a) Snapshots of a high-speed video of a tentacle with a PDMS core-limiting layer being thrown against concrete pavement at a speed of 27 m/s (~97 km/h). b) Actuation of the tentacle after the impact demonstrating that the soft actuator is still functional. See Supporting Information, Movie_M5 for the full movie.

Videos. The following videos are part of this supporting information section:

1. **Movie_M1.** A functional quadruped being hammered while at rest. The power of the hammer strike is sufficient to break a small glass bottle.
2. **Movie_M2.** A functional quadruped being hammered while walking. The power of the hammer strike is sufficient to drive a nail into a piece of wood.
3. **Movie_M3.** Video of a starfish gripper with a strain-limiting layer made of paper being run over by a car.
4. **Movie_M4.** Video of a starfish gripper with a Nylon mesh strain-limiting layer being run over by a car when resting over a pile of pieces of crushed glass (1-3 mm thick).
5. **Movie_M5.** Video of a soft tentacle impacting the concrete at 27 m/s (~97 km/h).

References:

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[2] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, G. M. Whitesides, *Angew. Chem., Int. Ed.* **2011**, *123*, 1930.

[3] R. V. Martinez, J. L. Branch, C. R. Fish, L. Jin, R. F. Shepherd, R. Nunes, Z. Suo, G. M. Whitesides, *Adv. Mater.* **2012**.

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[5] M. Sadraey, *Aircraft Performance Analysis*, VDM Verlag Muller, Saarbrucken **2009**.