Fabricating 3D Structures by Combining 2D Printing and Relaxation of Strain

Supporting Information

Brian J. Cafferty,[1†] Victoria E. Campbell,[1†] Philipp Rothemund,[1,2,3] Alar Ainla,[1] Nicolas Fulleringer,[1] Daniel J. Preston,[1] Alina C. Diaz,[1] Dan Sameoto,[1,4] Jennifer A. Lewis,[2,5] and George M. Whitesides[1,3,5*]

[1]Department of Chemistry and Chemical Biology, Harvard University
12 Oxford Street, Cambridge, MA 02138, USA

[2]School of Engineering and Applied Sciences, Harvard University
29 Oxford Street, Cambridge, MA 02138, USA

[3]Kalvi Institute for Bionano Science and Technology, Harvard University,
29 Oxford Street, Cambridge, MA 02138, USA

[4]Department of Mechanical Engineering, University of Alberta,
9211 116 Street NW, Edmonton, AB, Canada

[5]Wyss Institute for Biologically Inspired Engineering,
60 Oxford Street, Cambridge, MA 02138, USA

[†]These authors contributed equally to this work

*Author to whom correspondence should be addressed: gwhitesides@gmwgroup.harvard.edu

Materials: All silicones and pigments were purchased from Smooth-On, Inc. To prepare elastomeric strips and sheets, we used Dragon Skin® 10 SLOW (DS10). Dragon Skin® 10 SLOW is a high-performance platinum-cured silicone rubber that has a pot life of 45 minutes (pot life is the maximum time the materials remain liquid), a curing time of 7 hours at room temperature, and a Shore hardness of 10. To tune the material properties of the gripper, we used (separately and in combination) four elastomers with different mechanical properties (Shore hardness): Dragon Skin® 10 and 30, Ecoflex® 00-30, and Smooth-Sil® 960. These elastomers are platinum-catalyzed silicone rubbers, and adhere seamlessly to each other. Dragon Skin® 30 (DS30) is a high-performance platinum-cured silicone rubber that has a pot life of 45 minutes, a curing time of 16 hours at room temperature, and a Shore hardness of 30. Ecoflex® 00-30 is a high-performance platinum-cured silicone rubber that has a pot life of 45 minutes, a curing time of 4 hours at room temperature, and a Shore hardness of 00-30. Smooth-Sil® 960 is a high-performance platinum-cured silicone rubber that has a pot life of 45 minutes, a curing time of 16 hours at room temperature, and a Shore hardness of 60A. To aid in the visualization of the bilayers, we added red and white pigments (Silc Pig®) to the silicones of the stretched sheet and to the printed layer, respectively.

Fabrication of 3D structures: We prepared a bistrip hyperelastic system that consisted of elastomeric strips of fixed width (5 mm) and thickness (2 mm), and of different initial lengths. Elastomeric sheets were formed that were 28 cm by 28 cm with a thickness of 2 mm. Elastomeric strips and sheets were cut using a laser cutter into defined two-dimensional patterns. A custom built support was made to stretch the cut strips and sheets. On to these stretched strips and sheets, we printed elastomeric ink (made of the same material as the stretched elastomer) that acted as the second layer of the bilayer system (Figure 1).

Mechanical analysis: We analyzed the mechanical properties of the bilayers using an Instron (model 5966). The load cell had a capacity of 10 N, a tension rate of 20 mm/min, and a maximum displacement of 100 mm.

Printer: We used a TEVO Tarantula Prusa-I3 printer that we customized to print elastomeric silicone inks (Figures S1 and S2). We chose this printer for four reasons: i) It is based on the RepRap (replicating rapid prototyper) design, which is an open design project (i.e., all blueprints, and software produced by the RepRap project are released under a free licensing agreement). ii) Both the software and hardware are easily customizable. 3) It is inexpensive (< $300 from 3dprintersonlinestore.com). 4) It is equipped with a heated print stage, which decreased the time required to cure the silicone elastomer. The printer is equipped with a thermoplastic extruder nozzle. As it is delivered, the types of structural thermoplastics that the printer can print are rigid, break when subjected to compressive force, and have poor adhesion to the stretched silicone elastomers that we used. To print elastomeric silicone inks, we exchanged this extrusion nozzle for a custom-built syringe pump that used a stepping motor (SparkFun, 39HY34-0404AL), which was compatible with the TEVO Tarantula motor controller, to move the plunger of the syringe. All 3D printed parts were printed in ABS using a Dimension Elite (StrataSys). CAD files used to fabricate the 3D printed parts (Figure S3) are provided separately in supporting information.

Pattern design: We made 2D designs using Adobe Illustrator, exported them to Inkscape (an open source software), and used Inkscape to generate GCode (a numerical control language that the printer can read).

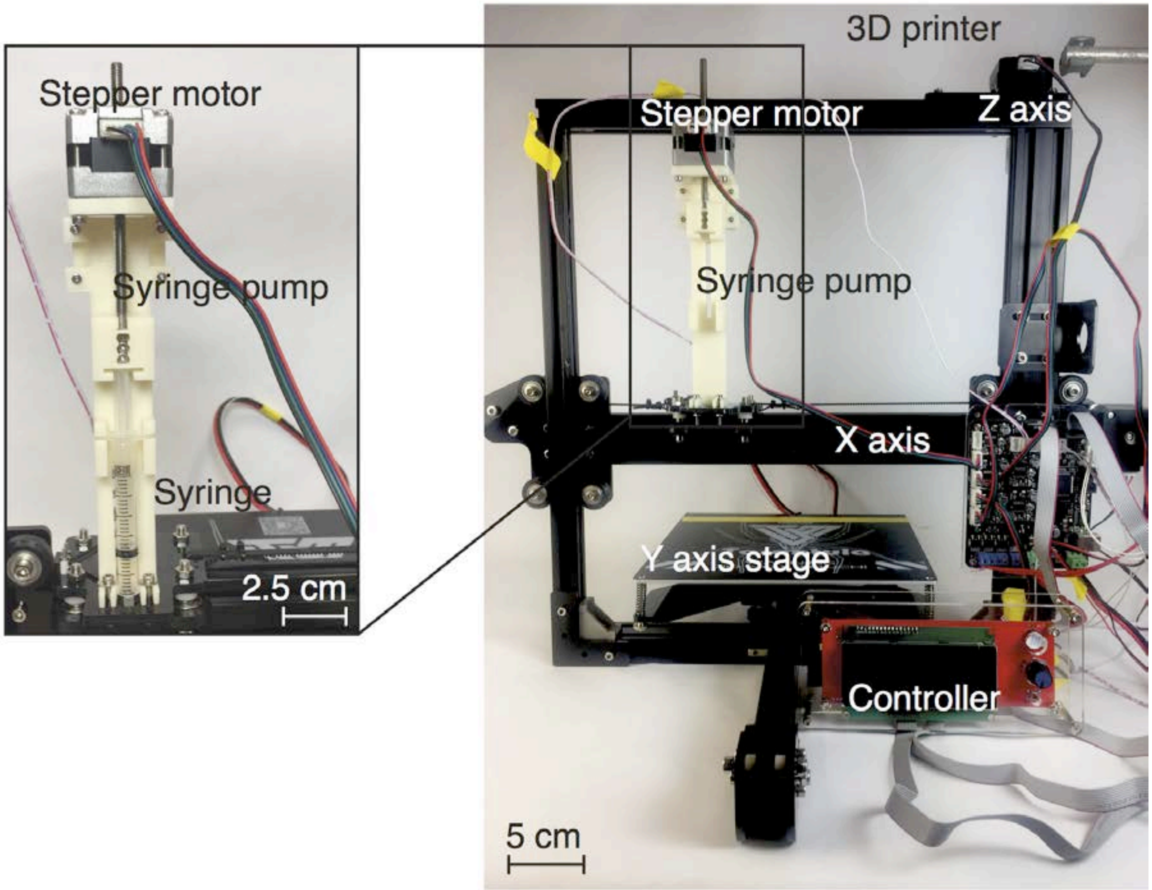

Figure S1. Photographic image of the customized TEVO Tarantula Prusa I3 3D printer (left), and of the custom built syringe-based extruder.

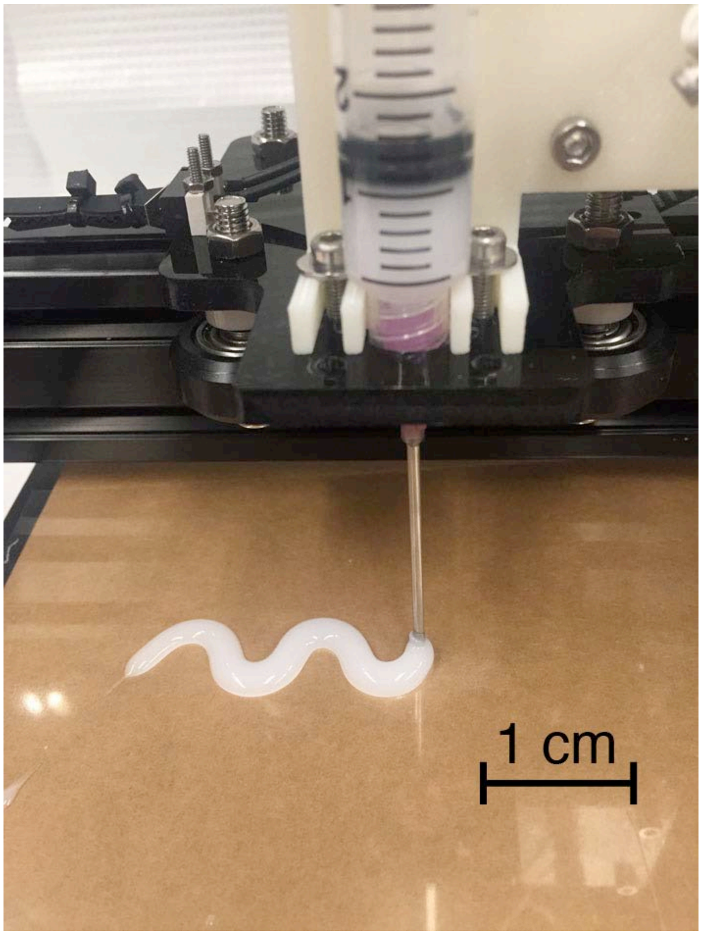

Figure S2. Photographic image of the printer printing curved lines.

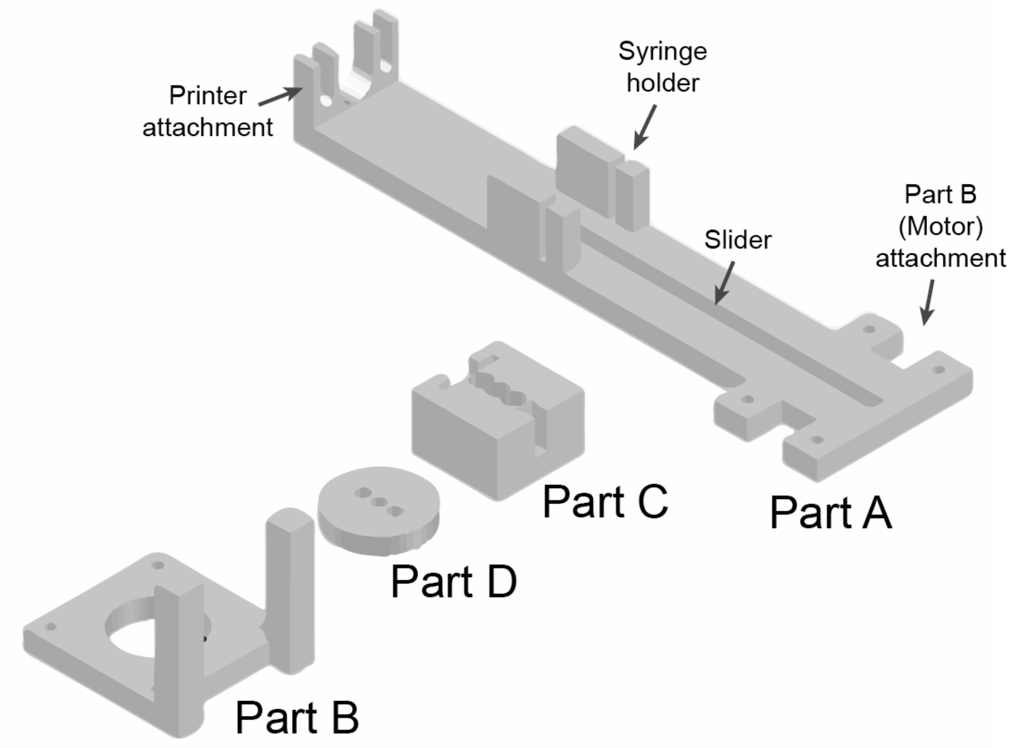

Figure S3. Images of the 3D printed parts of the syringe pump. Part description and STL files used to fabricate the parts can be found online in the Pump.zip file in the supplementary information.

Analytical model: In the undeformed state, strip 1 has length L_1, width W_1, and thickness H_1 (Figure S4A). Prestretched to length $L_1\lambda_p$, the width of the strip reduces to $W_1\lambda_p^{-0.5}$ and the height reduces to $H_1\lambda_p^{-0.5}$ because of incompressibility of the elastomer (Figure S4B). Strip 2 is printed onto the prestretched strip 1 with thickness H_2 (Figure S4B). Its undeformed width is therefore $W_1\lambda_p^{-0.5}$ and its undeformed length is $L_1\lambda_p$. When the bistrip is released (Figure S4C), it contracts to a length $L_1\lambda$ and curls to a curvature $\kappa = 1 / R$, both defined at the bonding interface between the layers.

We model the bilayer as an Euler-Bernoulli beam leading to axial stretch ratios (deformed length divided by undeformed length) that vary linearly across the thickness of the bilayer (coordinate z; Figure S4C) and can be described in strip 1 with eq. S1 and in strip 2 with eq. S2.

$$\lambda_1(z) = \lambda(1 + \kappa z) \qquad \text{(eq. S1)}$$

$$\lambda_2(z) = \frac{\lambda}{\lambda_p}(1 + \kappa z) \qquad \text{(eq. S2)}$$

These stretch ratios can be expressed in the undeformed coordinates of the strips (Z_1 for strip 1; Z_2 for strip 2; see Figure S4A and B) with eqs. S3 and S4. Here we assumed that the bending deformation of the bilayer does not cause any significant changes in thickness.

$$\lambda_1(Z_1) = \lambda\left(1 - \frac{\kappa Z_1}{\sqrt{\lambda}}\right) \qquad \text{(eq. S3)}$$

$$\lambda_2(Z_2) = \frac{\lambda}{\lambda_p}\left(1 + \kappa Z_2\sqrt{\frac{\lambda_p}{\lambda}}\right) \qquad \text{(eq. S4)}$$

We model the strain energy density of the elastomeric bistrip with an incompressible Neo-Hookean material model for uniaxial deformation (eq. S5). μ_1 and μ_2 are the shear moduli of the respective strips and λ_1 and λ_2 are described in eq. S3 and S4

$$W = \frac{\mu_{1,2}}{2}\left(\lambda_{1,2}^2 + \frac{2}{\lambda_{1,2}} - 3\right) \qquad \text{(eq. S5)}$$

Integrating eq. S5 over the volume of the bistrip in combination with eqs. S3 and S4 gives the total strain energy W_t of the bistrip (eq. S6). We find the deformed state of the bilayer by minimizing W_t with respect to λ and κ numerically with Matlab using the algorithm fminsearch. When $\mu_1 = \mu_2$, the result is independent of the values of μ_1 and μ_2.

$$W_t = \frac{\mu_1}{2} L_1 W_1 \int_0^{H_1} \lambda^2 \left(1 - \frac{\kappa Z_1}{\sqrt{\lambda}}\right)^2 + \frac{2}{\lambda\left(1 - \frac{\kappa Z_1}{\sqrt{\lambda}}\right)} - 3 \, \mathrm{d}Z_1$$

$$+ \frac{\mu_2}{2} L_1 W_1 \sqrt{\lambda_p} \int_0^{H_2} \frac{\lambda^2}{\lambda_p^2} \left(1 + \sqrt{\frac{\lambda_p}{\lambda}} \kappa Z_2\right)^2 + \frac{2}{\frac{\lambda}{\lambda_p}\left(1 + \sqrt{\frac{\lambda_p}{\lambda}} \kappa Z_2\right)} - 3 \mathrm{d}Z_2 \qquad \text{(eq. S6)}$$

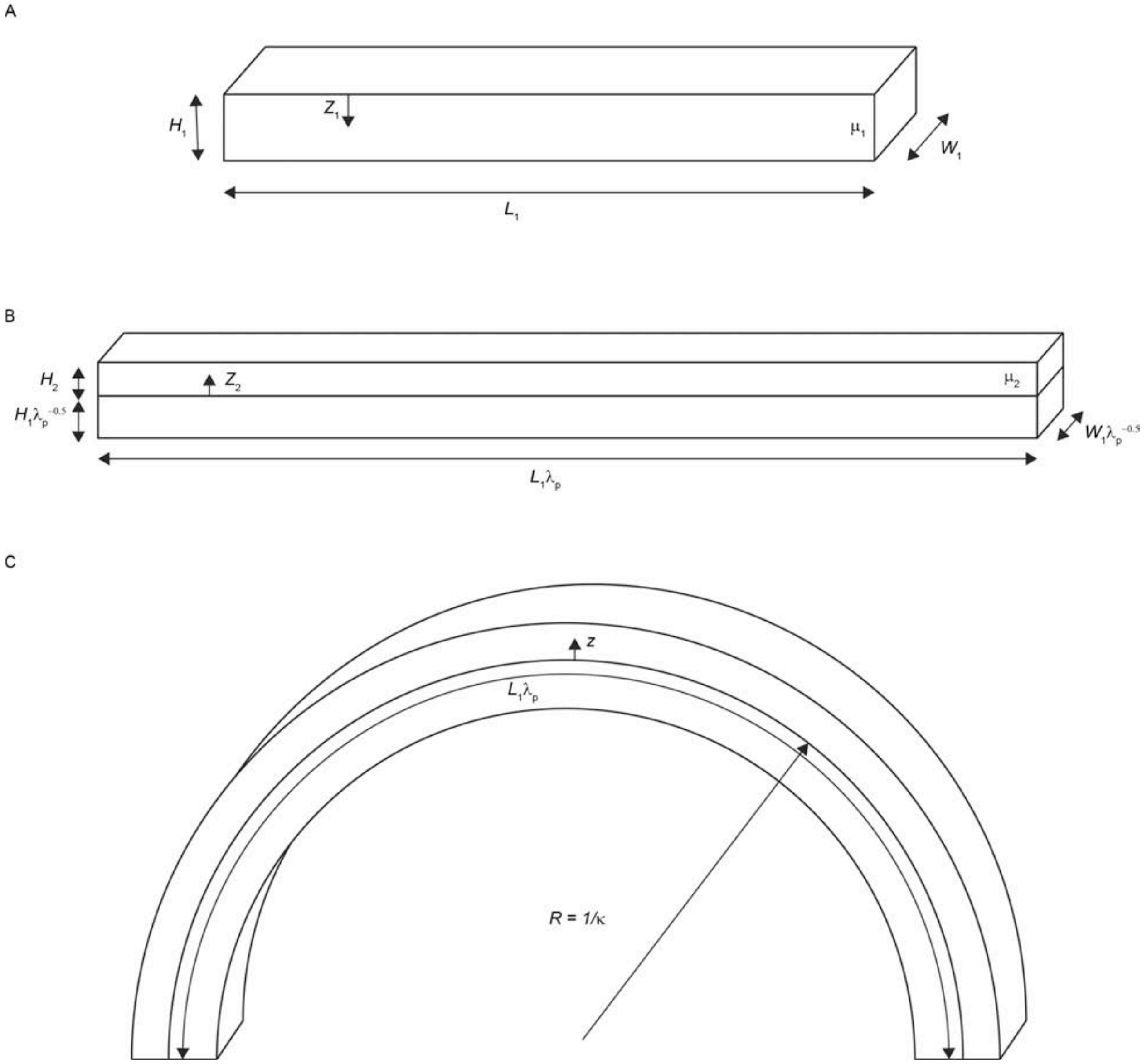

Figure S4. Model for bistrip. A) Strip 1 in the undeformed state. B) Prestretched strip 1 with strip 2 attached (i.e., strip 2 is undeformed in this state). C) Released bistrip.

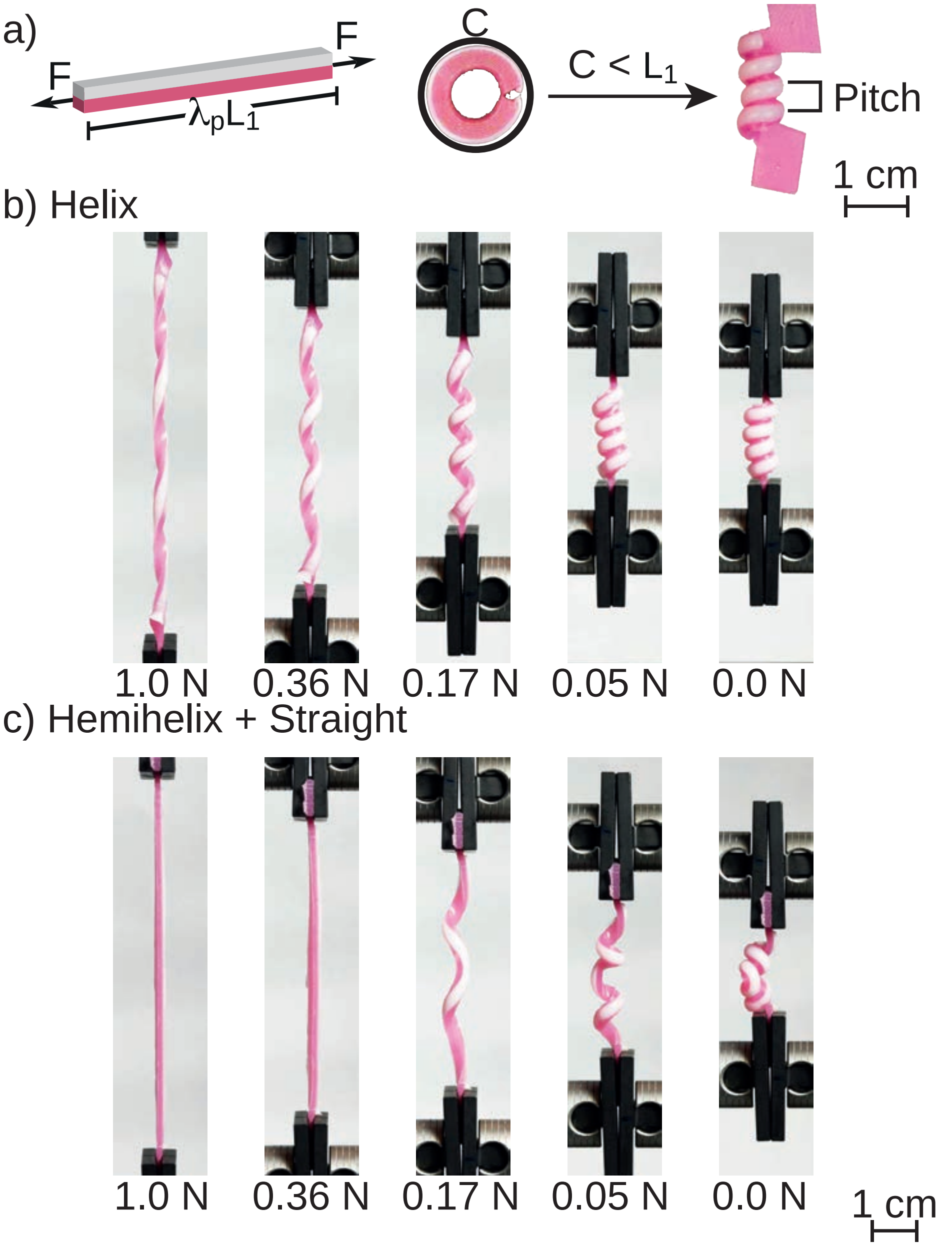

Figure S5. a) Schematic representation of the fabrication of helicies and hemihelicies. Left: the bistrip system in the strained configuration. Middle: photographic image of a curved bistrip system; C = circumference. When C < L_1 the unstretched bistrip bends out of plane and coils. Right: photographic image of the coil. b) Photographic images of a helical spring under tension, c) Photographic images of a hemihelical spring under tension. The elastomeric springs will regain their initial configuration after full extension.

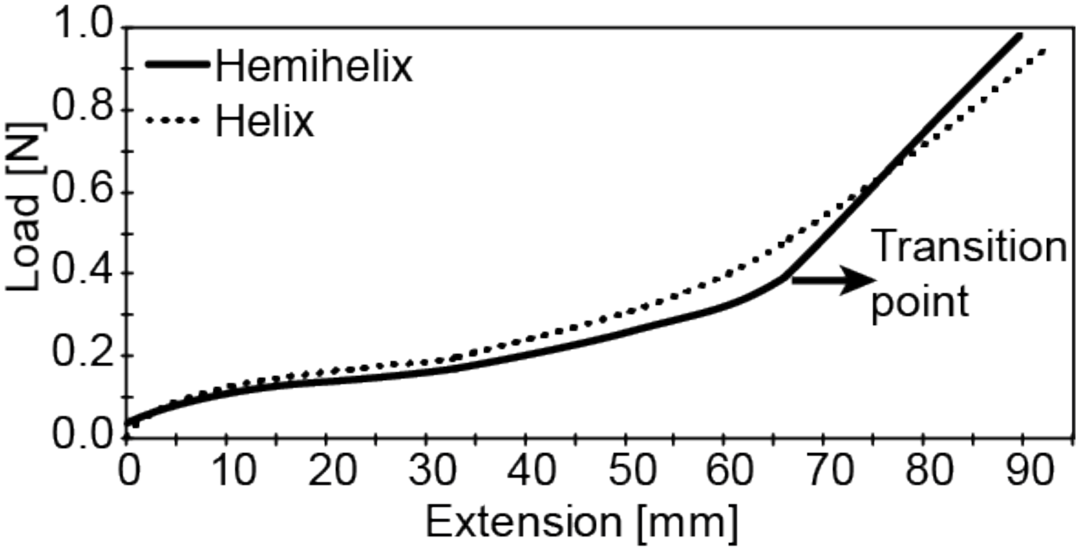

Figure S6. Plot of load as a function of extension for the helical and hemihelical configurations. The transition point is caused by the material transitioning from partially coiled to uncoiled (linear).

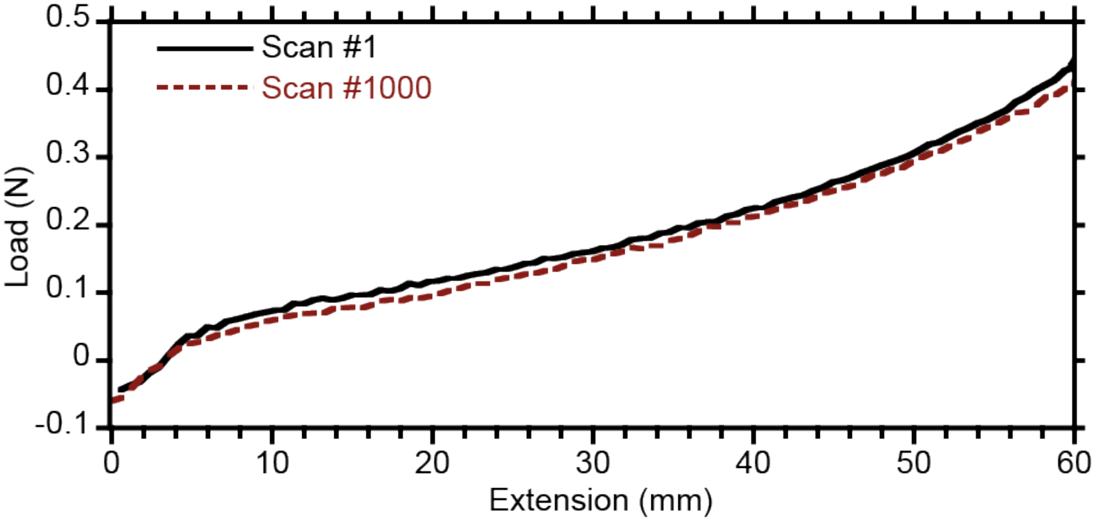

Figure S7. Load vs. extension curve for an elastic spring. Material: Dragon Skin 10; dimensions: L = 60 mm, H = 2 mm, W = 5 mm. Black line represents the first scan, dashed red line represents the scan taken after the material was stretched to 60 mm and released 1000 times.

Table S1. Radius of curvature (*R*) in mm obtained by stretching a DS10 strip of t_1 = 2.0 mm by six λ_p factors and printing an elastomeric strip of t_2 = 0.6, 0.4, and 0.2 mm.

λ_p	t_1 /mm	t_2 / mm	Radius of curvature / mm
1	2.0	0.6	∞
1.1	2.0	0.6	19.0
1.3	2.0	0.6	10.0
1.5	2.0	0.6	6.1
1.8	2.0	0.6	4.0
2.4	2.0	0.6	1.5
1	2.0	0.4	∞
1.1	2.0	0.4	26.0
1.3	2.0	0.4	14.0
1.5	2.0	0.4	9.0
1.8	2.0	0.4	4.5
2.4	2.0	0.4	2.0
1	2.0	0.2	∞
1.1	2.0	0.2	38.0
1.3	2.0	0.2	20.0
1.5	2.0	0.2	13.0
1.8	2.0	0.2	9.5
2.4	2.0	0.2	6.0

Table S2. Objects and weights that a gripper made from different materials can lift

Gripper Sheet/Fingers		
DS 10 / DS 30	**Object**	**Weight / g**
	Flower (small rose)	1.2
	Nylon sphere (d = 0.5 cm)	1.2
	Acrylic square (l = 1.0 cm)	2.3
	Small test tube	4.2
	Empty 20 mL glass vial	16
	Stainless steel sphere (d = 2cm)	20
	Full 20 ml glass vial of water	32
Ecoflex / DS 30		
	Flower (small rose)	1.2
	Nylon sphere (d = 0.5 cm)	1.2
	Acrylic square (l = 1.0 cm)	2.3
	Small test tube	4.2

d = diameter of the sphere; l = length of a side of the cube.