ADVANCED MATERIALS TECHNOLOGIES

Supporting Information

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Innervation of Sensing Microchannels for Three-Dimensional Stimuli Perception

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Other Supplementary Materials for this manuscript include the following:

Video S1 to S3

1. Theoretical analysis for 1D soft sensors

1.1. The theoretical model for stretching a 1D soft sensor

The electrical resistance is governed by:

$$R = \rho \frac{L}{A} \tag{S1}$$

where ρ is the electrical resistivity, L is the length of the sensing microchannel, A is the cross-sectional area.

Assuming the conductive liquid and elastomeric matrix are incompressible, we get:

$$A_0 L_0 = A_t L_t \tag{S2}$$

A_0 and L_0 are the initial length and cross-sectional area, respectively, and A_t and L_t are stretched length and cross-sectional area, respectively. Therefore, the resistance change $\Delta R/_{R_0}$ can be expressed as:

$$\frac{\Delta R}{R_0} = \frac{R_t - R_0}{R_0} = (\frac{L_t}{L_0})^2 - 1 = \varepsilon^2 + 2\varepsilon \tag{S3}$$

When measuring the resistance of the sensing microchannel, the contact resistance between the ionic liquid and conducting wires is also included. The actual resistance should be expressed as:

$$R = R_S + 2R_C \tag{S4}$$

R_S is the resistance of sensing microchannel, and R_C is the contact resistance.

We insert Equation (S4) into Equation (S3), and we get:

$$\frac{\Delta R}{R_0} = \frac{R_t - R_0}{R_0} = (\varepsilon^2 + 2\varepsilon)\frac{R_0 - 2R_C}{R_0} = k(\varepsilon^2 + 2\varepsilon) \tag{S5}$$

1.2 The theoretical model for pressing a 1D soft sensor

The finite element analysis was performed to calculate the cross-sectional area change with pressing displacement. Assuming the length is constant during the pressing process since the material is hyper-elastic. The resistance change is caused by the cross-sectional area variation. Therefore, according to Equation (S1), the resistance change during the pressing process is calculated by:

$$\frac{R}{R_0} = \frac{LA_0}{L_0A} = \frac{A_0}{A} \quad \text{(S6)}$$

$$\frac{\Delta R}{R_0} = \frac{A_0}{A} - 1 \quad \text{(S7)}$$

a

b

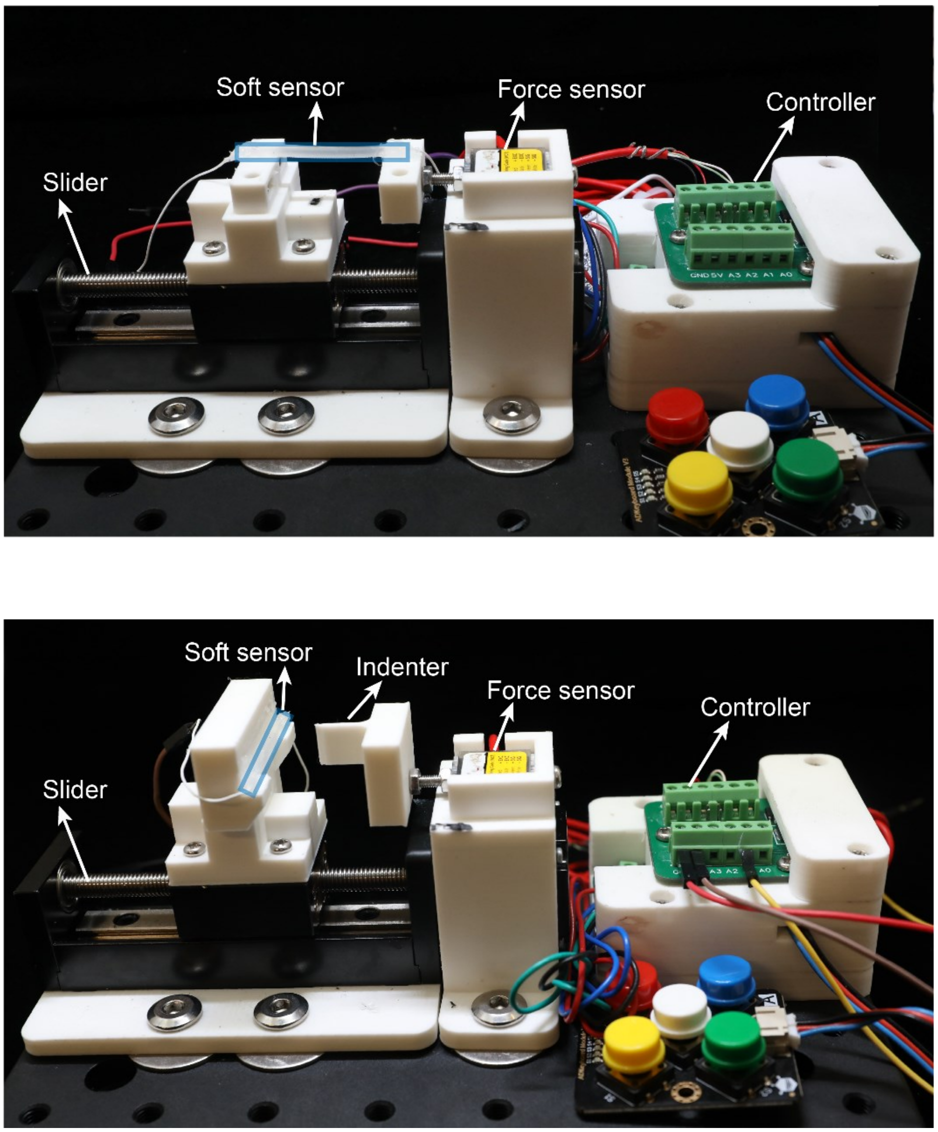

Figure S1. a) Stretching Setup for the 1D sensing microchannel. b) Pressing Setup for the 1D sensing microchannel.

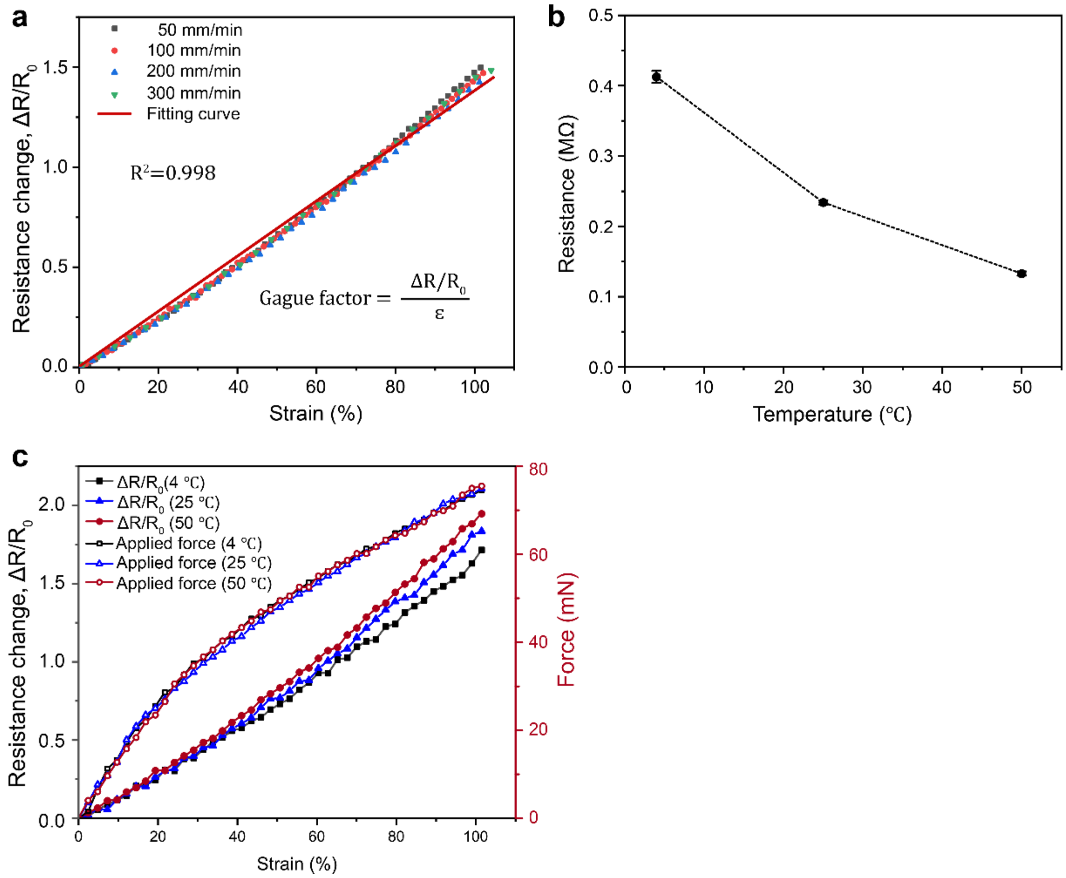

Figure S2. a) Linear fit for the resistance change with strain. b) Resistance under different temperatures. c) The effect of temperature on the resistance change and applied force.

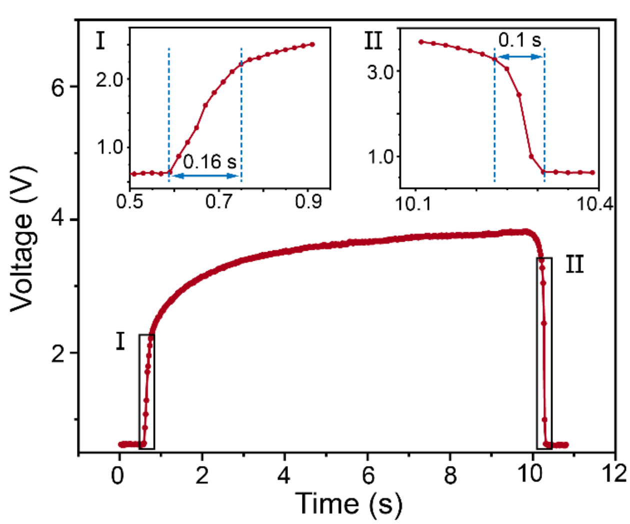

Figure S3. Dynamic response time and recovery time of the 1D soft sensor under pressing. The insets show the response time (I) and recovery time (II).

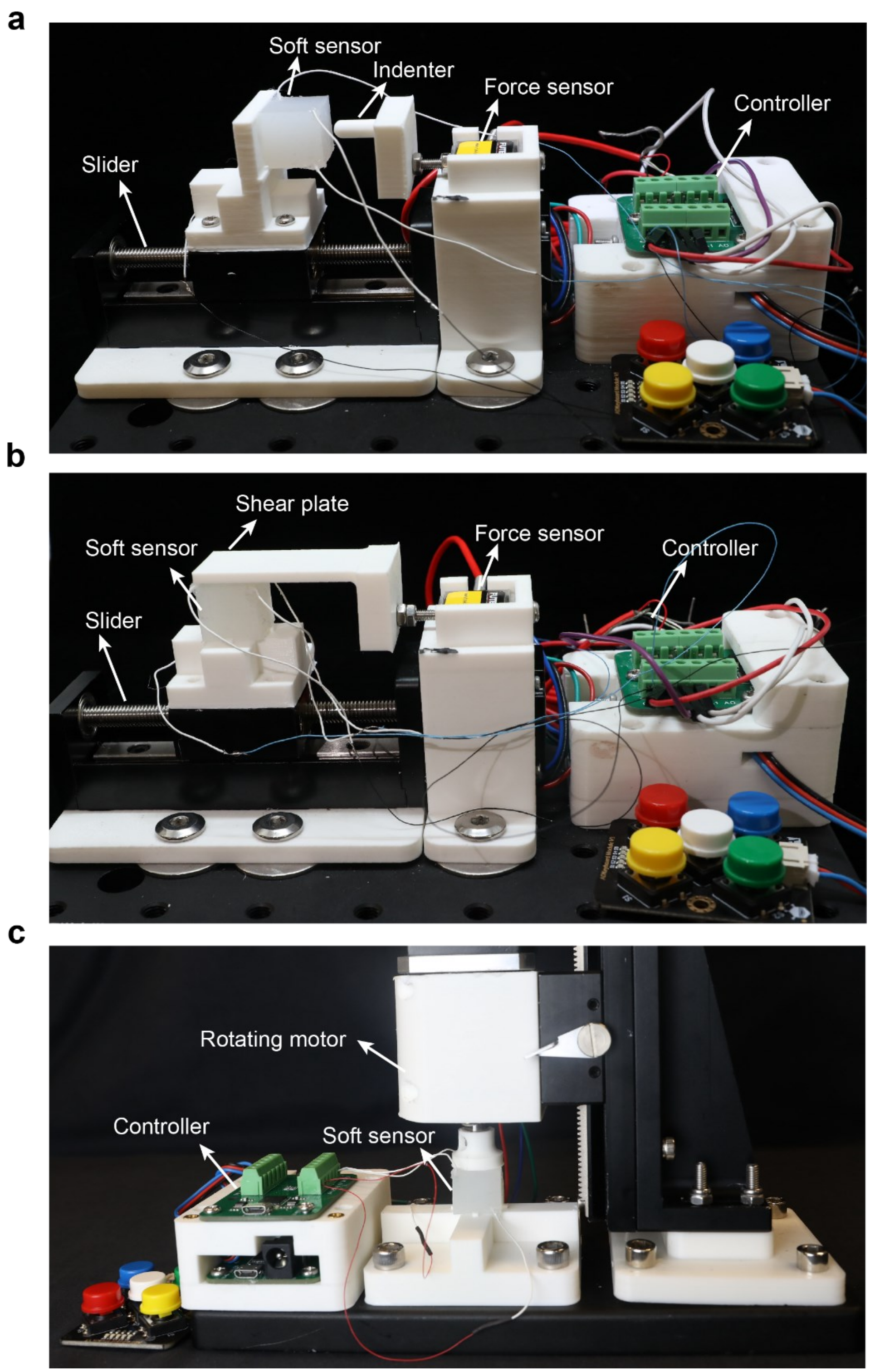

Figure S4. a) Pressing Setup for the 3D sensing microchannel. b) Shearing Setup for the 3D sensing microchannel. c) rotating Setup for the 3D sensing microchannel.

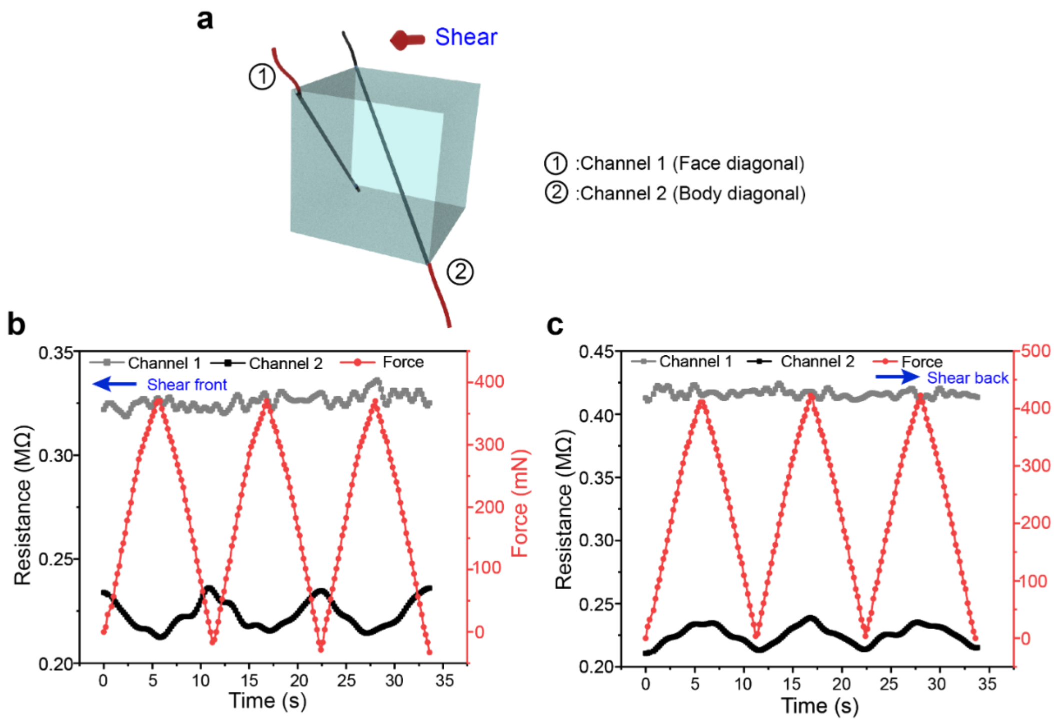

Figure S5. a) Schematic diagram of the 3D sensing microchannels under the front and back shearing deformation. b) Resistance under different temperatures. b) and c) Response of the resistance change of sensing microchannels under shearing in the front and back directions, respectively.

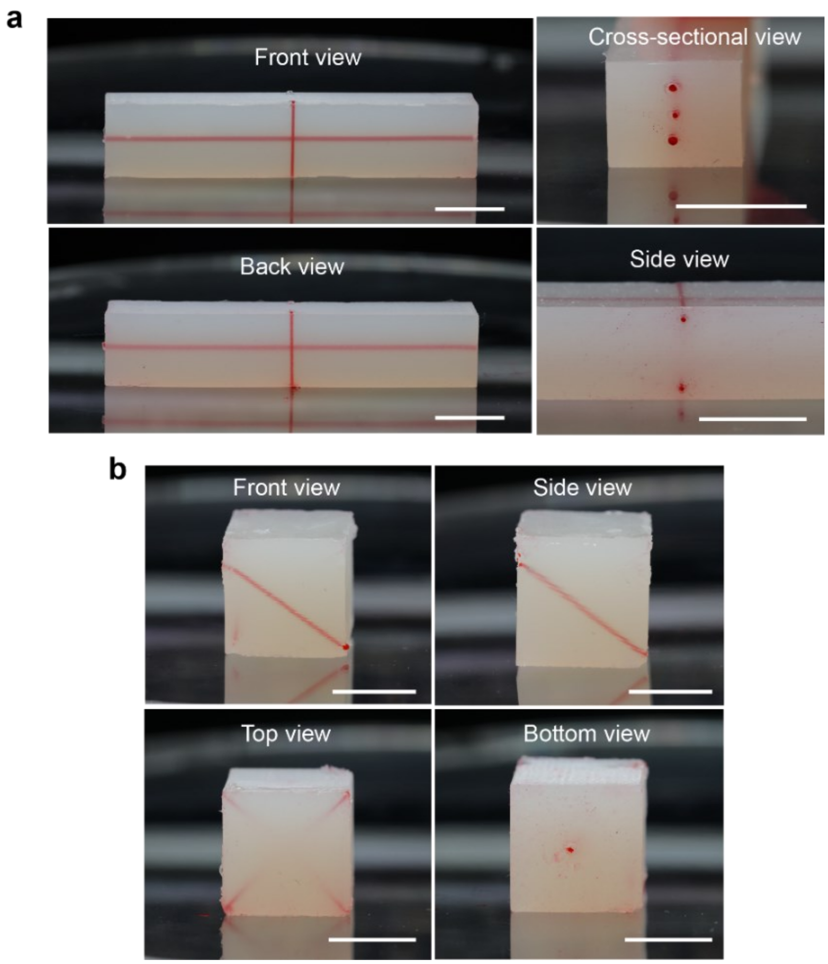

Figure S6. Detailed channel structures for sensorized actuator and cubic sensor. a) Different views of channels infused with red inks in the sensorized actuator. b) Different views of channels infused with red inks in the cubic sensor. Scale bars, 10 mm.

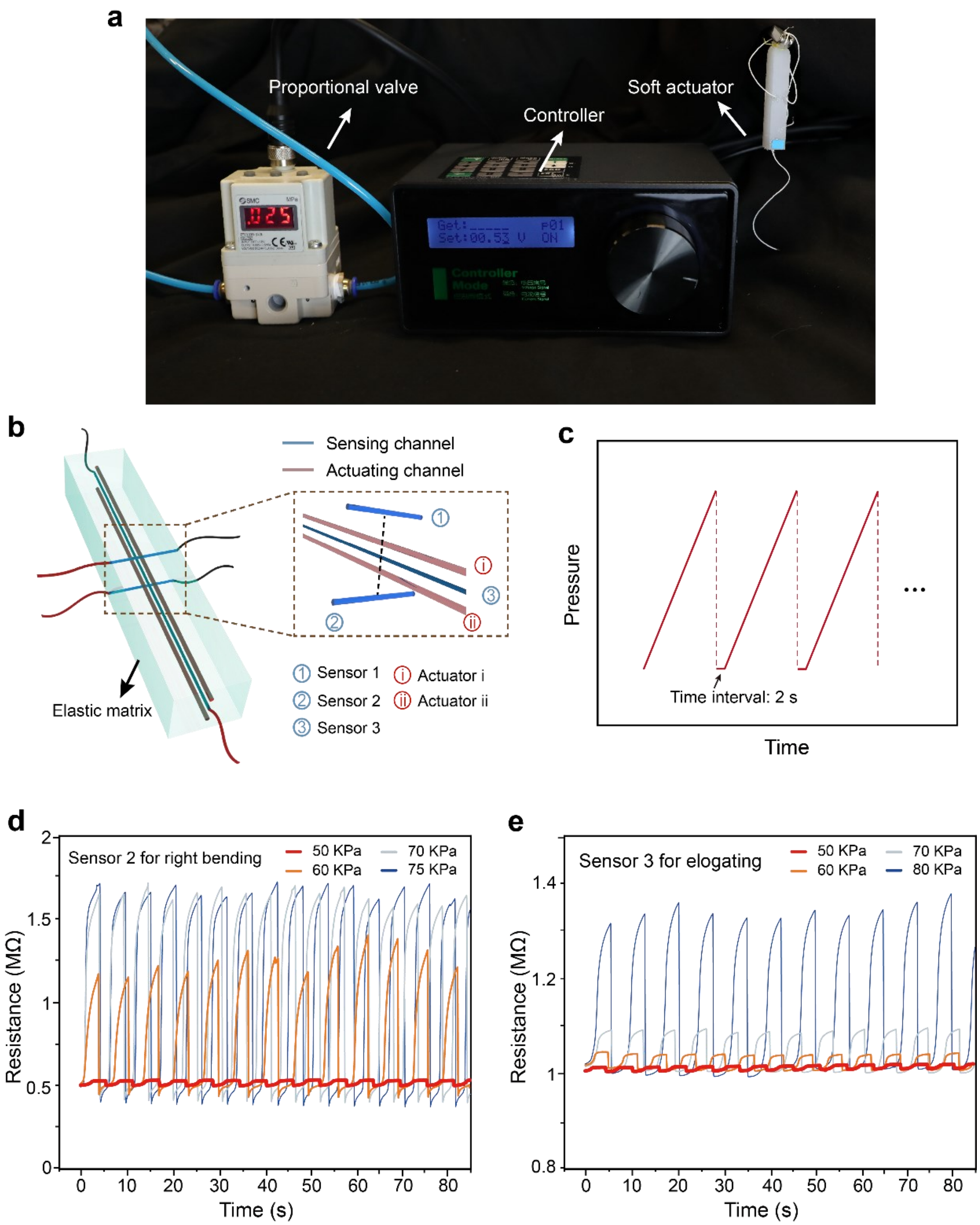

Figure S7. Cyclic tests for the sensorized soft actuators. a) Pressured air supply for inflating the soft actuator. b) Schematic of the sensorized soft actuator. c) Pressure pulse for cyclic tests. d) The response of Sensor 2 for right cyclic bending recording under different pressures. e) The response of Sensor 3 for cyclic elongating recording under different pressures.

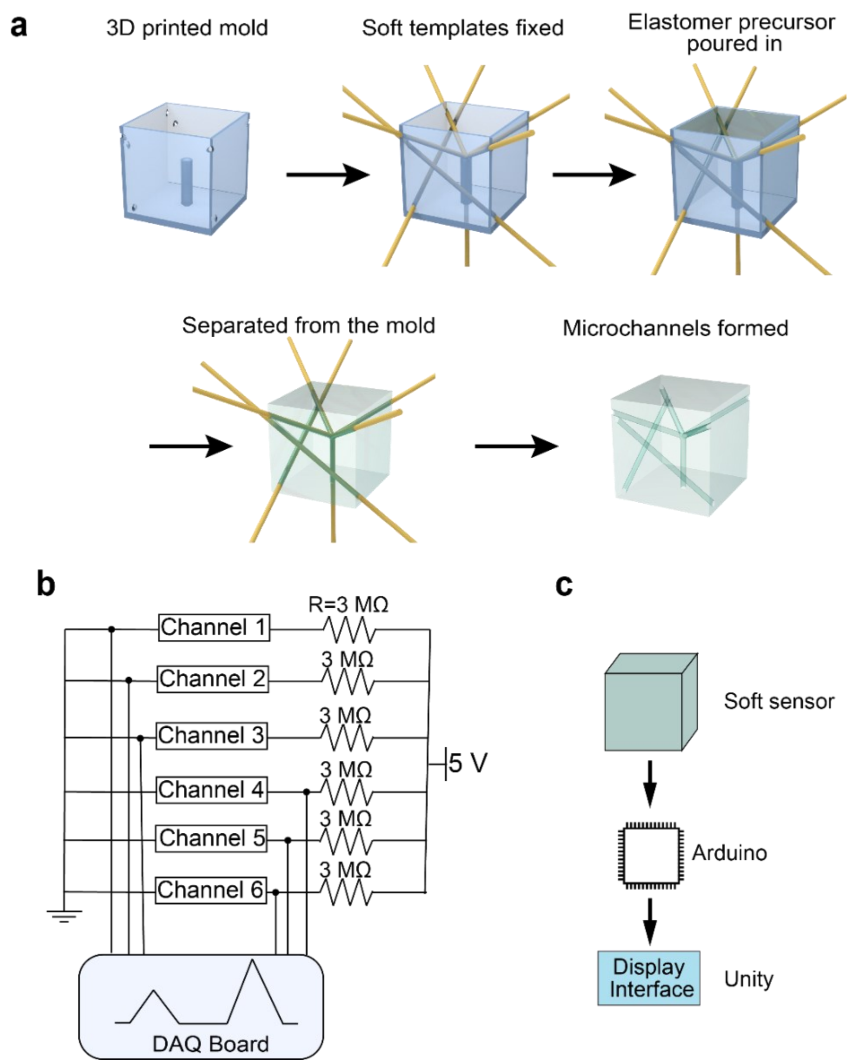

Figure S8. a) Fabrication process of the elastic matrix with designed microchannels for the soft fingertip sensor. A cubic mold with holes (diameter: 1 mm) inside was first fabricated by 3D printing. Next, six soft filaments were fixed to the holes, two of which were attached to the cubic surface, and the other four formed a dendriform pattern by twisting parts together. Then, silicone precursor (Ecoflex 0030, Smooth-on) was poured into the mold and thermally cured at 40 °C for 8 hours. Finally, these templates were extracted in sequence to generate microchannels. b) The electrical circuit diagram of the soft cubic sensor. c) Sensor read out and display process.

Table S1. Comparison of existing soft sensors for soft actuators.

Soft sensors	**Ref. 22**	**Ref. 30**	**Ref. 44**	**Ref. 46**	**Ref. 47**	**Our work**
Integration type	Embedding	Embedding	Adhering	Adhering	Embedding	Embedding
Dimension of sensor (mm)	1.5 (diameter)	2 × 2 (cross section)	0.2 × 5 (cross section)	2 mm (diameter)	0.5 × 4 (cross section)	0.4 (diameter)
Stretchability	Medium	High	Low	Low	Low	High
Bending deformation	Bending	Bending	Bidirectional bending	Bending	Bidirectional bending	Bidirectional bending
Elongating deformation	Elongating	N/A	N/A	N/A	N/A	Elongating

Video S1: Sensorized soft actuators for internal stimuli perception

Description: The soft sensorized actuators containing orthogonally distributed actuating and sensing microchannels, resembling muscle fiber and proprioceptors for internal stimuli perception, are demonstrated. Sensor 1 and 2 are employed for bending direction recognition of the soft actuator due to the inflating of the corresponding actuating channels. Sensor 3 is employed for elongating recognition of the soft actuator with limited layers since both Actuator i and ii are inflated.

Video S2: Soft cubic sensor for external stimuli perception

Description: The cubic sensor containing innervation of sensing microchannels for different external stimuli perception is demonstrated. We present the soft cubic sensor for external tactile motions (pressing, squeezing, shearing, and twisting) and their real-time directions (pressing faces, shearing, and twisting directions), recognizing when interacting with a human finger due to the corresponding resistance variance modes of different channels.

Video S3: Soft cubic sensor for VR applications

Description: The cubic sensor works as the controller with versatile control modes for VR applications. We endow different tactile motions, including pressing, squeezing, shearing, and twisting, with given orders (jumping, rolling, running, walking, and turning) for controlling the Robot in the Unity through the resistance responses of the corresponding channels.