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Supplementary Information for

A programmable powerful and ultra-fast water-driven soft actuator inspired from mutable collagenous tissue of sea cucumber

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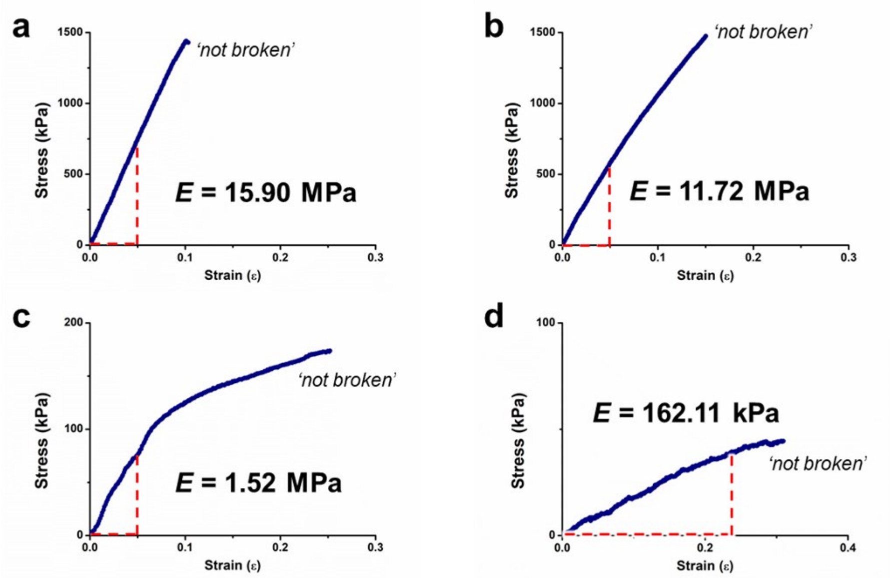
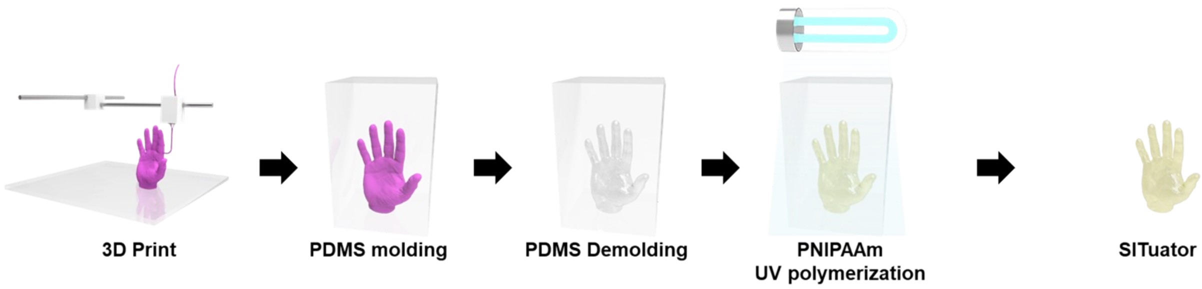
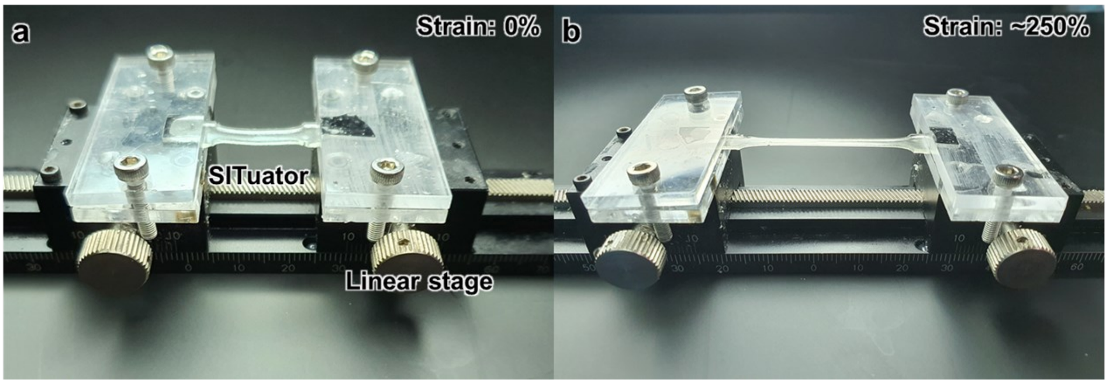


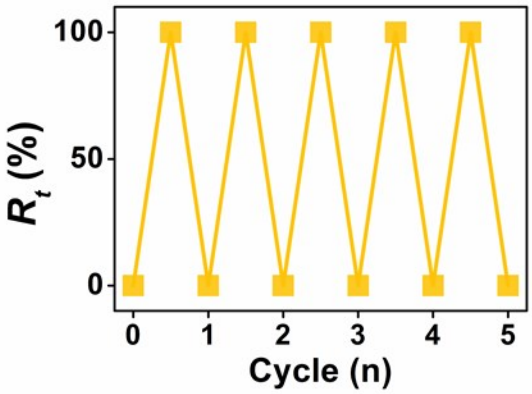
Supplementary Figure 1. Elastic modulus of a bulk PNIPAAm-based CS1 SITuator underwater at a temperature of 80 °C for (a) 0 s, (b) 5 s, (c) 30 s and (d) 30 min



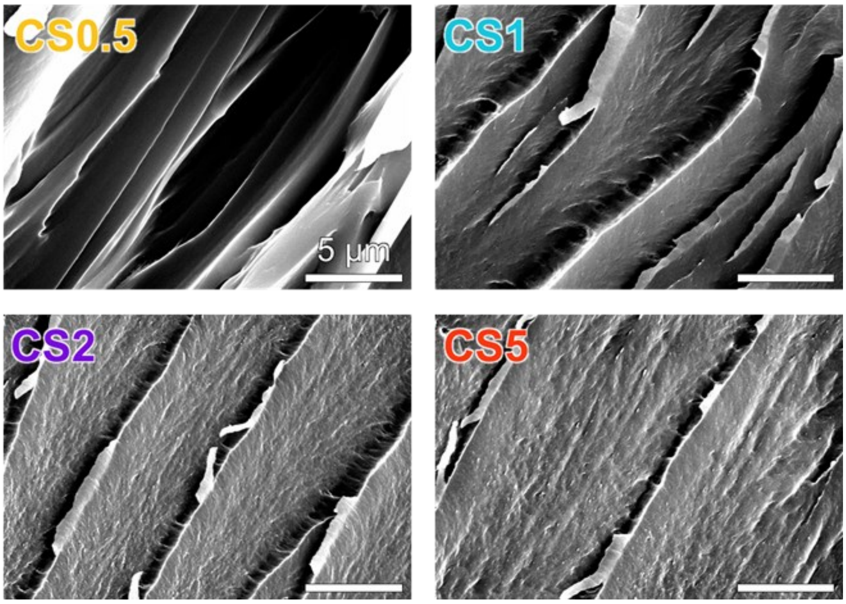
Supplementary Figure 2. Fabrication process of bulk PNIPAAm-based SITuator via UV-photopolymerization of highly concentrated N-isopropylacrylamide (NIPAAm) monomer solution



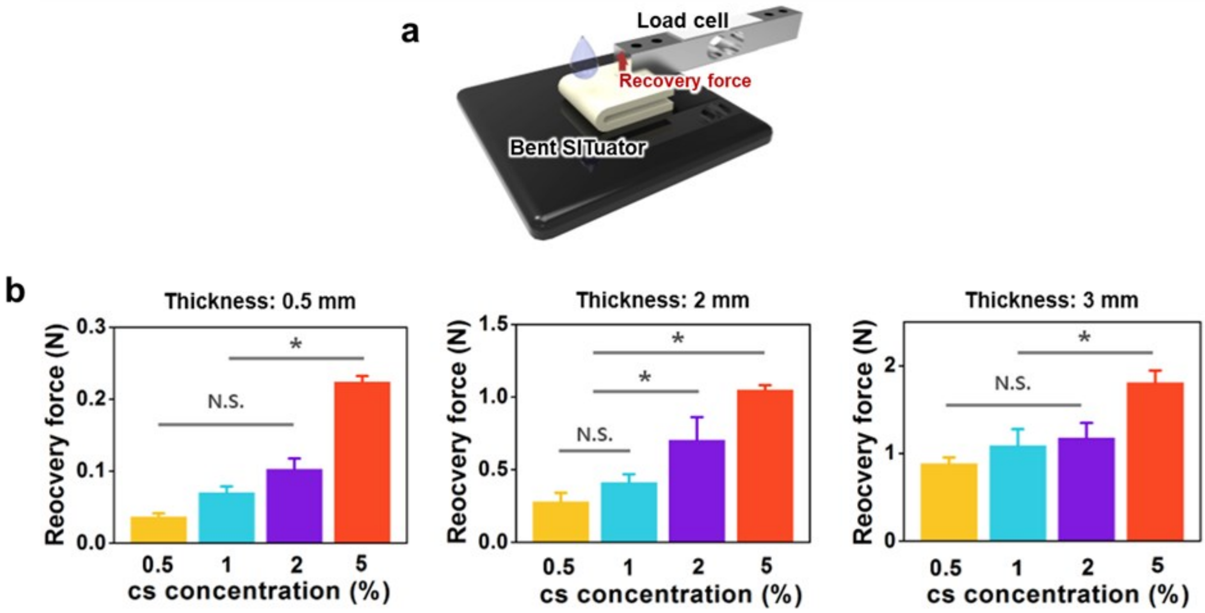
Supplementary Figure 3. Cyclic deformation-recovery test using a customized linear actuator. (a) Before the CS1 was stretched and (b) after stretched for 250%.



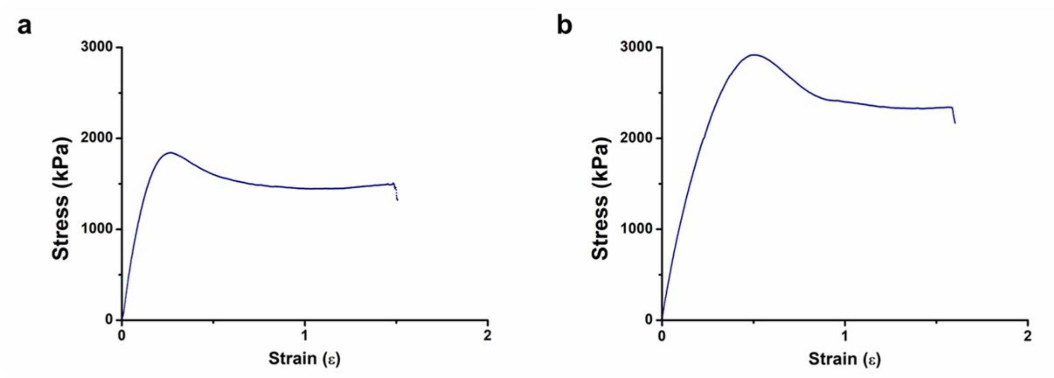
Supplementary Figure 4. Cyclic test results for shape recovery ratio of L-shape CS0.5 SITuator.



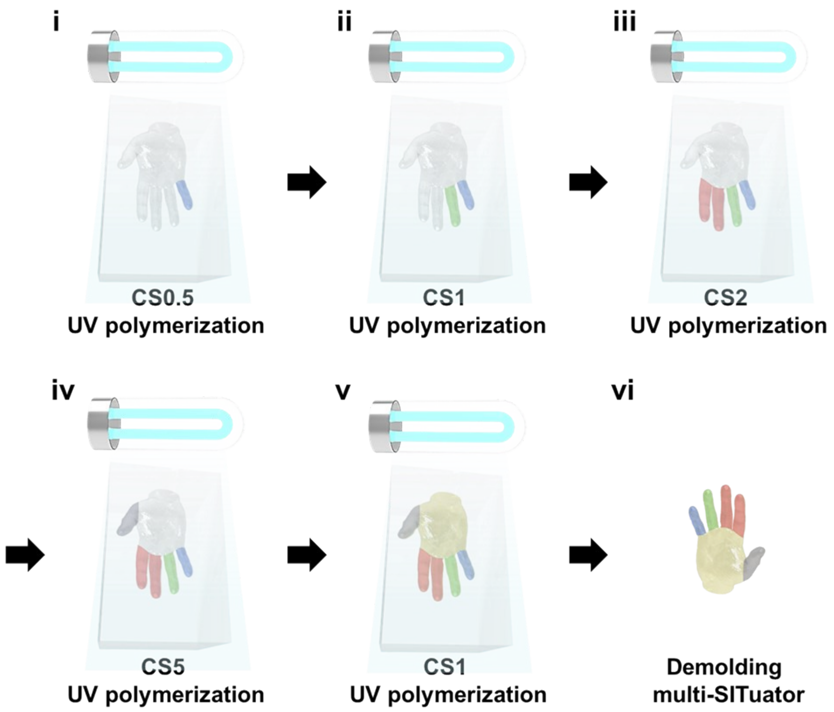
Supplementary Figure 5. SEM images for pore size of bulk PNIPAAm of CS0.5, CS1, CS2, and CS5.



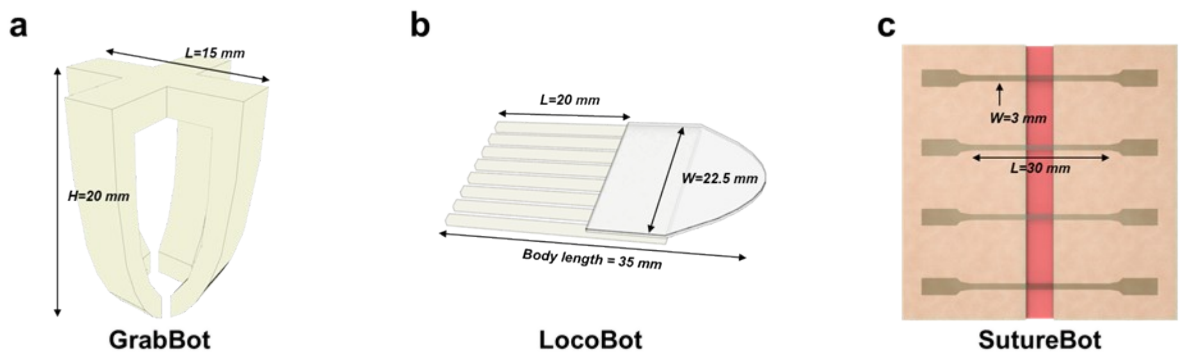
Supplementary Figure 6. (a) Deformed bulk PNIPAAm into U-shape to measure constrained recovery force. (b) Recovery force measurement of bulk PNIPAAm with both CS concentration and thickness.



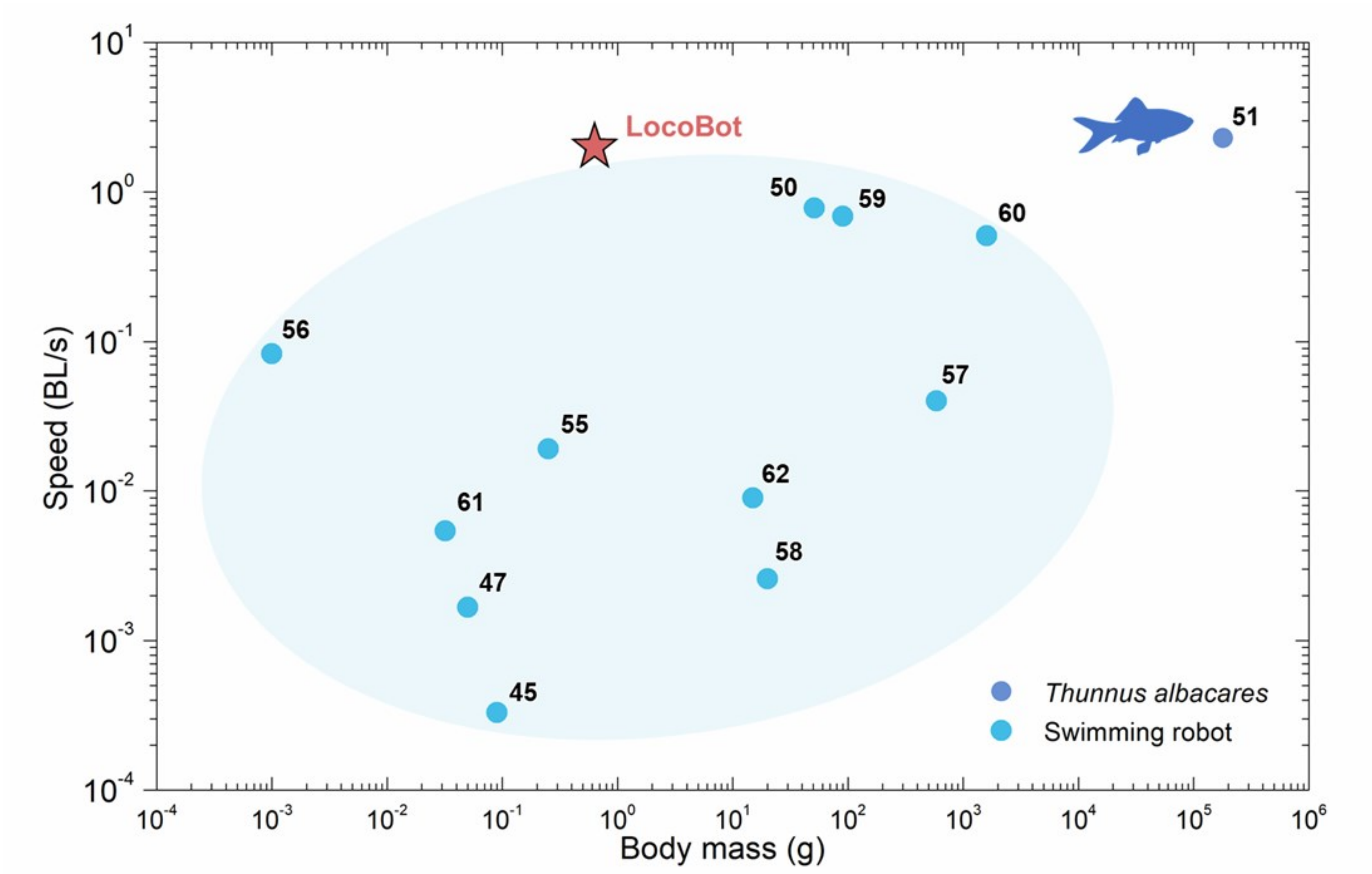
Supplementary Figure 7. Tensile test results for energy density calculation of CS1. (a) stress-strain curve of CS1 for upper line of energy density and (b) stress-strain curve of CS1 for lower line of energy density.



Supplementary Figure 8. Fabrication of multi-SITuator using various concentration solution.



Supplementary Figure 9. Design and dimensions of diverse SITuators, which are (a) GrabBot, (b) LocoBot, and (c) wound closure. In case of wound closure, the initial gauge length and width are 10 mm, 5 mm, respectively.



Supplementary Figure 10. Body length (BL) per second for swimming robots and *Thunnus albacares* (180 kg and 2.3 BL/s).[51] Specific data tables are summarized in Table S4

Table S1. Elastic modulus of CS1 SITuator underwater at a temperature of 80 °C for immersing time of 0 s, 5 s, 30 s and 30 min

N	*E* (MPa) for 0 s	*E* (MPa) for 5 s	*E* (MPa) for 30 s	*E* (kPa) for 30min
1	15.90	13.74	1.52	84.612
2	14.25	11.72	1.51	162.11
3	14.51	89.67	0.48	141.06
Average	14.89	11.48	1.17	129.26
Standard deviation	± 0.73	± 1.96	± 0.49	± 32.72

Table S2. Energy density calculation from tensile test results for CS1 SITuator

N	Elastic modulus (kPa)	Strain (ε)	Energy density (MJ/m^3)
1	13742	0.2	0.274840
2	11719	0.33	0.638100
3	8967	0.37	0.613791
4	8530.5	0.35	0.522493
Average	10739.6	0.3125	0.512306

Table S3. Actuating conditions of hydrogel actuators

Hydrogel actuator	Actuation force (N)	Actuation speed (s^{-1})	Dimension (m × m)	Maximum stress (Pa)	Elastic Modulus (MPa)	Conditions	Ref.
This work (SITuator)	0.0372 – 1.8124	0.0012 – 0.1429	0.01 × 0.003	60413.33	14.9 ± 0.7	Water-responsive (80 °C)	-

PR hydrogel	0.0015 – 0.0025	0.0028 – 0.0003	0.01 × 0.002	125	0.042	Photo-responsive (λ = 365, 430 nm)	(9)
Anisotropic hydrogel	0.0045 – 0.0085	0.28 – 1.2	0.01 × 0.0012	708.3333	0.011	Thermo-responsive (water of 45 °C)	(45)
TR hydrogel	0.015 – 0.025	0.002 – 0.0007	0.01 × 0.001	250	0.046 ± 0.004	Thermo-responsive (water of 37 °C)	(32)
Protein hydrogel	0.0015 – 0.0025	0.0025 – 0.0065	0.005 × 0.0025	200	-	Ionic-responsive (Ca^{2+} concentration)	(7)
Liquid crystalline hydrogel	0.0015 – 0.0025	0.9 – 2.2	0.00002 × 0.00002	62500	1.3	Photo-responsive (light pattern with λ = 532 nm)	(47)
Ion hydrogel	0.0058 – 0.008	0.0006 – 0.0008	0.01 × 0.001	800	0.3	Ionic-responsive (organic solvent, ethanol)	(48)
Composite hydrogel	0.0025 – 0.0045	0.1 – 0.2	0.001 × 0.001	4500	-	Photo-responsive (near-infrared, 750 – 2500 nm)	(49)

Table S4. Speed (BL/s) and body mass of swimming robots

Swimming robot	**Body mass (g)**	**Speed (BL/s)**	**Ref.**
This work (SITuator)	0.63	2	-
Soft phototactic swimmer	0.25	0.01917	(55)
A self-propelled biohybrid swimmer	0.001	0.083	(56)
Structured light enables biomimetic swimming	0.05	0.00167	(47)
Miniaturized swimming soft robot	0.0319	0.0054	(61)
Thermo-responsive actuation robot	0.09	0.00033	(45)
Translucent soft robots driven by frameless fluid	15	0.009	(62)
Spine-inspired high-speed and force soft robot	51	0.78	(50)
Acoustically controlled soft robotic fish (SoFi)	1600	0.51	(60)
Fast-moving soft electronic fish	90.3	0.69	(59)
Turtle mimetic soft robot	588	0.04	(57)
Biomimetic jellyfish-inspired robot	20	0.00259	(58)