

Supplementary Information

Inherently integrated microfiber-based flexible proprioceptive sensor for feedback-controlled soft actuators

*Hwajoong Kim, Hyunbin Na, Seungbeom Noh, Shinwon Chang, Jinho Kim, Taejune Kong, Gyowook Shin, Chankyu Lee, Seonggyu Lee, Yong-Lae Park, Sehoon Oh, and Jaehong Lee**

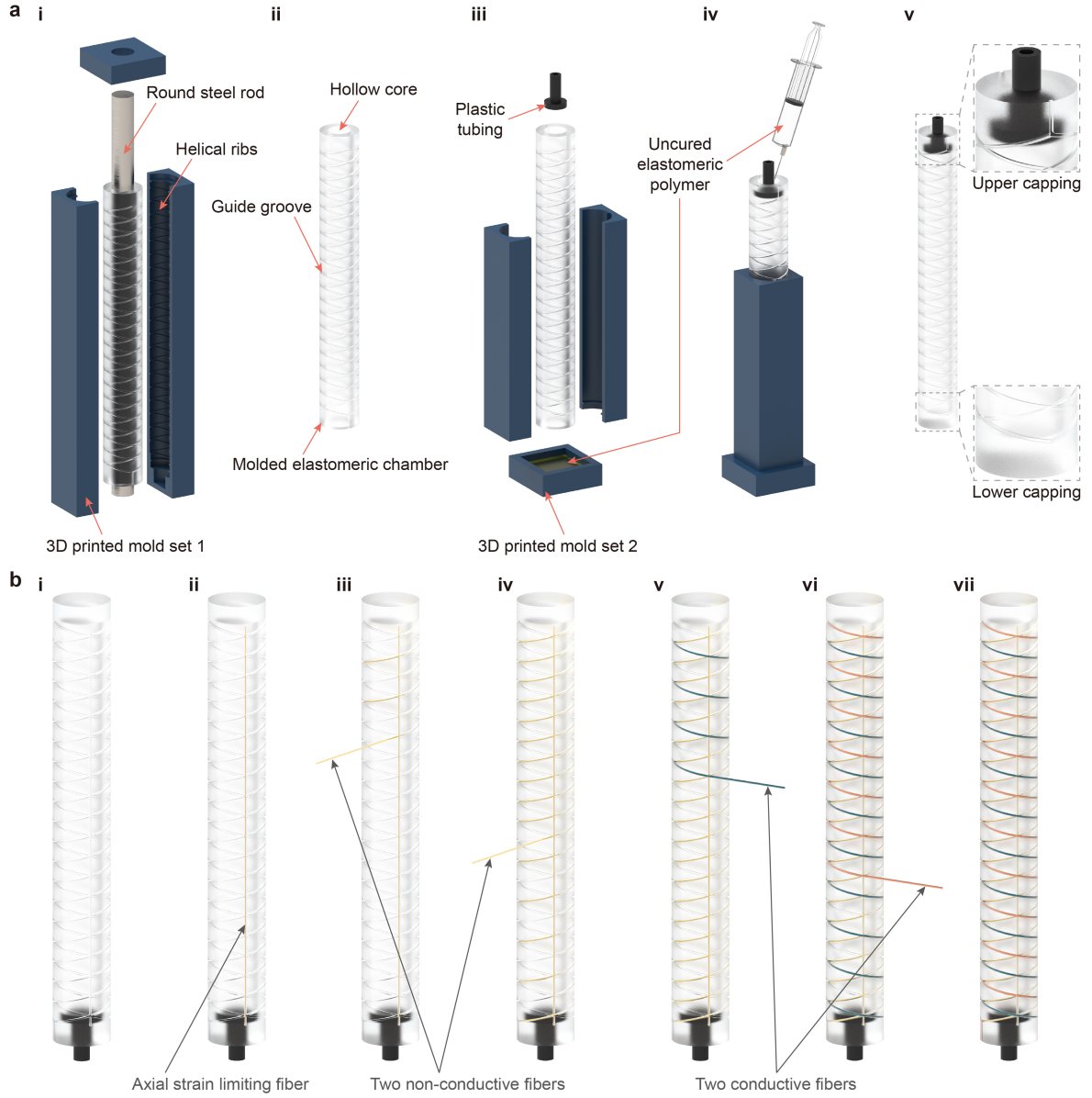
*Corresponding author: Jaehong Lee, jaelee@dgist.ac.kr

The PDF file includes:

- Supplementary notes
- Supplementary Table 1 to 3
- Supplementary Figures 1 to 27
- Supplementary References (1-34)

Other Supporting Information for this manuscript includes the following:

- Supplementary Videos 1 to 11



Supplementary Figure 1. Fabrication process of the fiber-reinforced soft actuator with proprioceptive sensing capability. **a** Molding process using 3D-printed plastic molds and a steel rod. Helical ribs in the plastic mold provide a guide groove on the surface of the elastomeric chamber for radial expansion limiting fibers (i-ii). Both open ends of the elastomeric chamber were capped with an elastomeric polymer and the upper end included a port for the inflow/outflow of air (iii-v). **b** Winding process of fiber reinforcements for the soft actuator. An axial strain limiting fiber was fixed along the soft actuator in the longitudinal direction (i-ii). As radial expansion limiting fibers for the soft actuator, two parallel nylon-based commercial microfibers were helically wound around the elastomeric chamber (iii-iv), and two parallel conductive microfibers were helically wound around the chamber in the opposite direction (v-vii).

Supplementary notes

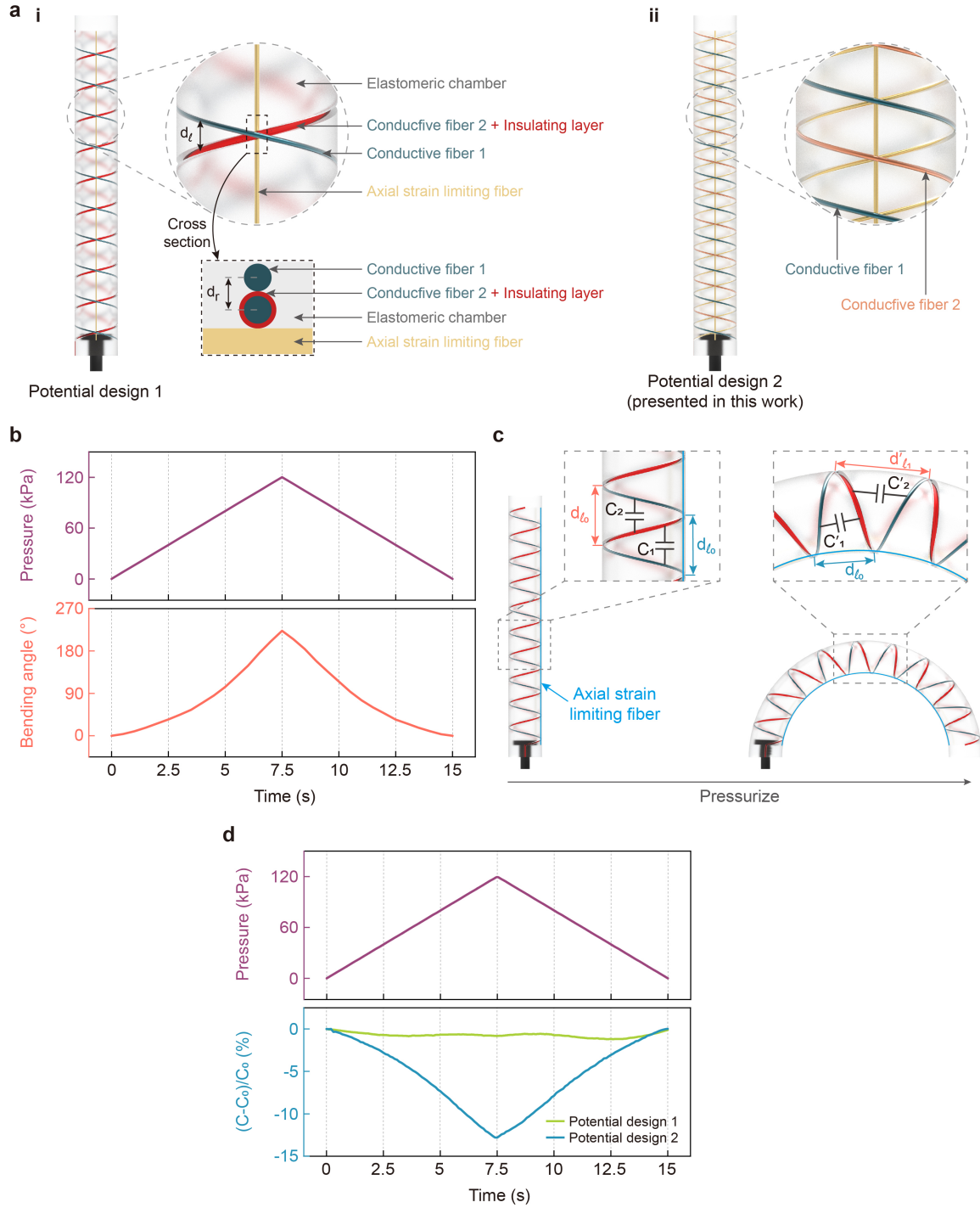
Comparison for optimal design of a proprioceptive fiber-reinforced soft actuator

To determine the optimal design for our proprioceptive fiber-reinforced soft actuator, we analyzed two potential designs that could allow a fiber-reinforced soft actuator to achieve proprioception using only its essential components. In a conventional fiber-reinforced soft actuator, a pair of radial expansion limiting fibers are helically wound in a cross pattern around the soft chamber. This configuration helps convert radial expansion into longitudinal extension of the actuator. In this work, we devised a design strategy to incorporate a microfiber-based capacitive proprioceptive sensor into a standard fiber-reinforced soft actuator, leveraging the radial expansion limiting fibers already present in these actuators. Supplementary Fig. 2 depicts two viable design variations that could facilitate the realization of a microfiber-based capacitive sensor by employing electrically conductive microfibers as the radial expansion limiting fibers in the actuator.

In the first potential design, the conductive microfiber electrodes were utilized as a substitute for the typical pair of radial expansion limiting fibers in the fiber-reinforced soft actuator. This design can preserve the actuation performance of the soft actuator, given that it follows the same fiber configuration as that of a conventional fiber-reinforced soft actuator (see Supplementary Fig. 2a and 2b). In particular, after ensuring the electrical insulation of the electrodes, the two microfiber electrodes, which are wound around the soft chamber, intersect along the axial strain limiting fiber within the soft actuator. In this configuration, the capacitances (C_1 and C_2 in Supplementary Fig. 2c) between the two microfiber electrodes predominantly arise at the intersection points, as this is the closest proximity between the two electrodes compared to any other location. Given that the intersection points on the concave and convex surfaces of the bent soft actuator remain fixed even during the bending actuation, the capacitances from the two microfiber electrodes cannot serve as effective measurement parameters for the proprioceptive sensing of the soft actuator (Supplementary Fig. 2d).

For the second potential design, two conductive microfiber electrodes were helically wound around the soft chamber in parallel, substituting part of the radial expansion limiting fibers in one direction (see Supplementary Fig. 2a). In order to preserve the conventional intersection configuration essential for fiber reinforcement, standard nylon microfibers were employed as radial expansion limiting fibers in the opposite direction. In this configuration, the bending

actuation effectively decreases the capacitance between the two parallel conductive microfiber electrodes, due to the deformation-dependent increase in the distance between the electrodes (see Fig. 1c). Therefore, we selected the second design as the foundation for developing our proprioceptive fiber-reinforced soft actuator in this study.



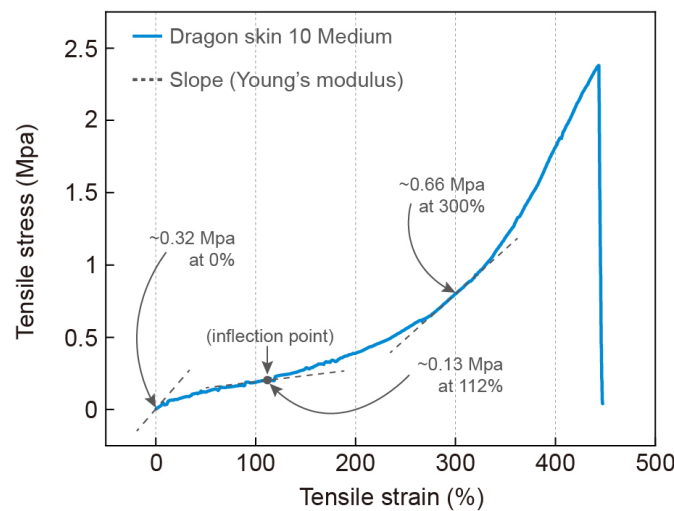
Supplementary Figure 2. **a** Schematic illustrations of two potential designs for a proprioceptive fiber-reinforced soft actuator based only on its essential components. **b**

Variation in the bending angle of the soft actuator, fabricated according to the first potential design, in response to applied pressure. **c** Schematic representation of the configurational change of the two microfiber electrodes in the soft actuator, designed as per the first potential design, under bending deformation. **d** Normalized capacitance alterations between the two microfiber electrodes in the soft actuators, constructed based on the two potential designs, as a function of applied pressure.

Supplementary notes

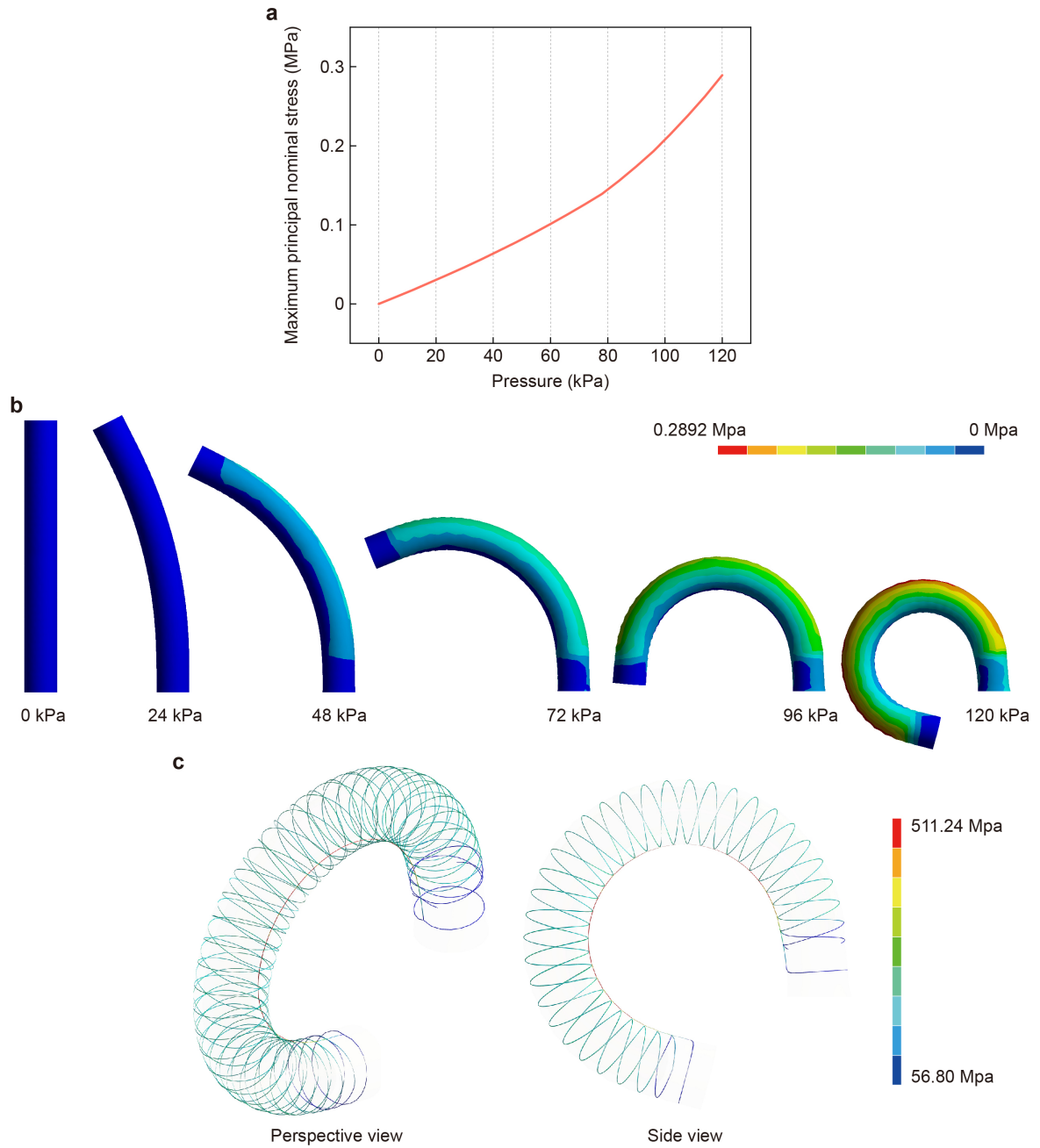
Finite element analysis for predicting the mechanical behavior of the soft actuator under bending actuation

In order to obtain more accurate and reliable analysis results, the stress-strain behavior of the elastomeric material, Dragon Skin 10 Medium, used for the fabrication of the soft actuator is required. To this end, the uniaxial stress-strain property of the material was measured at a stretching rate of 100 mm/min based on the ASTM D412 standard, a tensile test standard for rubber and elastomer (Supplementary Fig. 3).¹ The measurement was performed using a tensile testing machine (United Calibration Corp., SFM-100kN).

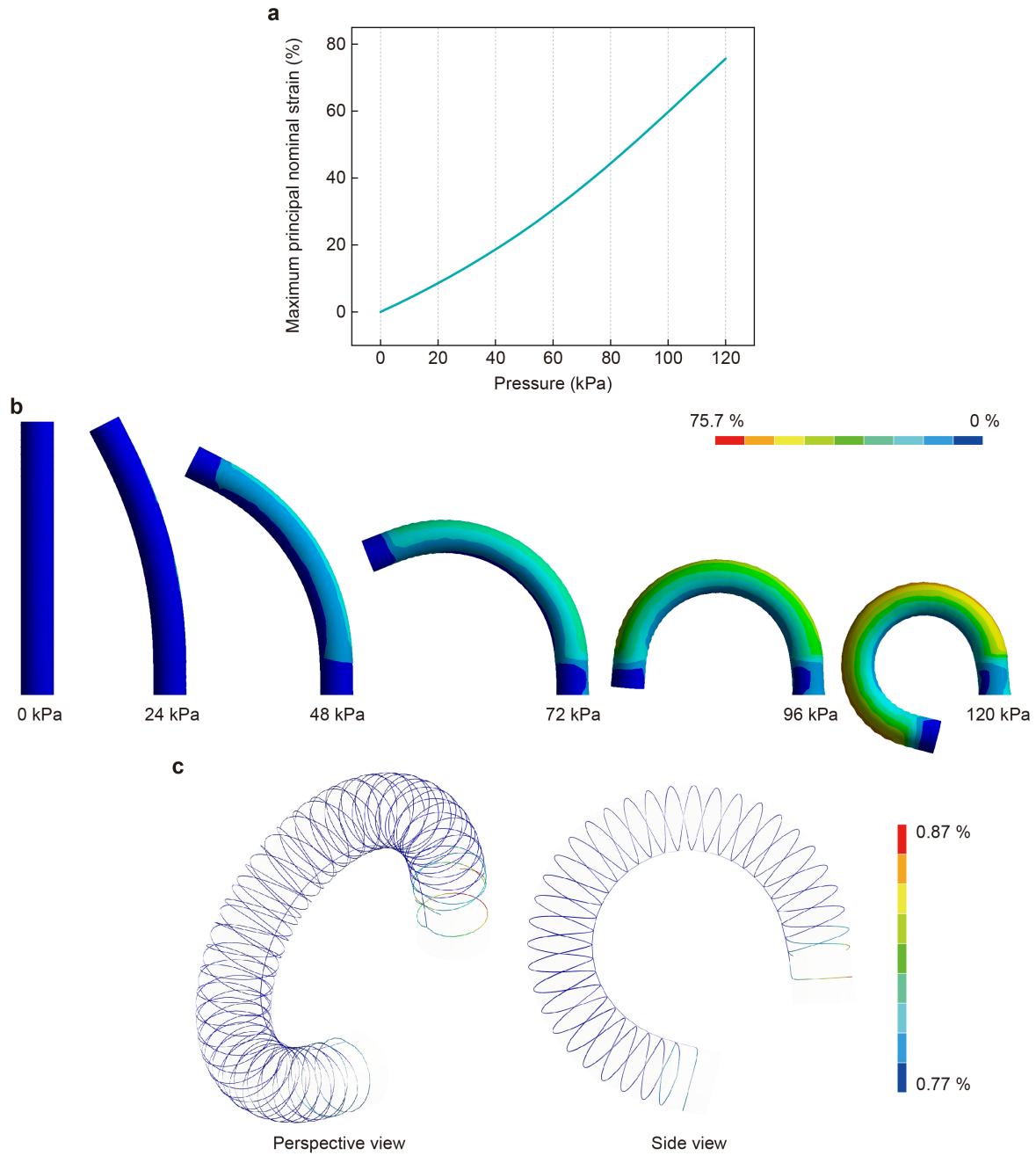


Supplementary Figure 3. Uniaxial stress-strain curve for Dragon Skin 10 Medium.

A hyperelastic model (material coefficients of the Yeoh model: $C_1 = 62.163 \text{ kPa}$, $C_2 = 0.731 \text{ kPa}$, $C_3 = 0.102 \text{ kPa}$) was used to capture the nonlinear behavior of the Dragon Skin 10 Medium. To analyze the mechanical behavior of the soft actuator, 3D finite element methods (FEM) models were constructed and simulated with Static Structural Analysis (ANSYS Inc., ANSYS V17.2). In the process of meshing the FEM model, solid tetrahedral hybrid elements (ANSYS element type solid187) and beam elements (ANSYS element type link180) were applied for the elastomeric chamber and fiber reinforcements, respectively.² As the fiber reinforcements were assumed to be completely immobilized with the elastomeric chamber without slipping, the contact condition was set as “bonded”.³ The degree of freedom of the soft actuator was constrained by designating the proximal tip as a fixed support, and the analysis was performed by applying a normal pressure of 120 kPa on the inner surface of the elastomeric chamber. The shape changes and distal tip trajectory of the soft actuator according to the internal pressure were simulated as shown in Fig. 2b, 2c, and 2e. The principal nominal stress and strain analysis for the elastomeric chamber and fiber reinforcements were also simulated as shown in Supplementary Fig. 4 and 5.



Supplementary Figure 4. FEM simulations of the principal nominal stress of the soft actuator. **a** Maximum principal nominal stress of the elastomeric chamber according to the applied internal pressure. **b** Simulated principal nominal stress distribution on the elastomeric chamber of the soft actuator under different internal pressures. The stress was concentrated on the convex area of the elastomeric chamber in the bent actuator. **c** Principal nominal stress distribution of the axial strain limiting and radial expansion limiting fibers of the bent soft actuator at an internal pressure of 120 kPa. The axial strain limiting fiber undergoes higher stress than the radial expansion limiting fibers under bending actuation.



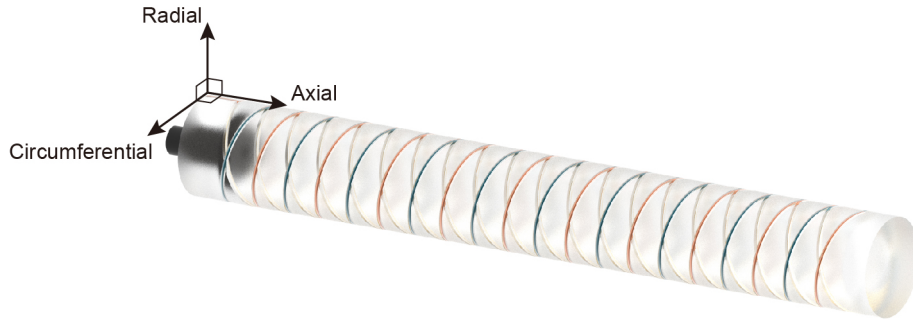
Supplementary Figure 5. FEM simulations of the strain distribution in the soft actuator.

a Maximum nominal strain over the elastomeric chamber with respect to increasing internal pressure. **b** Simulated strain distribution on the elastomeric chamber of the soft actuator under different internal pressures. The concave region of the chamber shows a near-zero strain due to the axial strain limiting fiber, but the convex region of the chamber undergoes the maximum strain under the bending actuation of the soft actuator. **c** Strain distribution of the microfibers in the soft actuator at an internal pressure of 120 kPa, showing the negligible strain on the non-stretchable microfibers under bending actuation.

Supplementary notes

Analytical solution to calculate the mechanical behavior of the soft actuator under bending actuation

Modeling assumptions. The following assumptions are used for analytically considering the bending actuation of the soft actuator: i) the elastic materials used for the soft actuator feature incompressibility and homogeneity; ii) the soft actuator does not expand in the radial direction due to the constraints provided by the several fiber reinforcements; iii) the wall thickness of the soft actuator is thin enough; iv) the internal pressure is slowly applied to the soft actuator, enabling the soft actuator to be in a steady state even during actuation; v) the soft actuator has a constant bending curvature over the entire length of the actuator in the axial direction (Supplementary Fig. 6); vi) the effect of gravity is not considered here.



Supplementary Figure 6. Local coordinates of the soft actuator with axial, radial, and circumferential direction.

Elastic material model. Among the various models for elastic materials, the Neo-Hookean (N-H) model was used in this work to analyze the mechanical behavior of the soft actuator under bending actuation.^{4,5} Considering the incompressible assumption, the strain energy density W is defined as follows:

$$W = \frac{\mu}{2}(I_1 - 3) \quad (S1)$$

where, μ is the shear modulus of the elastic material, and I_1 is the first invariant of the three principal stretch ratios (axial, circumferential, and radial) λ_1 , λ_2 , and λ_3 , namely,

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \quad (S2)$$

Considering the structure of the fiber-reinforced soft actuator, where the elastomeric chamber is wound with inextensible fiber reinforcements, the strain in the circumferential direction is

negligible ($\lambda_2 = 1$). In addition, the following equation can be derived based on the assumption of incompressibility:

$$\lambda_1 \lambda_2 \lambda_3 = 1 \quad (\text{S3})$$

The principal Cauchy stress σ_i is defined as follows:³

$$\sigma_i = \lambda_i \frac{\partial W}{\partial \lambda_i} - p \quad (\text{S4})$$

where, p is a common Lagrange multiplier for $i = 1, 2$, and 3 . Therefore, the stresses in the axial, circumferential, and radial directions can be calculated by substituting equation (S1) and (S2) into equation (S4) as follows:

$$\sigma_1 = \lambda_1 \frac{\partial W}{\partial \lambda_1} - p = \mu \lambda_1^2 - p \quad (\text{S5})$$

$$\sigma_2 = \lambda_2 \frac{\partial W}{\partial \lambda_2} - p = \mu \lambda_2^2 - p \quad (\text{S6})$$

$$\sigma_3 = \lambda_3 \frac{\partial W}{\partial \lambda_3} - p = \mu \lambda_3^2 - p = 0 \quad (\text{S7})$$

$$p = \mu \lambda_3^2 = \mu \frac{1}{\lambda_1^2} \quad (\text{S8})$$

The σ_3 of radial direction is assumed to be 0 because of the thin wall of the soft actuator, and p can be found through this assumption as shown in equations (S7) and (S8). Therefore, the principal Cauchy stress can be derived as a function of the principal stretch ratio by substituting equation (S8) into equations (S5) and (S6) as follows:

$$\sigma_1 = \mu \left(\lambda_1^2 - \frac{1}{\lambda_1^2} \right) \quad (\text{S9})$$

$$\sigma_2 = \mu \left(1 - \frac{1}{\lambda_1^2} \right) \quad (\text{S10})$$

Finally, the principal nominal stress s_i , required for the mathematical modeling of the mechanical behavior of the soft actuator, can be derived using $s_i = \sigma_i / \lambda_i$ as follows:

$$s_1 = \mu \left(\lambda_1 - \frac{1}{\lambda_1^3} \right) \quad (\text{S11})$$

$$s_2 = \mu \left(1 - \frac{1}{\lambda_1^2} \right) \quad (\because \lambda_2 = 1) \quad (\text{S12})$$

The circumferential principal stress s_2 is much smaller than the axial principal stress s_1 because λ_1 (principal stretch ratios in the axial direction) is greater than 1 under a general bending actuation. Therefore, s_2 is negligible and only s_1 is considered as a principal nominal stress in this mathematical analysis.

Moment equilibrium. Fig. 2d (i) and (ii) show the free body diagrams of the soft actuator under a certain internal pressure. The proximal tip of the soft actuator is fixed, and the distal tip is the free-end. The soft actuator is in a static state under a constant applied internal pressure due to the equilibrium between two bending moments: the moment M_p generated by the internal pressure, and moment M_t generated by the restoring force of the elastomeric chamber. The moment M_p is a function of the internal pressure, and the moment M_t can be expressed as a function of the bending angle. Therefore, the mechanical behavior of the soft actuator can be predicted using the equilibrium between the two bending moments as follows:

$$M_p = M_t \quad (\text{S13})$$

Fig. 2d (iii) presents the cross-section A-A' (inner surface of the distal tip) passing through the point O, which includes the several variables and constants required to calculate the bending moments M_p and M_t . The bending moment M_p is the sum of the infinitesimal moments occurring on the inner surface of the distal tip,⁶ and can be described as:

$$M_p = \int dM_p = \int h_p \cdot dF = \int h_p \cdot P_{in} \cdot dA = \iint h_p \cdot P_{in} \cdot r dr d\phi \quad (\text{S14})$$

where, P_{in} is the internal pressure (gauge pressure). r means the minimum distance from the center of the cross-sectional area to an arbitrary infinitesimal area where the internal pressure is applied to the inner surface of the distal tip. ϕ indicates the direction of the infinitesimal area. h_p is the height from the circumferential axis passing through point O to the infinitesimal area, and can be expressed geometrically as follows:

$$h_p = (r_{in} + t) + r \sin \phi \quad (\text{S15})$$

Therefore, for a soft actuator with inner radius r_{in} , M_p can be calculated as:

$$M_p = P_{in} \int_0^{2\pi} \int_0^{r_{in}} \{(r_{in} + t) + r \sin \phi\} r dr d\phi = \pi P_{in} r_{in}^2 (r_{in} + t) \quad (\text{S16})$$

In a similar manner, the bending moments M_t and h_t can also be obtained as:

$$M_t = \int dM_t = \int h_t \cdot dF = \int h_t \cdot s_t \cdot dA = \iint h_t \cdot s_t \cdot (r_{in} + \tau) d\tau d\phi \quad (\text{S17})$$

$$h_t = (r_{in} + t) + (r_{in} + \tau)\sin\phi \quad (S18)$$

where, s_t is the principal nominal stress generated at the side wall of the soft actuator and τ means the minimum distance from the inner surface of the side wall of the soft actuator to an arbitrary infinitesimal area where the elastic stress is applied to the side wall as shown in Fig. 2d (iii). h_t is the height from the circumferential axis passing through point O to the infinitesimal area. By substituting equation (S18) into equation (S17), the bending moment M_t for the soft actuator with a wall thickness of t can be calculated as:

$$M_t = \int_0^{2\pi} \int_0^t s_t \cdot \{(r_{in} + t) + (r_{in} + \tau)\sin\phi\} (r_{in} + \tau) d\tau d\phi \quad (S19)$$

We need to find s_t to calculate the accurate bending moment M_t . First, the axial principal stretch ratio λ_t can be calculated as follows by using the relationship between a radius, an arc, and a central angle of a circle.

$$\lambda_t = \frac{(R+h_t)\theta}{L_0} = 1 + \frac{h_t\theta}{L_0} = 1 + \frac{(r_{in}+t)+(r_{in}+\tau)\sin\phi}{L_0}\theta \quad (S20)$$

where, L_0 is the initial length of the soft actuator and θ indicates the bending angle of the soft actuator. By considering the s_t has the same direction as s_1 ($s_1 = s_t$ and $\lambda_1 = \lambda_t$) and substituting equation (S20) into equation (S11), the principal nominal stress s_t can be calculated as follows:

$$s_t = \mu \left\{ \left(1 + \frac{(r_{in}+t)+(r_{in}+\tau)\sin\phi}{L_0}\theta \right) - \left(1 + \frac{(r_{in}+t)+(r_{in}+\tau)\sin\phi}{L_0}\theta \right)^{-3} \right\} \quad (S21)$$

To simplify the equation, the binominal expansion can be used as follows:⁷

$$(1+x)^n \approx 1 + nx + \frac{n(n-1)}{2!}x^2 + \frac{n(n-1)(n-2)}{3!}x^3 + \dots \quad (S22)$$

If x is replaced as in equation (S23), s_t can be described:

$$x = \frac{(r_{in}+t)+(r_{in}+\tau)\sin\phi}{L_0}\theta \quad (S23)$$

$$s_t = \mu(4x - 6x^2 + 10x^3 - 15x^4 + 21x^5 - \dots) \quad (S24)$$

Substituting equations (S23) and (S24) into equation (S19), the bending moment M_t can be expressed as follows:

$$M_t = 4k_1\theta - 6k_2\theta^2 + 10k_3\theta^3 - 15k_4\theta^4 + \dots \quad (S25)$$

where, k_i is coefficient that can be calculated based on the following relationship:

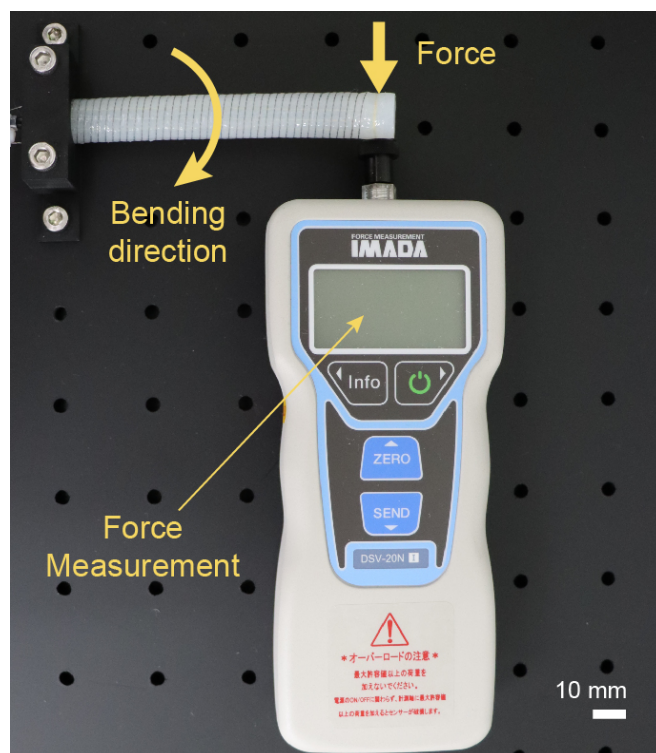
$$k_i = \frac{\mu}{L_0^i} \int_0^{2\pi} \int_0^t \{(r_{in} + t) + (r_{in} + \tau)\sin\phi\}^{i+1} (r_{in} + \tau) d\tau d\phi \quad (S26)$$

Finally, the equilibrium equation (S13) and bending moment equations (S16 and S25) can be utilized to mathematically derive the relationship between the applied internal pressure and bending angle of the soft actuator,

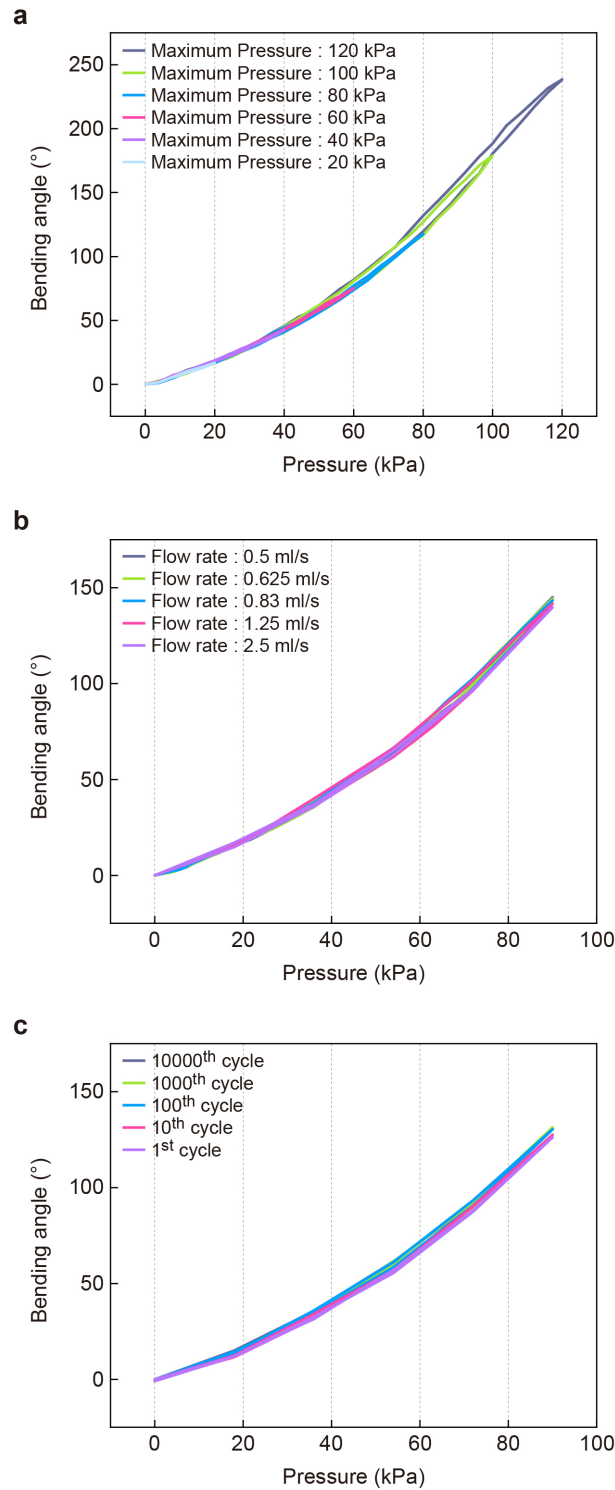
$$P_{in} = 4A_1\theta - 6A_2\theta^2 + 10A_3\theta^3 - 15A_4\theta^4 + \dots \quad (S27)$$

$$A_i = \frac{k_i}{\pi r_{in}^2 (r_{in} + t)} \quad (S28)$$

where, A_i is a constant from dividing k_i by coefficient of P_{in} . According to the final equation, A_i depends on the shear modulus μ and geometrical dimensions of the soft actuator such as r_{in} , t , and L_0 . Shear modulus was referred to literature values and the geometrical properties are specified in the fabrication process. Fig. 2b shows this expectation of the mechanical response of the soft actuators fabricated with a diameter of 14 mm and helical pitch of 3 mm from the mathematical model using the following parameters ($\mu=0.072$ Mpa for Dragon Skin elastomer⁸, $L_0=110$ mm, $t=3$ mm, $r_{in}=4$ mm).

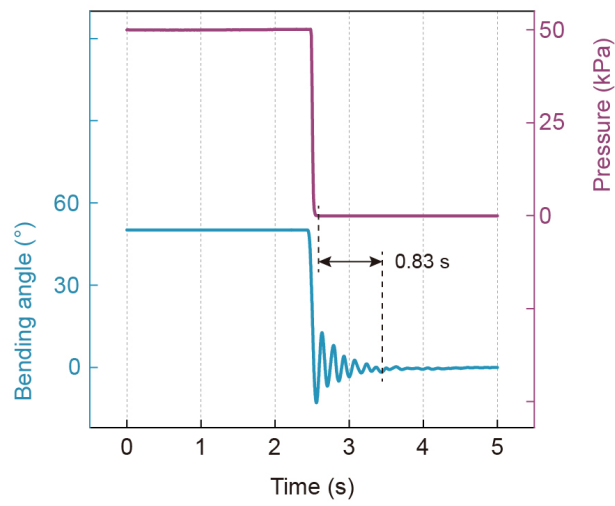


Supplementary Figure 7. Photograph of the measurement set-up for the isometric and isotonic force response of the proprioceptive soft actuator. The force generated on the distal tip of the soft actuator was measured by the force meter.

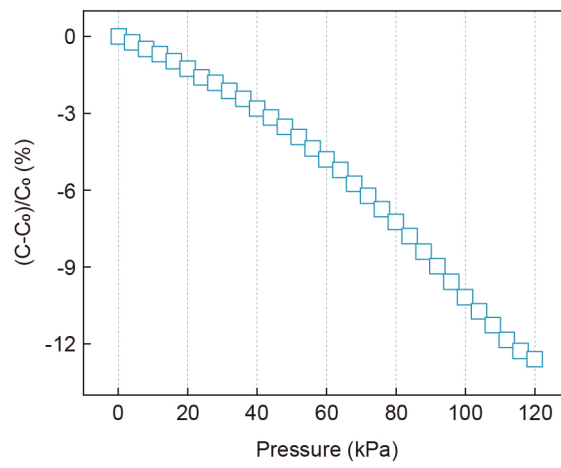


Supplementary Figure 8. Mechanical hysteresis of the proprioceptive soft actuator.

Bending angles of the soft actuator upon the pressurized and unpressurized cycles with (a) different maximum internal pressures from 20 to 120kPa, (b) flow rates from 0.5 to 2.5 ml/s, and (c) pressurizing-releasing cyclic tests from 1 to 10,000 repeated cycles.



Supplementary Figure 9. Bending angle of the soft actuator upon release of 50 kPa of applied pressure, showing the recovery time of the actuator.



Supplementary Figure 10. Relative change in the capacitance of the proprioceptive bending sensor according to increasing input pressure applied to the soft actuator.

Supplementary notes

Analytical solution to calculate the capacitance between two parallel conductive microfibers of the soft actuator under bending actuation

Based on the classical electromagnetic theory, a capacitance between two parallel conductive microfibers can be derived as follows:^{9,10}

$$C = \frac{\pi \varepsilon l}{\ln(\frac{d}{r})} \quad (\text{S29})$$

where, ε denotes the permittivity between the two parallel conductive microfibers, l is the length of each microfiber, d is the distance between the two conductive microfibers, and r indicates the radius of the conductive microfibers. In this study, the dielectric constant for the permittivity is assumed to be constant ($\varepsilon=0.0301$ pF/mm for Dragon Skin elastomer) during bending actuation of the soft actuator.¹¹ Moreover, it is assumed that the elastic material used for the soft actuator is not affecting the behavior of the microfibers in the actuator. Fig. 3b shows a schematic illustration of the two conductive microfibers in the soft actuators to establish an analytical model of the electrical behavior of the proprioceptive capacitive sensor. The non-conductive radial expansion limiting fiber not involved in the proprioceptive sensing of the soft actuator is not presented in the schematic illustration to simplify the analysis. The highlighted part in Fig. 3b (i) indicates a single turn of the two parallel conductive microfibers helically wound around the soft actuator without bending actuation. Because the radial expansion limiting fibers in the soft actuator consist of multiple and identical single turns of two parallel conductive microfibers, the capacitance for only a single turn of the two parallel conductive microfibers can be considered to simplify the mathematical analysis. According to Equation S29, the capacitance for the single turn of the two parallel conductive microfibers in the soft actuator without bending actuation can be calculated as follows:

$$C_{1turn, \theta=0} = \frac{\pi \varepsilon l_{1turn}}{\ln(\frac{d_0}{r})} \quad (\text{S30})$$

where l_{1turn} is the length of the conductive microfiber for the single turn in the soft actuator, d_0 indicates the distance between the two parallel conductive microfibers without bending actuation of the soft actuator (the pitch), r means the radius of the conductive microfiber (100 μm), and θ is the bending angle of the soft actuator under bending actuation. The distance between the two conductive microfibers without bending actuation (d_0) can be derived by

dividing an initial length of the soft actuator by the number of pitches in the soft actuator as follows:

$$d_0 = \frac{L_0}{2n+1} \quad (\text{S31})$$

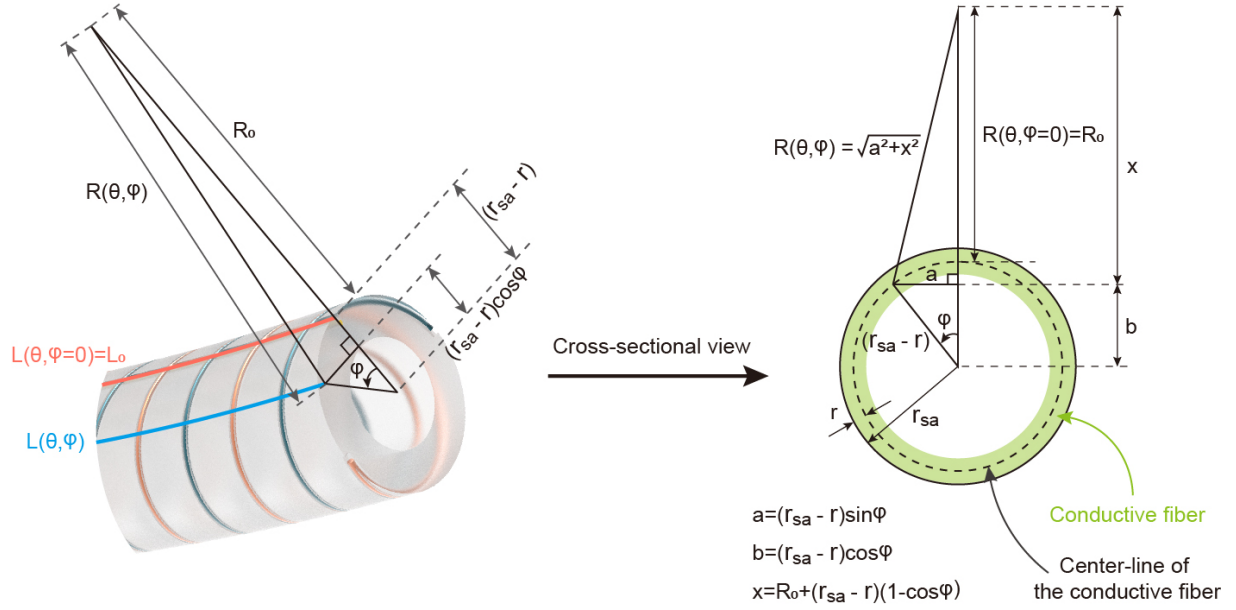
where L_0 means the initial longitudinal length of the helically wound capacitive sensor (88 mm) and n is the total number of turns of the two parallel conductive microfibers in the soft actuator (~ 14.2). When the soft actuator is bent with increasing internal pressure, the distance between the two parallel conductive microfibers is spatially increased from the concave part to convex part of the bent soft actuator according to the longitudinal expansion of the elastomeric chamber under the bending actuation (Fig. 3b (ii)). In particular, the distance (d) between the two conductive microfibers varies according to the corresponding azimuthal angle φ in the cross section of the soft actuator (Fig. 3b (ii)). Therefore, the capacitance between the two conductive microfibers for a single turn in the soft actuator with bending angle θ can be calculated by integrating the capacitance between the two conductive microfibers against the azimuthal angle φ as follows:

$$\begin{aligned} C_{1turn}(\theta) &= \int_0^{l_{1turn}} dC(\theta) \\ &= \int_0^{l_{1turn}} \frac{\pi\epsilon dl}{\ln\left(\frac{d(\theta,\varphi)}{r}\right)} \\ &= \int_0^{2\pi} \frac{\pi\epsilon (r_{sa}-r)d\varphi}{\ln\left(\frac{d(\theta,\varphi)}{r}\right)} = \int_0^{2\pi} \frac{\pi\epsilon (r_{sa}-r)}{\ln\left(\frac{d(\theta,\varphi)}{r}\right)} d\varphi \end{aligned} \quad (\text{S32})$$

where, r_{sa} is the outer radius of the soft actuator (7 mm). Similarly to d_0 from Equation S31, the distance between the two conductive microfibers at the azimuthal angle φ and the bending angle θ can also be calculated by dividing the corresponding stretched length along the soft actuator ($L(\theta, \varphi)$) by the number of pitches (Fig. 3b (ii)) as follows:

$$d(\theta, \varphi) = \frac{L(\theta, \varphi)}{2n+1} = \frac{R(\theta, \varphi)\theta}{2n+1} \quad (\text{S33})$$

where $R(\theta, \varphi)$ is the radius of curvature for the arc $L(\theta, \varphi)$. The radius of curvature $R(\theta, \varphi)$ can be derived by considering the cross section of the soft actuator under bending actuation with bending angle θ (Supplementary Fig. 11).



Supplementary Figure 11. Schematic illustration of the cross section of the soft actuator with a certain bending angle θ .

Based on the Pythagorean theorem, the following equation can be derived from the cross section of the soft actuator shown in Supplementary Fig. 11.

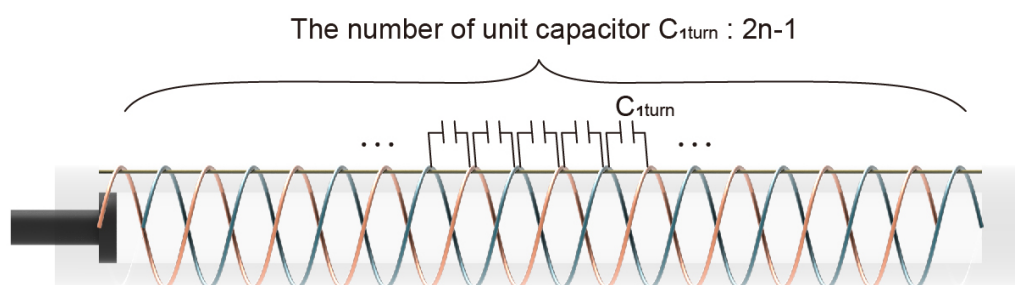
$$\begin{aligned}
 R(\theta, \varphi) &= \sqrt{\{(r_{sa} - r) \sin \varphi\}^2 + \{R_0 + (r_{sa} - r)(1 - \cos \varphi)\}^2} \\
 &= \sqrt{\left(\frac{L_0}{\theta}\right)^2 + 2(r_{sa} - r)\left(\frac{L_0}{\theta} + r_{sa} - r\right)(1 - \cos \varphi)} \quad (S34)
 \end{aligned}$$

Based on Equation S32, S33, and S34, the capacitance between the two conductive microfibers for a single turn in the soft actuator with a bending angle θ can be calculated as follows:

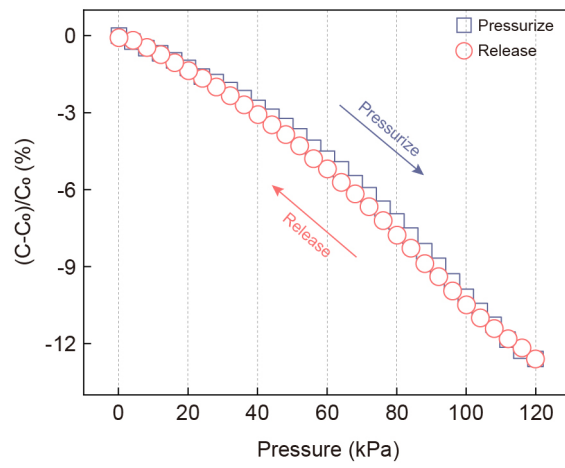
$$C_{1turn}(\theta) = \int_0^{2\pi} \frac{\pi \epsilon (r_{sa} - r)}{\ln\left(\frac{\theta}{r(2n+1)} \sqrt{\left(\frac{L_0}{\theta}\right)^2 + 2(r_{sa} - r)\left(\frac{L_0}{\theta} + r_{sa} - r\right)(1 - \cos \varphi)}\right)} d\varphi \quad (S35)$$

Because there also be a capacitance between two neighboring pairs of the two helical conductive microfibers in the soft actuator (Supplementary Fig. 12), the total capacitance of the proprioceptive sensor in the soft actuator is equivalent to $(2n - 1)$ capacitors connected in parallel.

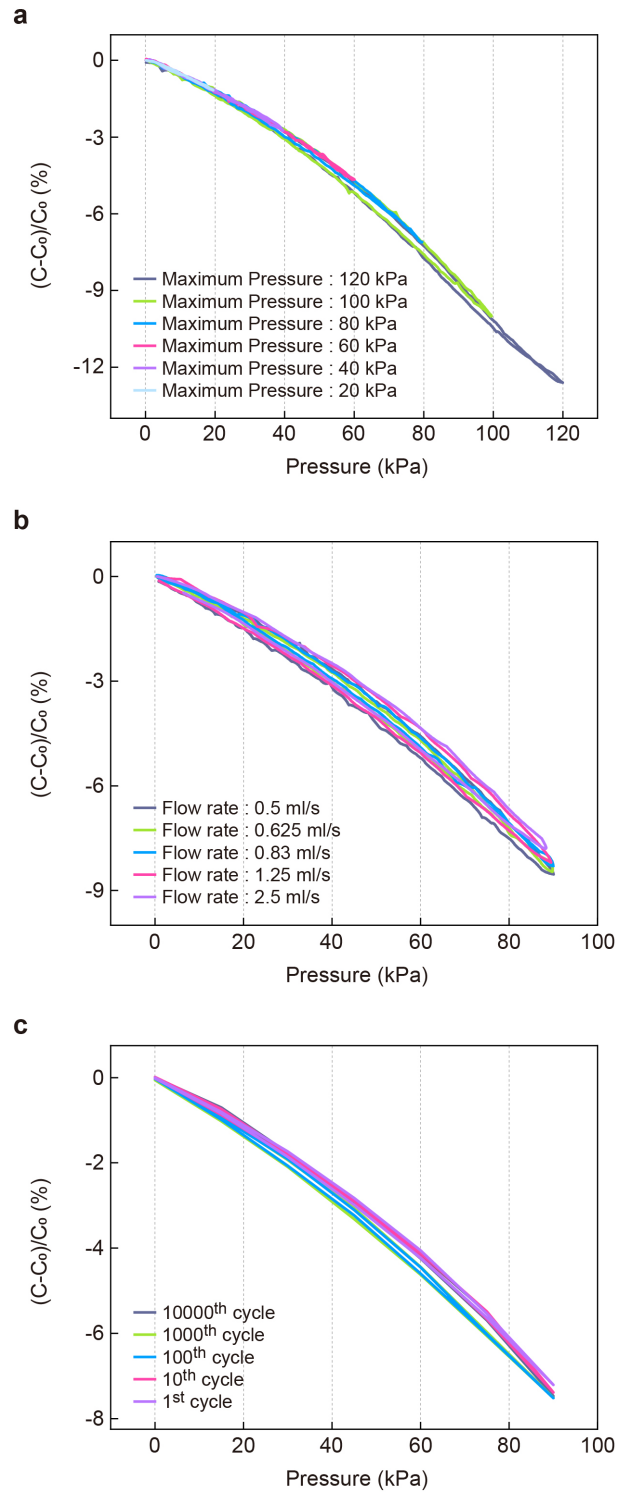
$$C_{total}(\theta) = (2n - 1) \cdot C_{1turn}(\theta) \quad (S36)$$



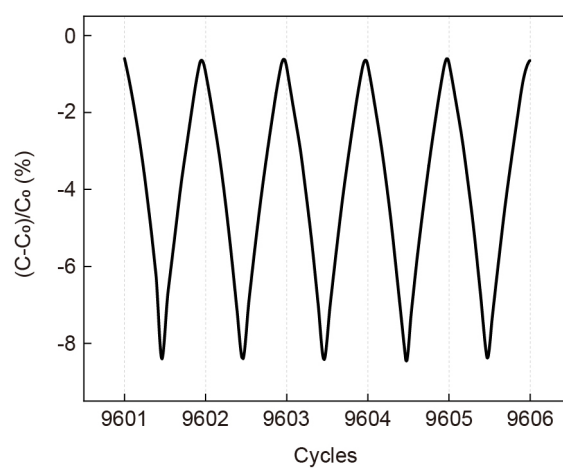
Supplementary Figure 12. Schematic illustration showing the parallel connection of unit capacitors corresponding to a single turn of the two conductive microfibers helically wound around the soft actuator.



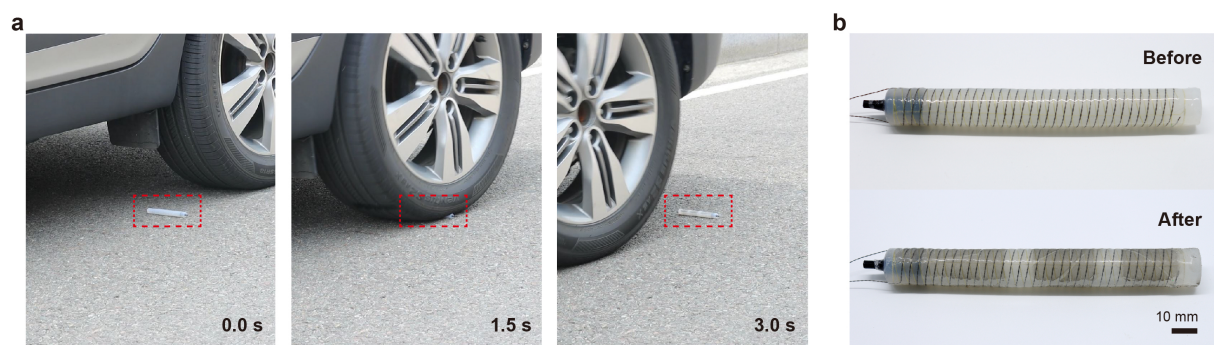
Supplementary Figure 13. Capacitive response of the proprioceptive bending sensor upon consecutive pressurized-unpressurized cycle of the soft actuator with a maximum internal pressure of 120 kPa.



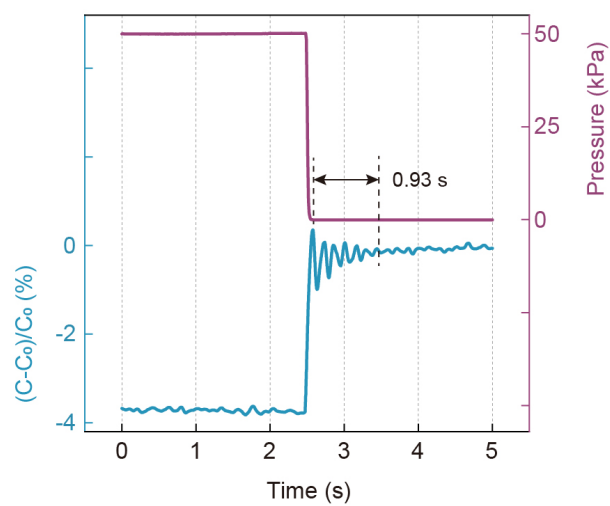
Supplementary Figure 14. Hysteresis of the capacitive response of the proprioceptive bending sensor under diverse conditions such as different **(a)** maximum pressures from 20 to 120kPa, **(b)** flow rates from 0.5 to 2.5 ml/s, and **(c)** pressurizing-releasing cyclic tests from 1 to 10,000 repeated cycles.



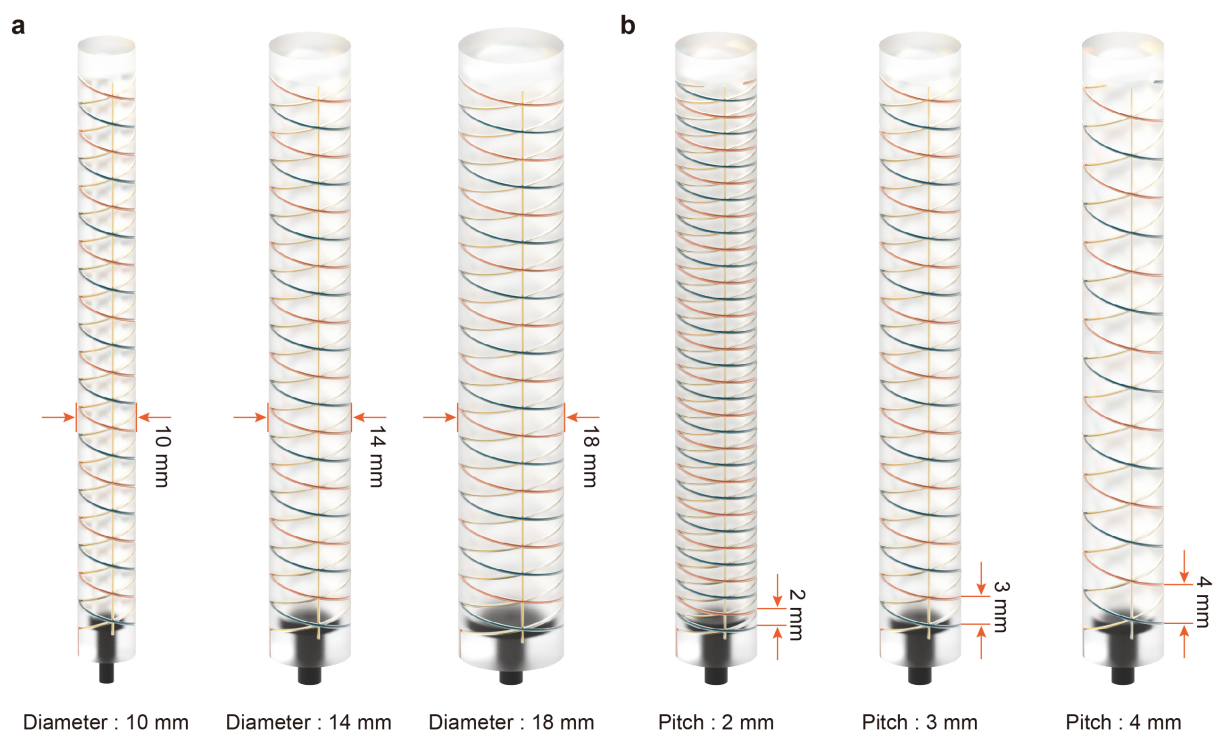
Supplementary Figure 15. Capacitive response of the proprioceptive soft actuator during the intensive cyclic test with an internal pressure of 90 kPa, showing high durability of the proprioceptive bending sensors.



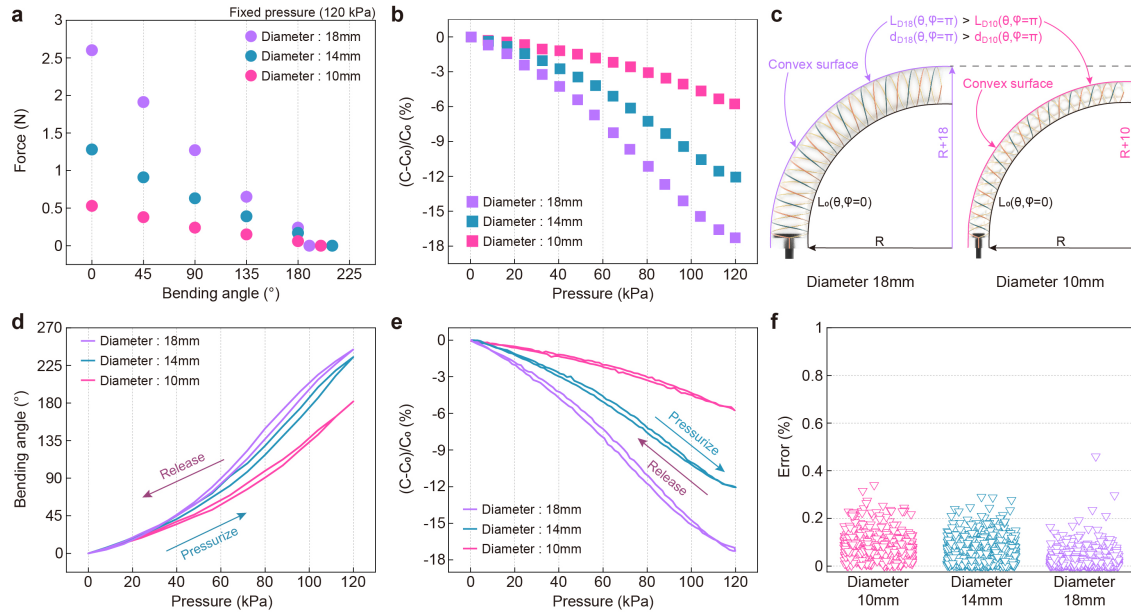
Supplementary Figure 16. Photographs showing the mechanical impact test. a Photographs showing the soft actuator run over by a vehicle **b** Photographs before and after the mechanical impact test.



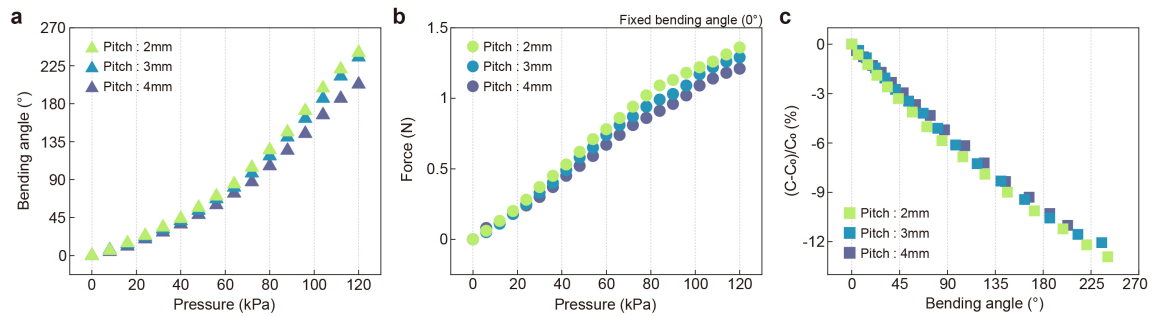
Supplementary Figure 17. Capacitive response of the proprioceptive bending sensor upon release of 50 kPa of the applied internal pressure, showing the recovery time of the actuator.



Supplementary Figure 18. Schematic illustrations showing the proprioceptive soft actuators with different structural parameters. a Proprioceptive soft actuators with different diameters of the elastomeric chamber of 10, 14, and 18 mm. **b** Proprioceptive soft actuators with different pitches of 2, 3, and 4 mm. Pitch indicates the distance between adjacent conductive microfibers in the radial expansion limiting fibers.

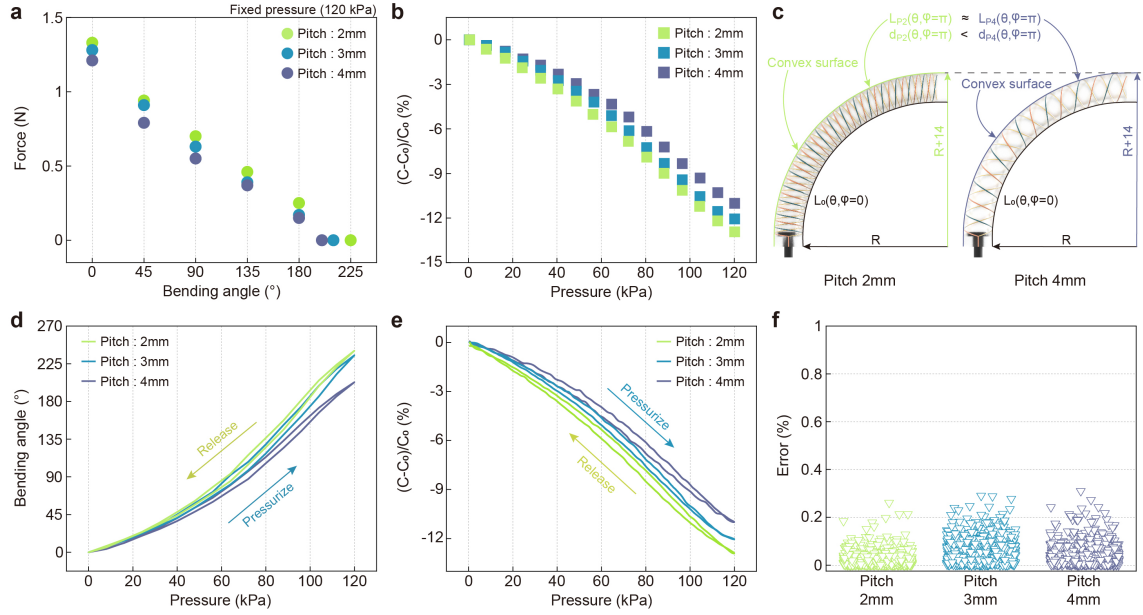


Supplementary Figure 19. Characterization of the proprioceptive soft actuators with different diameters of an elastomeric chamber (fixed pitch: 3mm). **a** Force generated at the distal tip of the soft actuator with different bending angles and fixed internal pressure of 120 kPa. **b** Capacitive response of the proprioceptive sensors in the soft actuators with respect to the internal pressure. **c** Schematic illustration showing the location of the convex surface, and differences in distance between the conductive microfibers according to the diameter of the elastomeric chamber at a specific bending angle. **d** Change in the bending angle of the soft actuators during the consecutive pressurizing-releasing deformation. **e** Relative change in the capacitance of the proprioceptive sensors during a pressurizing-releasing cycle. **f** Error for capacitance values measured at 90 kPa during an intensive pressurizing-releasing cyclic test (1,000 cycles with the internal pressure of 0 to 90 kPa). The error was calculated based on the capacitance measured in the first cycle.

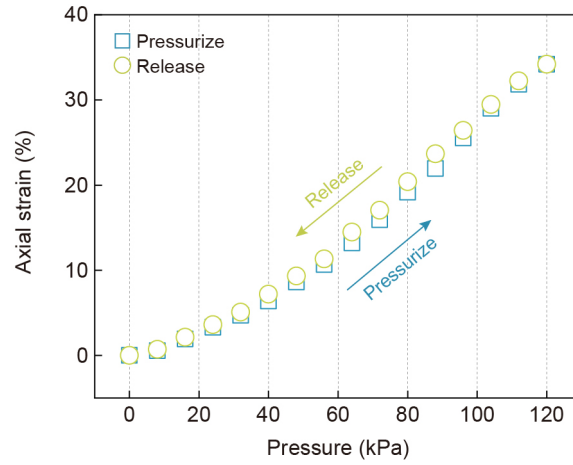


Supplementary Figure 20. Main characterization of the proprioceptive soft actuators with different pitches between the wound conductive microfibers (fixed diameter: 14 mm).

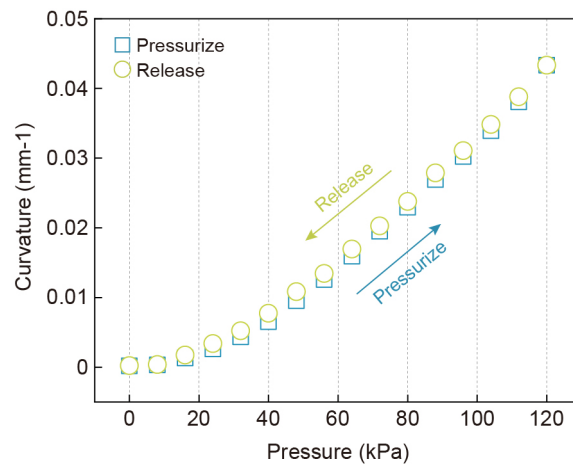
a Bending angle of the proprioceptive soft actuators with different pitches in response to increasing internal pressure. **b** Force generated at the distal tip of the soft actuators under fixed bending angle of 0° and increasing internal pressure. **c** Capacitive response of the proprioceptive bending sensors in the soft actuators according to bending angle of the actuators.



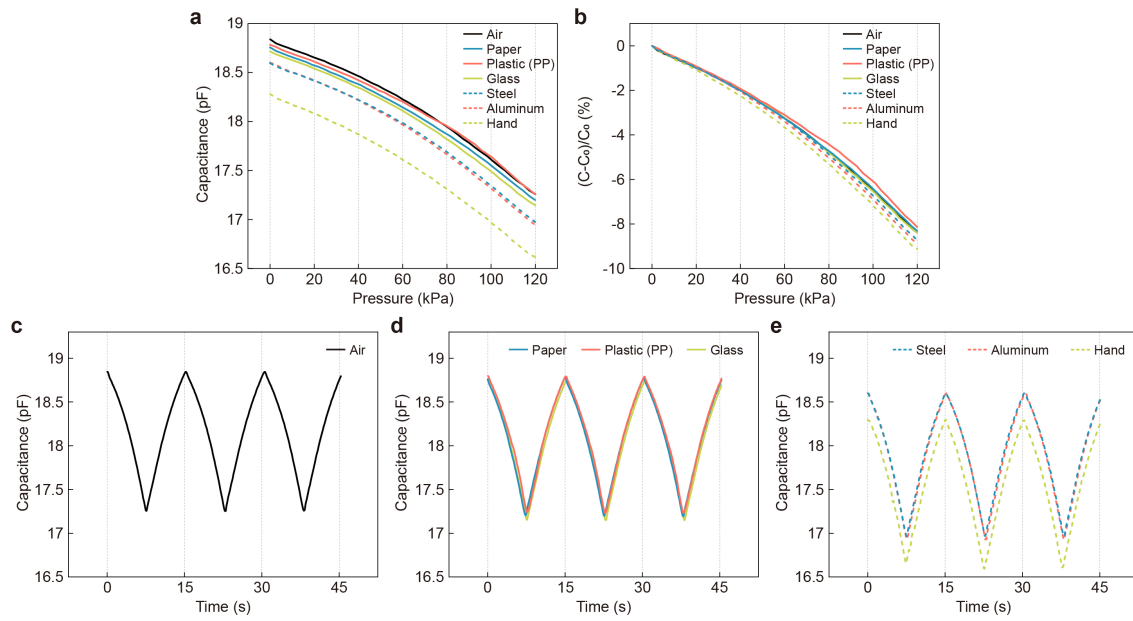
Supplementary Figure 21. Characterization of the proprioceptive soft actuators with different pitches between the wound conductive microfibers (fixed diameter: 14mm). a Force generated at the distal tip of the soft actuator with different bending angles and fixed internal pressure of 120 kPa. **b** Capacitive response of the proprioceptive sensors in the soft actuators with respect to the internal pressure. **c** Schematic illustration showing the location of the convex surface, and the distances between the conductive microfibers according to the diameter of the elastomeric chamber at a specific bending angle. **d** Change in the bending angle of the soft actuators during the consecutive pressurizing-releasing deformation. **e** Relative change in the capacitance of the proprioceptive sensors during a pressurizing-releasing cycle. **f** Error for capacitance values measured at 90 kPa during an intensive pressurizing-releasing cyclic test (1,000 cycles with the internal pressure of 0 to 90 kPa). The error was calculated based on the capacitance measured in the first cycle.



Supplementary Figure 22. Stretching actuation of the soft actuator without the axial strain limiting fiber according to the consecutive pressurizing-releasing cycle with an internal pressure up to 120 kPa.



Supplementary Figure 23. Helical actuation of the soft actuator with the helically wound axial strain limiting fiber with respect to the consecutive pressurizing-releasing cycle with an internal pressure up to 120 kPa.



Supplementary Figure 24. Effect of surrounding objects on the capacitive response of the proprioceptive bending sensor. (a) Absolute capacitance and (b) normalized capacitance changes of the proprioceptive bending sensor in the soft actuator according to the bending actuation of the actuator in the vicinity of the various objects. c-e Capacitance changes of the sensor during repeated bending actuations in the vicinity of the various objects.

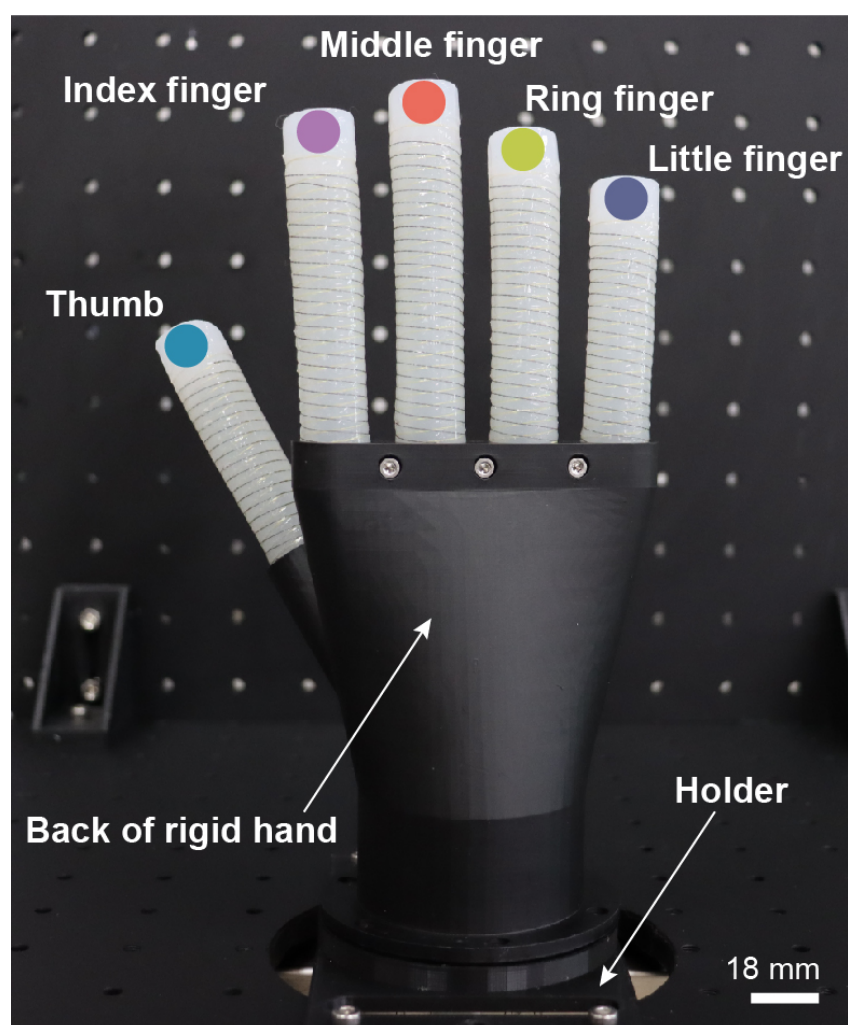
Supplementary notes

Detailed explanation regarding scheme of control algorithm and system identification to obtain the transfer function

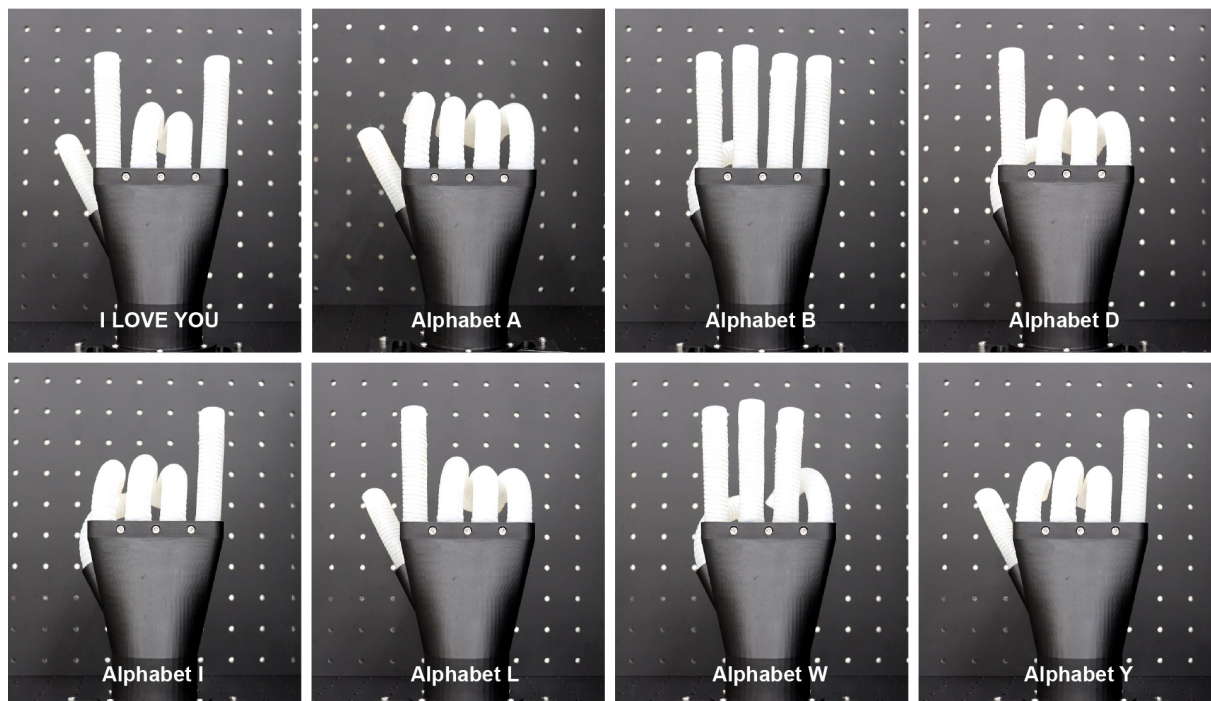
C_{ref} means the desired capacitance of the soft actuator maintaining a specific bending angle, d is a disturbance such as an external loading, and Q indicates a low pass filter for solving the causality problem and noise reduction. $\hat{d}$ denotes the estimated disturbance, G_{soft} is the actual model of the soft actuator, and $G_{n,soft}$ is a transfer function of the nominal model estimated by system identification. The system identification is performed by applying a random phase multi sinusoidal input pressure to the soft actuator with a frequency range of 0.01 to 5 Hz. The system characteristics in the frequency domain can be obtained by Fast Fourier Transform (FFT) of the sinusoidal input signal to the system and output signal. Then, a frequency domain-based transfer function $G_{n,soft}$, red line in Fig. 5b, can be acquired as follows:

$$G_{n,soft}(s) = \frac{C}{P_{in}} = \frac{1.25s}{28.4s^2 + 470s} \quad (S37)$$

NI Labview (National Instruments Corp., Labview V20.0) was utilized in this study to control the soft actuator by integrating the measurements obtained from the pressure controller and LCR meter.



Supplementary Figure 25. Photograph showing a prosthetic hand fabricated with five proprioceptive soft actuators as fingers for the soft gripping system.



Supplementary Figure 26. Operation of the soft prosthetic hand. Photographs of the soft prosthetic hand actuating to present various sign language meaning a specific sentence (“I love you”) and several alphabets.



Supplementary Figure 27. Soft prosthetic hand gripping diverse objects. Grasping a (a) ripe avocado, (b) expanded balloon, (c) apple, (d) eyeglasses, (e) egg, (f) wine glass, (g) tennis ball, (h) spatula, (i) wireless mouse, (j) book, (k) pipette, and (l) plastic bottle with water.

Supplementary Table 1. Comparison of various parameters for self-sensing soft actuators reported in the literature.

Actuator type	Sensor type	Type of Sensor assembly	Heterogeneous sensing elements	Need for intricate wiring	Sensing range	Sensitivity	Response time [ms]	The number of cyclic tests	Ref.
								Mechanical (Electrical)	
Pneumatic	Cap ^{a)}	Embedded	O	O	0.9 ~ 30.0 kPa (internal pressure)	~ 0.29 pF/kPa	-	- (-)	12
Pneumatic	Cap	Embedded	O	O	0 ~ 38 kPa (internal pressure)	~ 1.1 pF/kPa	-	- (-)	13
Pneumatic	Cap	Attached	O	O	0 ~ 19 mm (contraction length)	-	32	10,000 (-)	14
Thermal	Cap	Embedded	O	O	0 ~ 160 kPa (internal pressure)	~ 0.1 pF/kPa	-	10,000 (10,000)	15
Cable-driven	Cap	Embedded	O	O	0 ~ 79 kPa (normal stress)	~ 0.95 pF/mm	-	- (-)	16
Cable-driven	Cap	Attached	O	O	-	~ 8.3 pF/kPa	-	- (10)	17
Pneumatic	Res ^{b)}	Embedded	O	O	0 ~ 4 mm (actuation height)	GF : ~ 1	-	- (1 million)	18
Pneumatic	Res	Embedded	O	O	0 ~ 32 ° (bending angle)	~ 45 Ω/kPa	-	- (-)	19
Pneumatic	Res	Embedded	O	O	-20 ~ 20 mm (position)	-	-	- (-)	20
Pneumatic	Vol ^{c)}	Embedded	O	O	-60 ~ 60 ° (bending angle)	~ 0.57 V/rad	-	- (-)	21
Pneumatic	Res	Embedded	O	O	0 ~ 28° (bending angle)	-	-	- (-)	22
Pneumatic	Res	Printed	O	O	0 ~ 35 % (compressed strain)	GF : ~ 2.5	12.4	- (-)	23
Pneumatic	Res	Printed	O	O	-	GF : ~1	-	- (-)	24
Pneumatic	Opt ^{d)}	Embedded	O	O	0 ~ 200 1/m (curvature)	~ 0.02 dB/cm	-	- (-)	25
Pneumatic	Opt	Embedded	O	O	0 ~ 140 % (tensile strain)	~ 14.23 dB/ε	-	- (3,000)	26
Thermal	Opt	Embedded	O	O	1.5 ~ 2.5 mm/m (displacement)	-	-	- (-)	27
Pneumatic	Opt	Embedded	O	O	0 ~ 175 ° (bending angle)	~ 2 dB/rad	600	- (-)	28
Pneumatic	Mag ^{e)}	Embedded	O	O	0 ~ 20 N (force)	~ 2.85 mV/N	-	- (-)	29
Pneumatic	Mag	Embedded	O	O	0 ~ 220 ° (bending angle)	~ 0.1 rad/kPa	550	- (-)	30
Pneumatic	Mag	Embedded	O	O	-150 ~ 150 1/m (curvature)	~ 40 mV/G	2500	- (-)	31
Pneumatic	Cap	Inherent component	X	X	0 ~ 240 ° (bending angle)	~ 1.2 pF/rad	320	10,000 (10,000)	This work

^{a)}(Capacitive type); ^{b)}(Resistive type); ^{c)}(Voltage type); ^{d)}(Optical type); ^{e)}(Magnetic type);

Supplementary Table 2. A comparison of the fabrication process used for our proposed proprioceptive soft actuator and previously documented self-sensing soft actuators.

Actuator type	# of fab steps	Main fabrication process		Ref.
		Soft sensor	Soft actuator	
Pneumatic	4	-	[Actuator with inherent sensor] 1. Casting an actuator body 2. Casting an end cap 3. Attaching an axial strain limiting fiber 4. Winding radial expansion limiting fibers (forming a fiber-type capacitive sensor simultaneously)	This work
Pneumatic	5	1. Ink fabrication process (hydrogel, crosslinking agent, ionic liquid, fluorescently labeled monomer)	2. Casting an actuator body 3. Inserting tubing and wires into the actuator body 4. Wiring process 5. Ink injecting	13
Pneumatic	8	1. Cutting a conductive fabric 2. Wiring process 3. Casting the silicone rubber layer 4. Attaching the conductive fabric to the rubber layer	5. Cutting a fabric 6. Coating the fabric with silicone adhesive 7. Attaching the overlapping area 8. Fixing the fabric part with end fittings	14
Thermal	6	1. Stacking two conductive electrodes and a dielectric layer 2. Wiring process	[Joule heater] 3. Material patterning by a laser cutter 4. Cutting a fabric by a laser cutter [Actuator] 5. Cutting a fabric 6. Incorporating a sensor and joule heater on the actuator by a bonding process	15
Pneumatic	7	1. Commercial sensor	2. Casting an actuator body 3. Attaching the commercial sensor 4. Attaching a strain limiting layer 5. Winding radial expansion limiting fibers 6. Casting a thin rubber sheath for insulation 7. Casting an end cap	32
Pneumatic	10	1. Casting a waveguide 2. Inserting LED & photo diode 3. Injecting ionic liquid 4. Wiring process 5. Attaching conductive fabric 6. Casting a sensor body	7. Material patterning by a laser cutter 8. Folding of origami pattern 9. Attaching the sensor 10. Enclosing the actuator with fabric housing	33
Electro-hydraulic	7	1. Magnetic silicone block fabrication process (Neo-powder, Ecoflex 0030) 2. Casting the magnetic sensor 3. Magnetization of the magnetic sensor	4. Material patterning by a laser cutter 5. Filling the shell with liquid dielectric 6. Sealing with a soldering iron 7. Cutting the outline of a soft actuator	34

Supplementary Table 3. The unit price per one proprioceptive soft actuator, including the sensing component.

Use	Items	Materials	Company	Unit price per one proprioceptive soft actuator
For actuator	Body of the soft actuator	Dragon skin 10 medium	Smooth-on Inc.	~0.32 USD
For actuator	Strain limiting fiber & radial expansion limiting fibers	Para-aramid	Sueco Ltd.	~0.13 USD
For actuator & sensor	Radial expansion limiting fibers	Stainless steel fiber	Adafruit Inc.	~0.45 USD
For actuator	Air inlet part	Tough PLA	Ultimaker Ltd.	~0.02 USD
Total price				~0.92 USD (60.5 \$/kg)

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