

Supplementary Information for ***FibTac*: A Fiber-based Pneumatic Gripper with Embodied Tactile Sensing**

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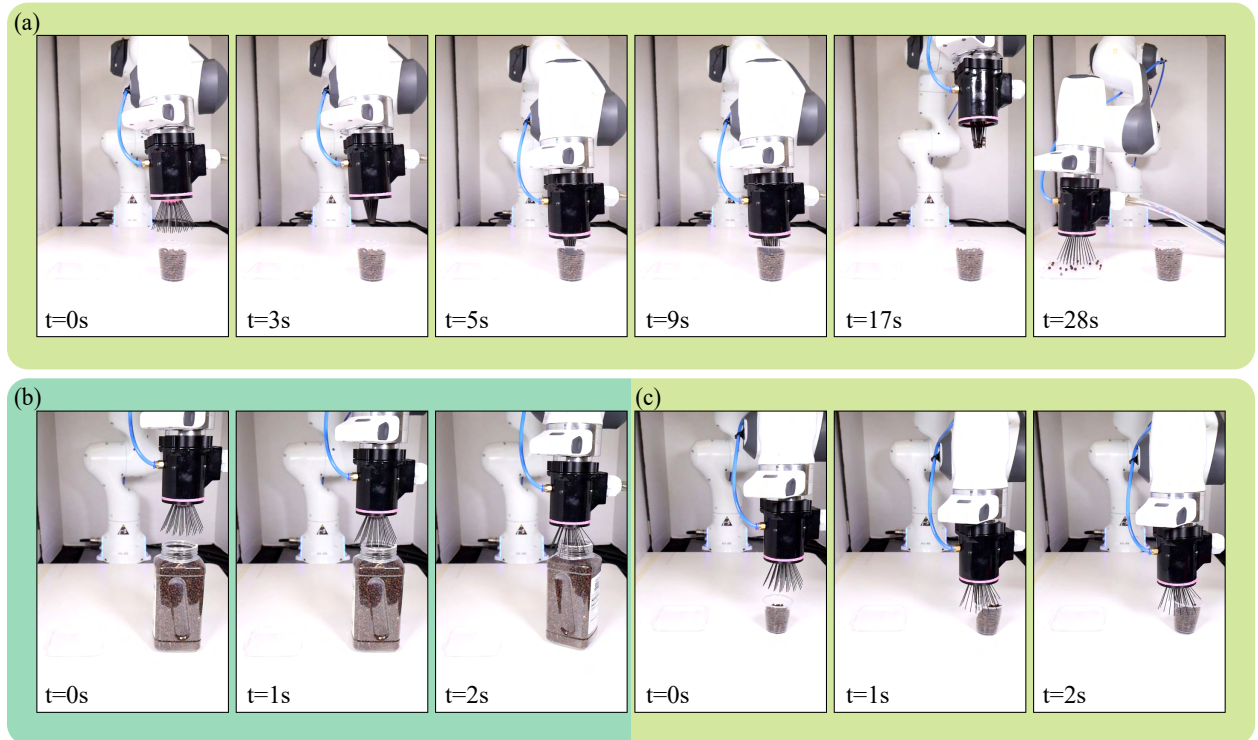
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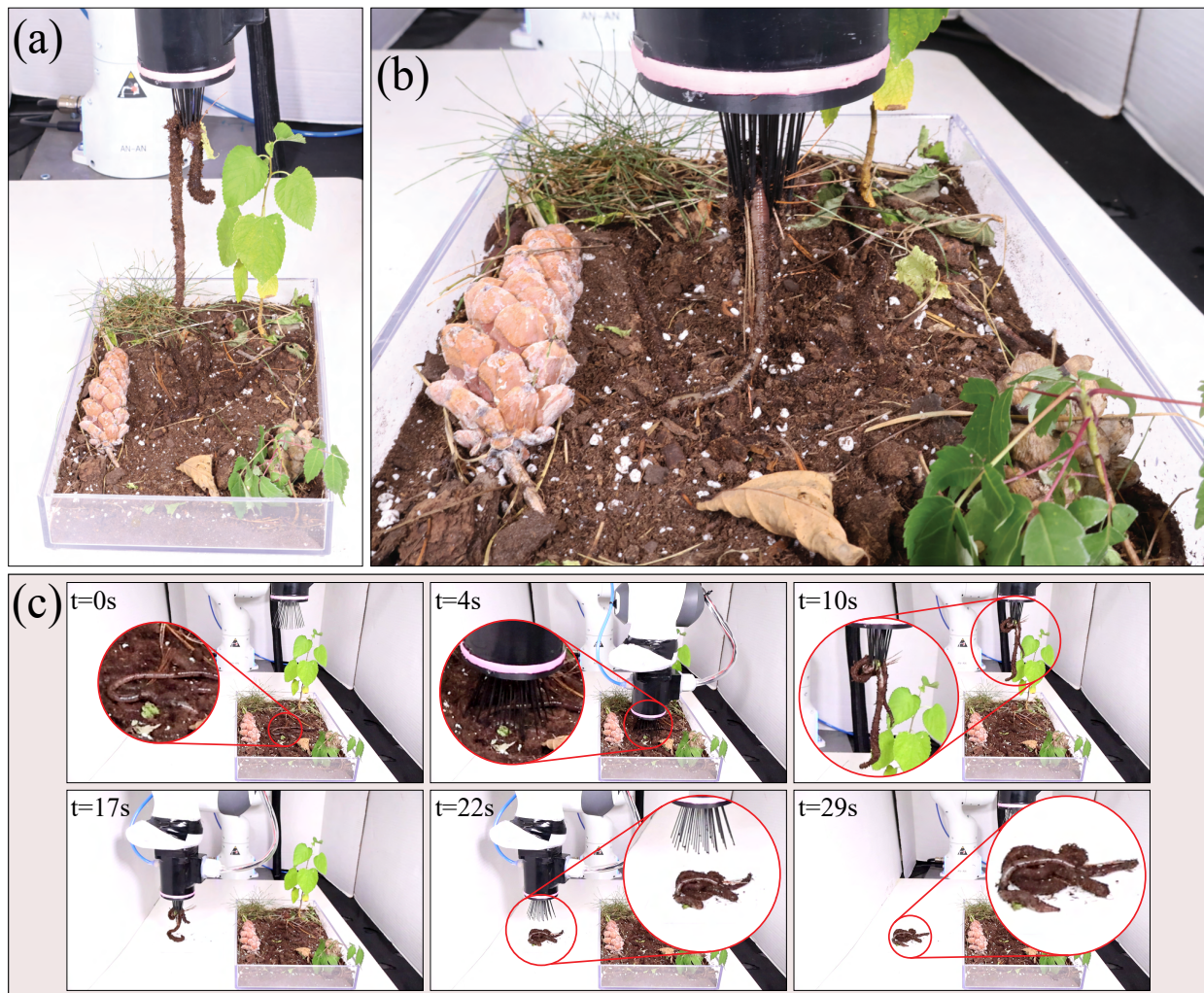
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Year	Sensing Principle	Actuation Method	Payload	Underwater	Workspace
2020 [1]	Strain gauges at whisker base (mechanical deflection)	Passive	–	–	Limited (bending only)
2014 [2]	Resistive nanocomposite on flexible fibers (electronic whisker)	Passive	–	–	Limited
2017 [3]	Mechanical modeling of base forces using flexible rod	Passive	–	–	Limited
2022 [4]	MEMS barometer array at whisker base for flow detection	Passive	–	–	Limited
2021 [5]	Vision-based tracking of whisker tip deflection	Passive (visual)	–	–	Moderate
2022 [6]	Base deflection + proprioceptive estimation (optical)	Passive	–	–	Moderate
2023 [7]	Vision-based whisker with mechanoluminescence sensing	Passive (optical)	–	–	Moderate
2024 [8]	Specklegram optical fiber sensing for flow and contact	Passive (optical)	–	–	Limited (lab demo)
2024 [9]	Fiber Bragg Grating (FBG)-based optical whisker array	Passive (FBG)	–	–	Moderate
2024 [10]	Hybrid e-skin integrated with whisker-like filaments	Passive	–	–	Limited
2025 [11]	Vision + magnetic actuation for active whisker control	Magnetic actuation	~10 g	–	Limited (small rotation angle)
This work	Pneumatic fiber-based tactile sensing (optical + mechanical)	Pneumatic actuation	186 g	✓	Wide (large deflection angles)

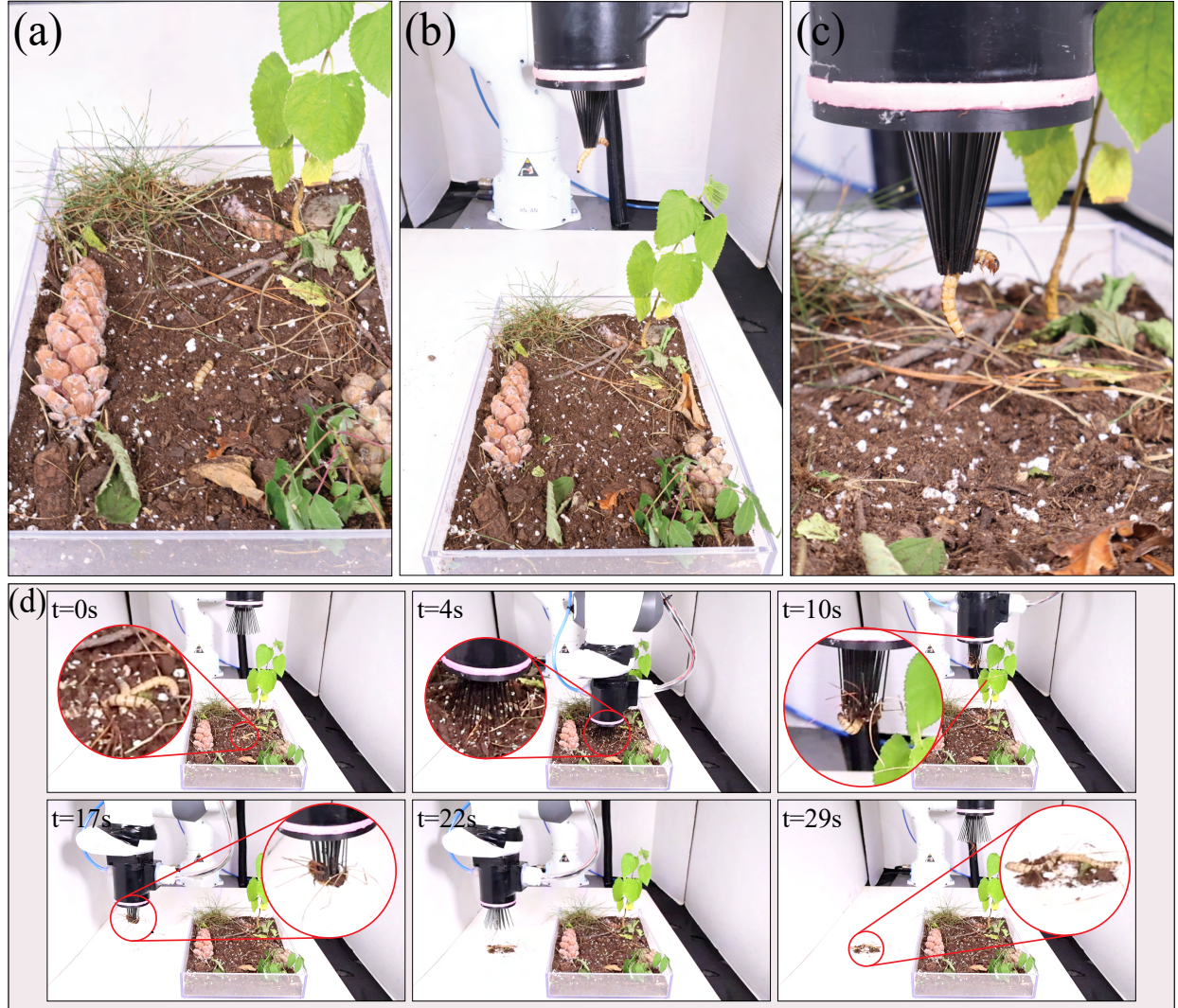
Supplementary Table 1. Comparison of whisker-inspired tactile sensors. Comparison across sensing principles, actuation method, payload capacity, underwater usability, and workspace.



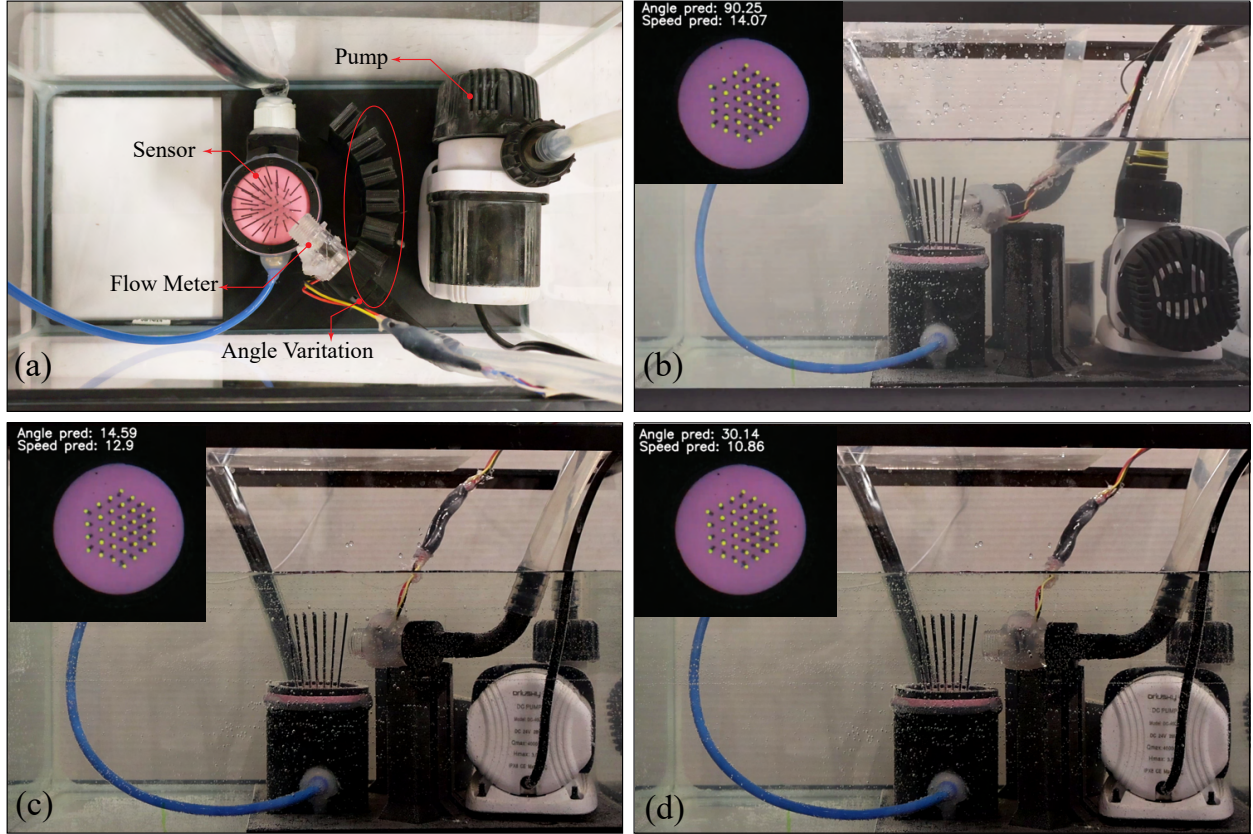
Supplementary Figure 1. Confined-Space Grasping. (a) Retrieval of black pepper seeds from a small cup using the *FibTac* gripper. (b) Failure case for the container when no vacuum is applied. (c) Failure case for the small cup when the vacuum is not applied. Time stamps are indicated on all images. Additional details are provided in Supplementary Movie 4.



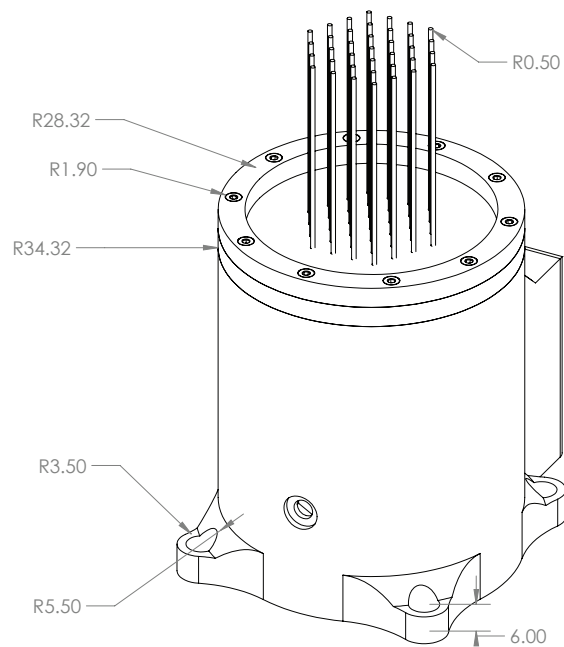
Supplementary Figure 2. Live Nightcrawler Grasping. (a) Setup for the grasping demo, and the gripper grasps the nightcrawler worms. (b) Close-up view of the gripper grasping the worms. (c) Snapshots of the grasping and placement demo with time stamps indicated. More details in Supplementary Movie 3.



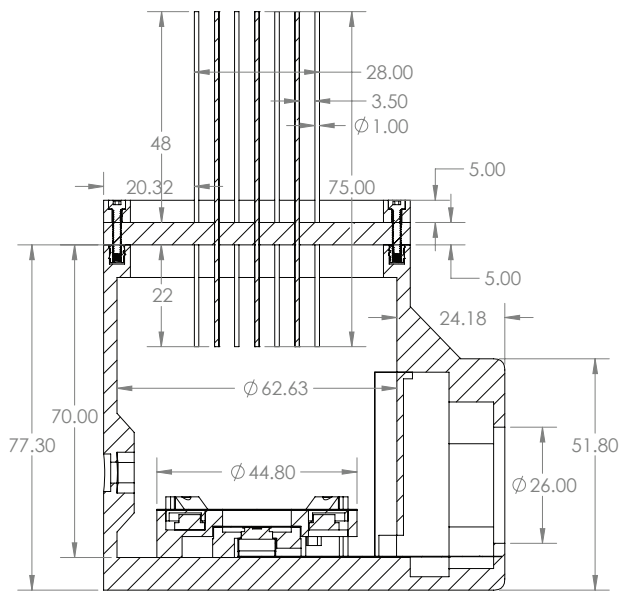
Supplementary Figure 3. Live Superworms Grasping. (a) Setup for the grasping demo showing the environment created for the grasping and super worm inside the soil, (b) Gripper grasps the superworm, (c) Close-up view of the gripper grasping the superworms. (d) Snapshots of the grasping and placement demo with time stamps indicated. More details in Supplementary Movie 3.



Supplementary Figure 4. Flow Sensing. (a) Setup used to record data and perform the flow estimation experiment (b)-(d) *FibTac* estimating flow speed and angle at different configurations.

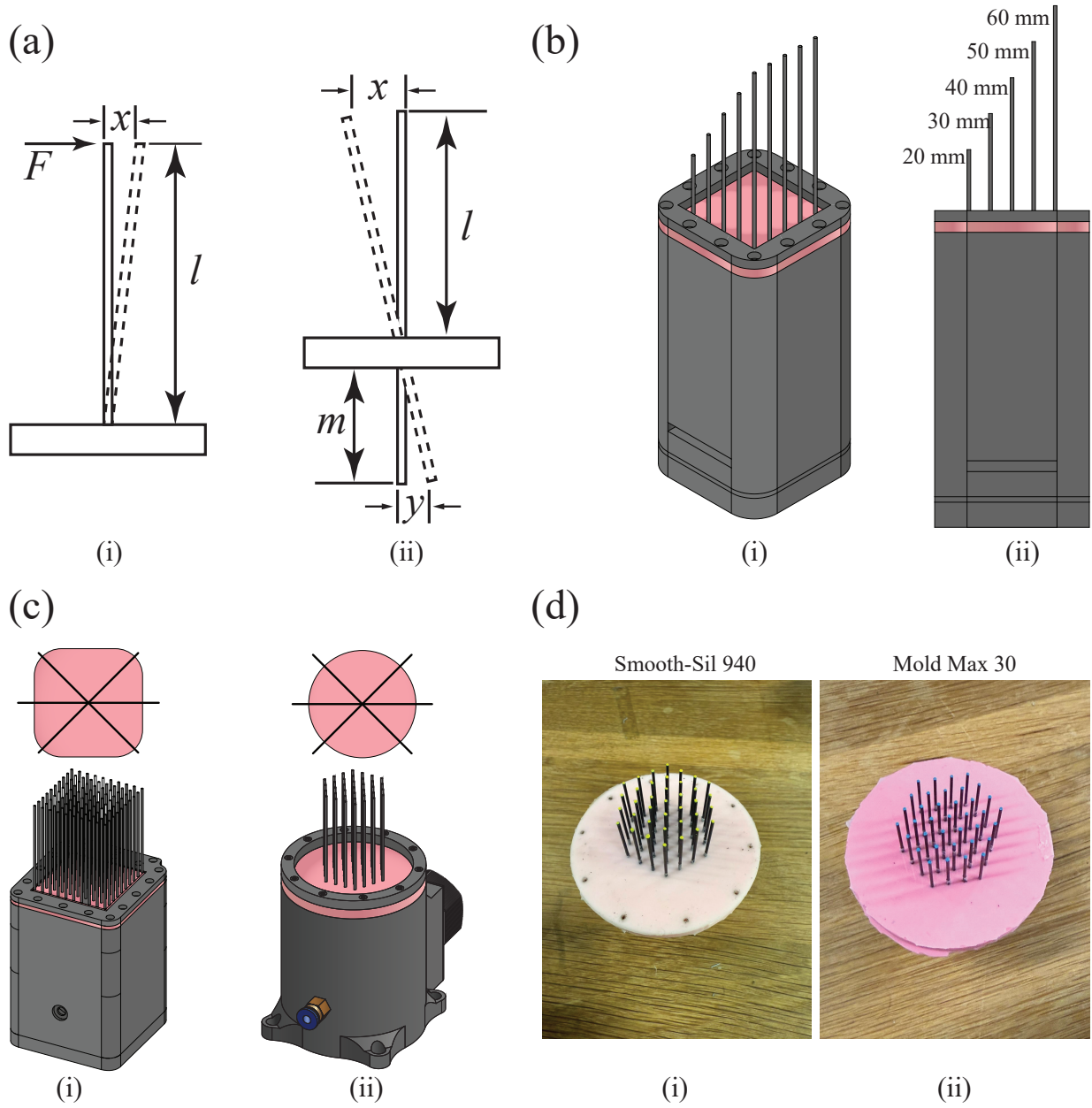


(a)

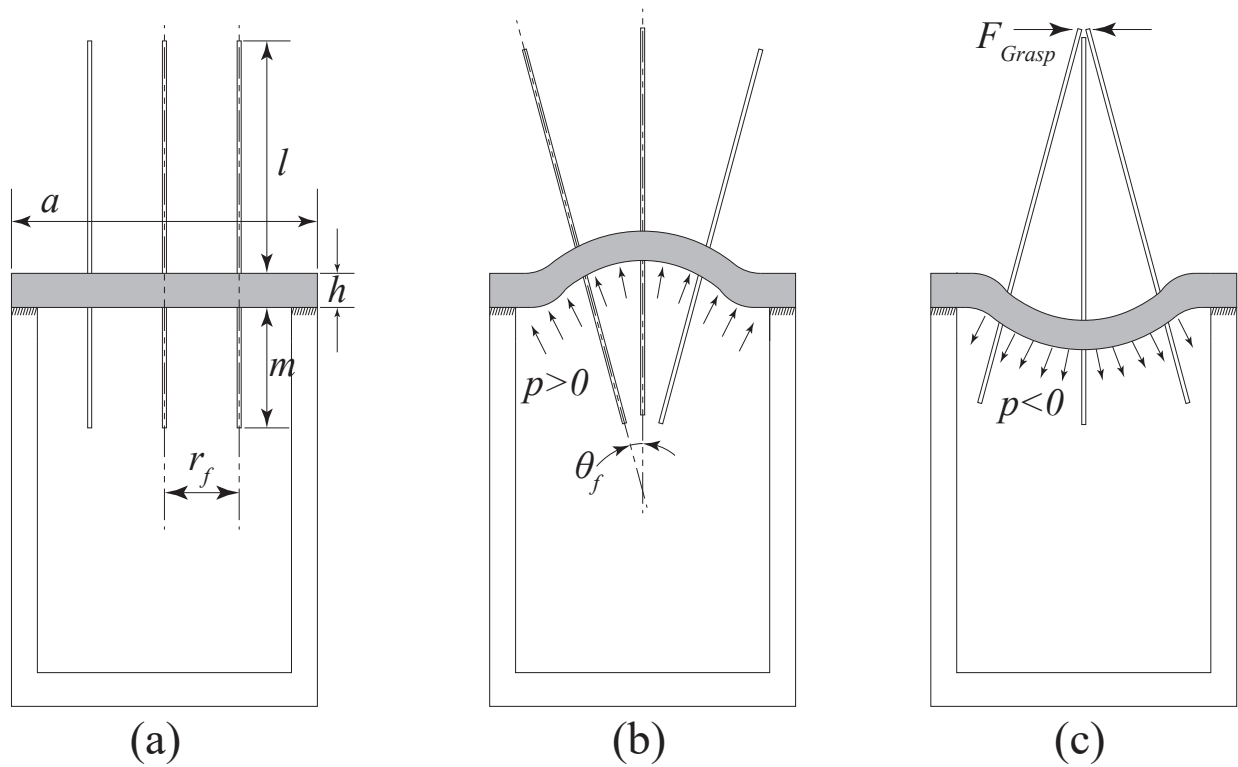


(b)

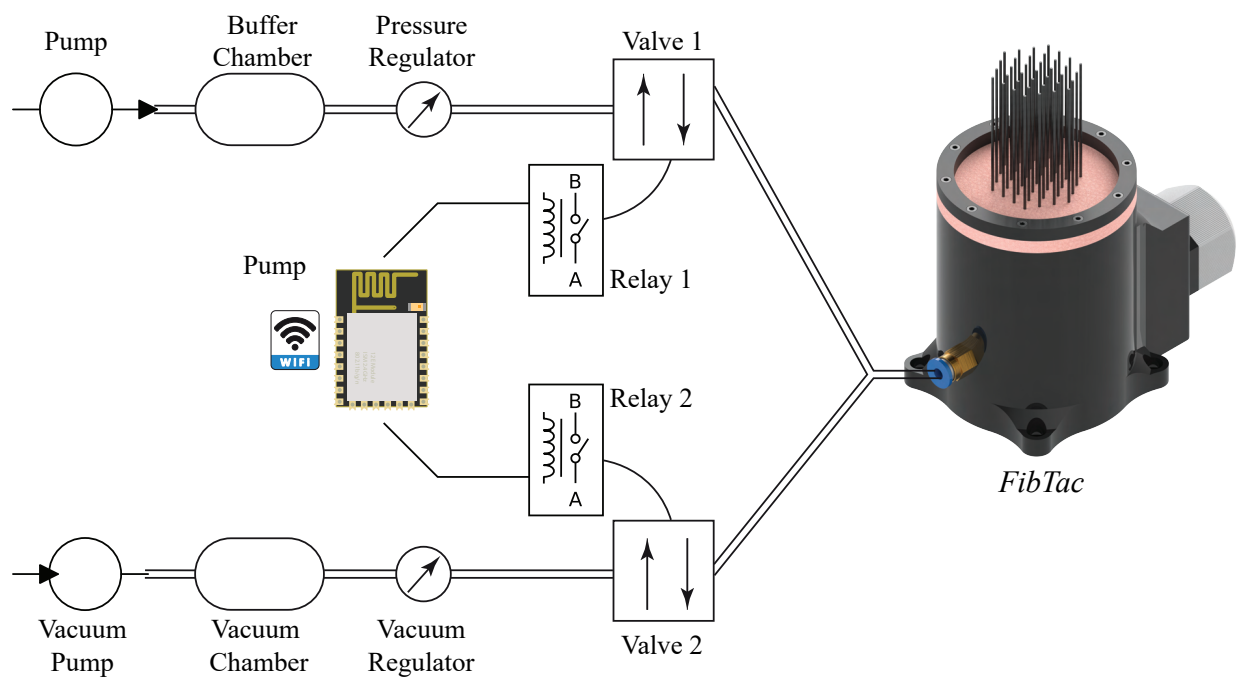
Supplementary Figure 5. Detailed Dimensions of *FibTac* Housing. (a) Isometric View, (b) Side View cross-section



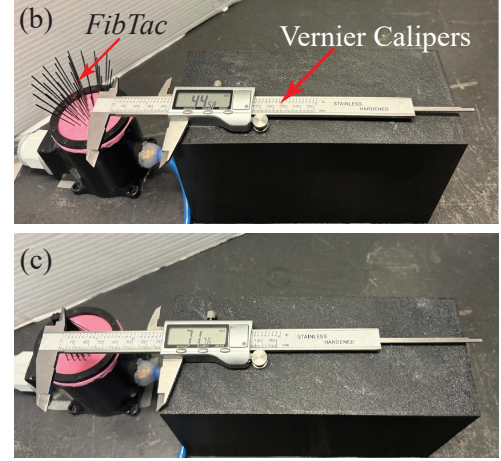
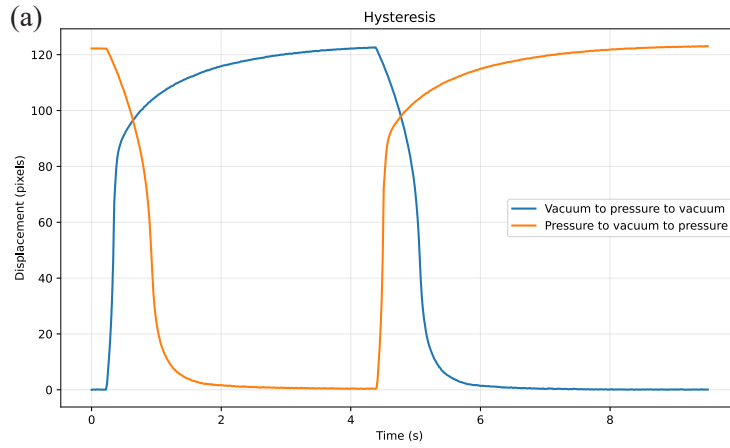
Supplementary Figure 6. Design parameters of *FibTac*. (a) Optimizing Fiber length- (i) Lateral Stiffness model, (ii) Movement when suspended in the silicone (b) Experiment to check the effect of fiber length on sensitivity and stiffness - (i) Isometric of the setup, (ii) Side view of the setup with different fiber lengths indicated, (c) Optimizing the cross section of the fiber- (i) Square Cross Section, (ii) Circular cross-section, (d) Experimenting with optimum silicone gel- (i) Smooth-Sil 940 with 40A hardness, (ii) Mold Max 30 with 30A hardness.



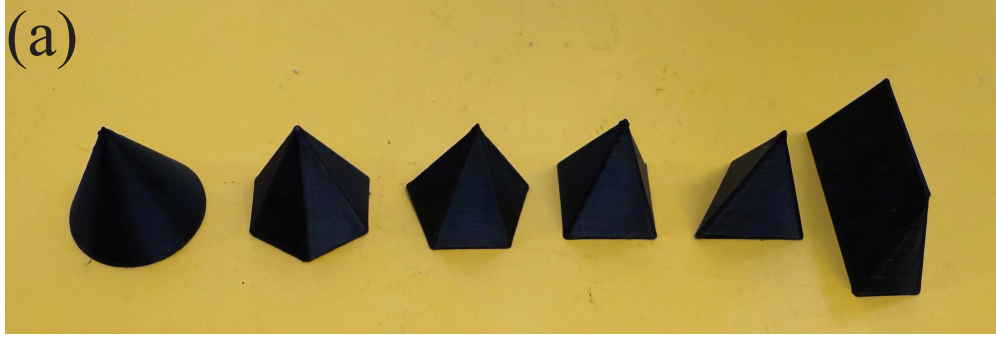
Supplementary Figure 7. Pneumatic Design. (a) Neutral State, (b) Pressurized State, (c) Vacuumed State



Supplementary Figure 8. Pneumatic Actuation System. Schematic design of the pneumatic actuation system deployed to actuate *FibTac*



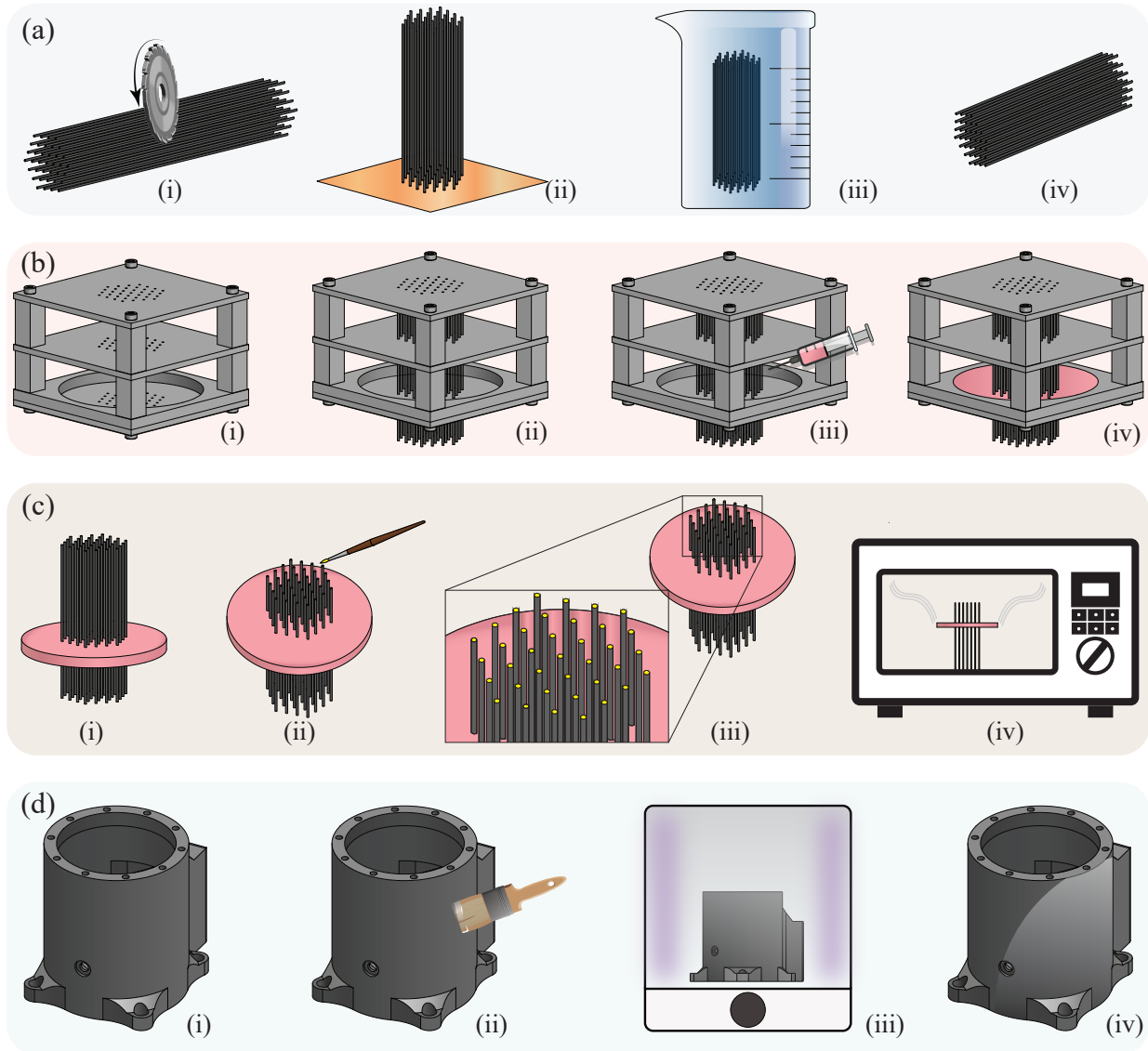
Supplementary Figure 9. Characterization. (a) Hysteresis evaluation through cyclic pneumatic actuation experiments showing fiber-tip displacement during vacuum-to-pressure-to-vacuum and pressure-to-vacuum-to-pressure transitions. The close overlap between loading and unloading trajectories and the small residual displacement indicate negligible hysteresis and stable mechanical recovery. (b) Experimental setup used for physical displacement repeatability measurement in the pressurized state using Vernier calipers. (c) Experimental setup used for displacement repeatability measurement in the vacuumed state.



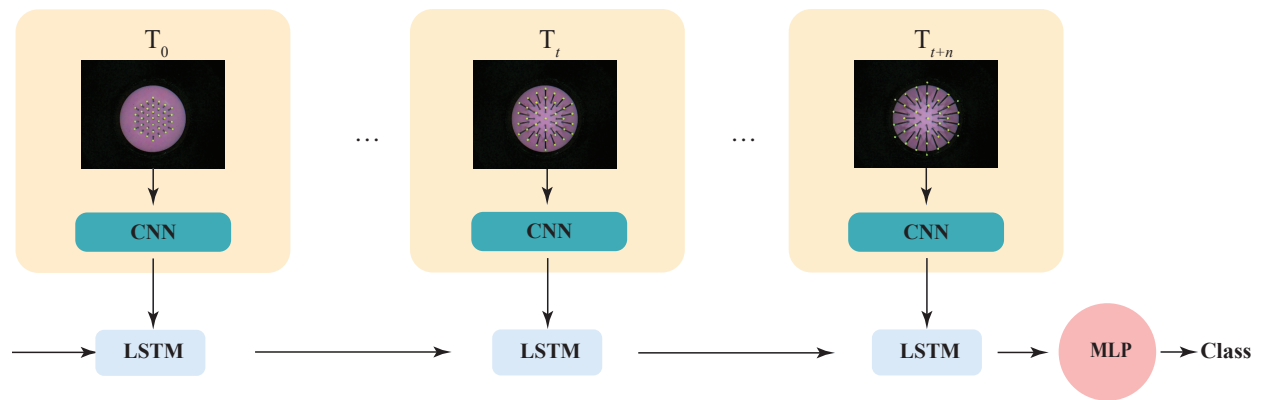
(b) Confusion Matrix (in %) - Overall Accuracy: 97.22

True Label \ Predicted Label	Cone	Hexagon	Pentagon	Rectangle	Square	Triangle
Cone	100.00	0.00	0.00	0.00	0.00	0.00
Hexagon	0.00	91.67	0.00	0.00	8.33	0.00
Pentagon	0.00	0.00	100.00	0.00	0.00	0.00
Rectangle	0.00	0.00	4.17	95.83	0.00	0.00
Square	0.00	4.17	0.00	0.00	95.83	0.00
Triangle	0.00	0.00	0.00	0.00	0.00	100.00

Supplementary Figure 10. Shape Estimation. (a) Basic geometric objects used for tactile shape-classification experiments, including cone, hexagon, pentagon, rectangle, square, and triangle geometries. (b) Offline confusion matrix obtained using the CRNN model trained with the same settings as the chess-piece classification task, demonstrating high classification accuracy across different geometric shapes based on the deformation patterns captured by *FibTac*.



Supplementary Figure 11. Fabrication and Assembly. (a) Preparation of fibers: (i) cutting the fibers to the desired length, (ii) sanding the ends for smoothness, (iii) dipping the fibers in primer solution to enhance adhesion with the silicone, and (iv) air-drying the fibers. (b) Preparation of mold and casting: (i) assembling the mold, (ii) inserting fibers into predrilled holes, (iii) injecting silicone into the mold cavity, and (iv) allowing the silicone to cure at room temperature for 24 hours. (c) Post-processing: (i) demolding the cured fiber-elastomer composite, (ii) painting the fiber tips for enhanced visual perception, (iii) close-up view of the painted fiber ends, and (iv) curing the paint by placing the gel in an oven. (d) Waterproofing the housing: (i) 3D printing and sanding the housing for a smooth finish, (ii) applying a clear UV epoxy coating, (iii) curing the epoxy under UV light, and (iv) final waterproofed housing ready for assembly.



Supplementary Figure 12. Model Architecture. Architecture of the CRNN machine learning model used in this study

Supplementary Note 1

Design Parameters of *FibTac*

This supplementary note presents the experimental studies conducted to optimize various design parameters of the *FibTac* sensor. Supplementary Figure 6 illustrates the different experimental setups used for evaluating these design parameters.

Fiber Length

The fiber length is one of the most critical design parameters influencing both the mechanical stiffness and the displacement sensitivity of the sensor. The effect of length can be analytically approximated using the lateral stiffness of a cantilever beam under a tip load, as illustrated in Supplementary Figure 6(a)(i). For a fiber of Young’s modulus E , area moment of inertia I , and free length l , the effective lateral stiffness k_y is expressed as

$$k_y = \frac{3EI}{l^3}. \quad (1)$$

This inverse cubic dependence indicates that longer fibers exhibit lower stiffness and therefore larger tip deflections for a given force F , which enhances the displacement sensitivity. Conversely, shorter fibers are mechanically stiffer, reducing their sensitivity to small contact forces. An optimal length is therefore required to balance sensitivity and stiffness for stable and responsive grasping performance.

When the fiber is embedded through the silicone gel, the portion above and below the gel are denoted as l and m , respectively, as shown in Supplementary Figure 6(a)(ii). The small-angle geometry of the deflected fiber gives the relation

$$\frac{x}{y} = \frac{l}{m}, \quad (2)$$

where x and y represent the lateral displacements at the outer (visible) and inner (embedded) ends of the fiber, respectively. If the embedded length m is too small, the corresponding motion y at the inner tip becomes negligible, making it difficult for the camera to detect. To ensure measurable deformation, the fibers are suspended through the silicone layer so that both l and m contribute effectively to the observed motion.

To experimentally determine the optimal fiber length, a silicone pad is cast with fibers of five different lengths (Supplementary Figure 6(b)). Each configuration is evaluated for its perceived stiffness and sensitivity. It is observed that fibers with an overall free length of approximately 50 mm provided the best trade-off—sufficiently compliant for high sensitivity while maintaining adequate stiffness for stable grasping and repeated actuation.

Cross-Section

We also test two different cross-sections: square and circular. In experiments, the circular one performed better due to its equal distribution. On the other hand, the square cross-section doesn’t work well due to non-uniform stretch in the lateral and diagonal directions, and occasionally breaks during actuation. See Supplementary Figure 6.

Silicone Gel

The mechanical properties of the silicone gel encapsulating the fibers significantly influence both the sensor’s sensitivity and structural durability. To evaluate this effect, three different silicone materials are tested: P-565, Smooth-Sil 940, and Mold Max 30 (Supplementary Figure 6).

Among these, P-565 exhibits the poorest performance, as it is relatively fragile and prone to tearing during cyclic actuation. Smooth-Sil 940 demonstrates sufficient stiffness to withstand repeated deformation

without rupture; however, its high modulus limits the overall compliance of the structure, thereby reducing displacement sensitivity. Mold Max 30 offers an optimal balance between these two extremes—providing adequate stiffness to prevent mechanical failure while maintaining enough elasticity to enable detectable fiber-tip motion during successive actuation cycles.

This combination of resilience and compliance makes Mold Max 30 the preferred material for the final sensor assembly. See Supplementary Figure 6(d).

Pneumatic Actuation

The actuation behavior of the *FibTac* sensor-gripper is governed by the deformation of a clamped circular silicone pad subjected to an internal pneumatic pressure. Figure 7 illustrates three key states of operation: (a) the neutral state with no pressure applied ($p = 0$), (b) the pressurized state ($p > 0$), where the membrane bulges outward and fibers splay, and (c) the vacuum state ($p < 0$), where the membrane deflects inward and the fibers converge to grasp an object. The governing relationships linking the applied pressure, membrane deformation, and fiber response are described below.

(1) Pressure–deflection relationship of the silicone pad. The circular silicone pad of radius a and thickness h behaves as a thin elastic plate clamped along its periphery. When a uniform pneumatic pressure p is applied inside the chamber, the pad deflects out of plane. Under small deflection conditions ($w_0 \ll h$), its deformation follows the classical Kirchhoff–Love thin plate equation [12, 13]:

$$D\nabla^4 w = p, \quad D = \frac{E_g h^3}{12(1 - \nu_g^2)}, \quad (3)$$

where $w(r)$ is the transverse deflection of the silicone surface at a radial position r (measured from the center of the pad), E_g and ν_g are the Young’s modulus and Poisson’s ratio of the silicone, and D is the flexural rigidity.

The solution for a clamped circular plate under a uniform pressure p is given by [12]:

$$w(r) = \frac{p}{64D}(a^2 - r^2)^2, \quad w_0 = w(0) = \frac{pa^4}{64D}. \quad (4)$$

Here, r denotes the *radial coordinate* varying from $r = 0$ at the center to $r = a$ at the clamped edge. The deflection $w(r)$, therefore, represents the vertical displacement of any point on the silicone surface. In the *FibTac* design (Supplementary Figure 7a), the fibers are embedded at a specific radius $r = r_f$, and the local membrane slope at this location determines the fiber tilt angle.

The central deflection w_0 scales linearly with the applied pressure and strongly with the geometric ratio a^4/h^3 . As shown in Supplementary Figure 7b, a positive pressure ($p > 0$) produces an outward bulge, whereas a negative pressure ($p < 0$) causes the membrane to deflect inward (Supplementary Figure 7c).

(2) Large-deflection (nonlinear) behavior. When the applied pressure is sufficiently high such that the deflection becomes comparable to or greater than the membrane thickness ($w_0/h > 1$), the assumptions of the Kirchhoff–Love theory no longer hold. The bending energy is then accompanied by significant in-plane stretching, and the system must be described by the *Föppl–von Kármán* (FvK) equations [12, 14]:

$$D\nabla^4 w = p - [w, \phi], \quad \nabla^4 \phi = -\frac{E_g h}{2}[w, w], \quad (5)$$

where ϕ is the Airy stress function representing in-plane stresses, and $[f, g] = f_{xx}g_{yy} + f_{yy}g_{xx} - 2f_{xy}g_{xy}$ is the Monge–Ampère operator. These coupled, nonlinear equations capture the additional stiffening response due to membrane tension.

For axisymmetric loading (as in the *FibTac* pad), Eq. (5) simplifies to a radial form that includes both bending and stretching terms. In practice, this behavior is often approximated by an empirical nonlinear pressure–deflection relation [12]:

$$p = k_1 \frac{E_g h^3}{a^4} w_0 + k_2 \frac{E_g h}{a^2} \left(\frac{w_0}{h} \right)^3, \quad (6)$$

where k_1 and k_2 are geometry-dependent constants. The first term corresponds to the bending contribution (dominant at small deflections), while the cubic term represents stretching (dominant at large deflections). Thus, for small w_0/h , $p \propto w_0$, whereas for large w_0/h , $p \propto w_0^3$. This transition from bending- to stretching-dominated deformation explains the nonlinear stiffening observed in silicone pads under high positive or negative pressures.

(3) Local slope and fiber tilt angle. The angular displacement of each fiber is governed by the slope of the membrane at the position where it is embedded ($r = r_f$). Differentiating Eq. (4) with respect to r gives the radial slope:

$$\frac{\partial w}{\partial r} = -\frac{p}{16D} r (a^2 - r^2). \quad (7)$$

The local tilt angle of the fiber base, θ_f , corresponds to the negative of this slope evaluated at $r = r_f$:

$$\theta_f = -\left(\frac{\partial w}{\partial r} \right)_{r=r_f} = \frac{p}{16D} r_f (a^2 - r_f^2). \quad (8)$$

For small angles, θ_f approximates the angular deviation of the fiber from the vertical axis. This tilt results in lateral displacements of the fiber tips above and below the silicone layer, given by $x = l \theta_f$ and $y = m \theta_f$, respectively, where l and m denote the fiber lengths above and below the silicone pad (as defined in Supplementary Figure 7a). The displacement ratio thus follows $x/y = l/m$, confirming that the visible motion scales with fiber geometry.

(4) Pressure-to-grasp force mapping. Each fiber can be modeled as a cantilever beam with lateral stiffness [15]

$$k_y = \frac{3E_f I_f}{m^3}, \quad I_f = \frac{\pi r_f^4}{4}, \quad (9)$$

where E_f and r_f denote the elastic modulus and radius of the fiber, respectively. The lateral reaction force on a single fiber due to membrane-induced displacement is

$$F_{\text{fiber}}(p) = k_y y(p) = \frac{3E_f I_f}{m^2} \frac{p}{16D} r_f (a^2 - r_f^2). \quad (10)$$

Assuming N fibers make contact symmetrically with an object, the net grasping force scales as

$$F_{\text{grasp}}(p) \approx N F_{\text{fiber}}(p) = \frac{3E_f I_f N}{m^2} \frac{p}{16D} r_f (a^2 - r_f^2), \quad (11)$$

and the friction-limited holding capacity is

$$F_{\text{hold}} = \mu F_{\text{grasp}}, \quad (12)$$

where μ is the effective friction coefficient at the fiber–object interface.

These relationships establish a direct link between the pneumatic pressure p , the membrane’s geometric and material parameters (a , h , E_g , ν_g), and the resulting fiber mechanics (E_f , r_f , m , l , N). Collectively, they enable predictive control over both sensitivity (via θ_f and x) and grasping strength (via F_{grasp}), as visualized in Supplementary Figure 7.

Animal Handling Statement

Experiments involving biological specimens were limited to non-invasive interaction tasks using commercially obtained invertebrates, including mystery snails, nightcrawler worms, and superworms. No vertebrate animals were used in this study. No surgical procedures, anesthesia, or euthanasia were performed during the experiments. Under Purdue University policy, IACUC review and approval are required for research or teaching activities involving live vertebrate animals; therefore, this invertebrate-only study did not require IACUC approval.

Supplementary Movie Legends

Supplementary Movie 1. Grasping Tests. Demonstration of *FibTac* performing grasping and pick-and-place operations on a variety of objects, including thin, flexible, delicate, cluttered, and granular items.

Supplementary Movie 2. Food Plating. Demonstration of *FibTac* autonomously transferring and arranging diverse food items with different shapes, textures, and material properties.

Supplementary Movie 3. Live Animal Grasping. Demonstration of *FibTac* gently grasping and relocating live invertebrates, including mystery snails, nightcrawler worms, and superworms.

Supplementary Movie 4. Confined-Space Manipulation. Demonstration of *FibTac* retrieving black pepper seeds from containers with narrow openings using pneumatic contraction and expansion of the fiber array.

Supplementary Movie 5. Chess Pick-and-Place. Demonstration of tactile object recognition and autonomous pick-and-place of chess pieces based on shape-dependent tactile signatures.

Supplementary Movie 6. Liquid Classification. Demonstration of liquid classification using *FibTac*, including water, honey, syrup, dish liquid, and oil.

Supplementary Movie 7. Granularity Classification. Demonstration of granular material classification using *FibTac*, including flour, beans, rice, oats, and sugar.

Supplementary Movie 8. Flow Sensing. Demonstration of underwater flow-direction and flow-speed estimation using *FibTac*.

Supplementary Movie 9. Underwater Grasping. Demonstration of underwater object grasping and classification using *FibTac* in aquatic environments.

Supplementary References

References

- [1] Nguyen, N. H., Ngo, T. D., Nguyen, D. Q. & Ho, V. A. Contact distance estimation by a soft active whisker sensor based on morphological computation. In *2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)*, 322–327 (IEEE, 2020).
- [2] Takei, K. *et al.* Highly sensitive electronic whiskers based on patterned carbon nanotube and silver nanoparticle composite films. *Proceedings of the National Academy of Sciences* **111**, 1703–1707 (2014).
- [3] Huet, L. A., Rudnicki, J. W. & Hartmann, M. J. Tactile sensing with whiskers of various shapes: Determining the three-dimensional location of object contact based on mechanical signals at the whisker base. *Soft robotics* **4**, 88–102 (2017).
- [4] Xiao, C., Xu, S., Wu, W. & Wachs, J. Active multiobject exploration and recognition via tactile whiskers. *IEEE Transactions on Robotics* **38**, 3479–3497 (2022).
- [5] Kent, T. A. *et al.* Whisksight: A reconfigurable, vision-based, optical whisker sensing array for simultaneous contact, airflow, and inertia stimulus detection. *IEEE Robotics and Automation Letters* **6**, 3357–3364 (2021).
- [6] Lin, M. A., Reyes, E., Bohg, J. & Cutkosky, M. R. Whisker-inspired tactile sensing for contact localization on robot manipulators. In *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 7817–7824 (IEEE, 2022).
- [7] Wang, S. *et al.* Potential applications of whisker sensors in marine science and engineering: A review. *Journal of Marine Science and Engineering* **11**, 2108 (2023).
- [8] Glick, R., Brückner, C., Fabian, M. & Grattan, K. T. Tracking hydrodynamic disturbances with fibre-optic whiskers. *Optics and Lasers in Engineering* **177**, 108125 (2024).
- [9] Wang, J. *et al.* Bio-inspired whisker sensor based on orthometric fbgs for underwater applications. *IEEE Transactions on Instrumentation and Measurement* (2024).
- [10] Zarei, M., Jeong, A. W. & Lee, S. G. Whisker-implanted biomimetic electronic skin for tactile sensing and blind perception. *Advanced Science* **12**, 2408162 (2025).
- [11] Hu, Z., Wachs, J. & She, Y. A magnetic-actuated vision-based whisker array for contact perception and grasping. *arXiv preprint arXiv:2503.00133* (2025).
- [12] Timoshenko, S. & Woinowsky-Krieger, S. Theory of plates and shells (1959).
- [13] Young, W. C., Budynas, R. G., Sadegh, A. M. *et al.* *Roark’s formulas for stress and strain*, vol. 7 (McGraw-hill New York, 2002).
- [14] Landau, L. D., Pitaevskii, L., Kosevich, A. M. & Lifshitz, E. M. *Theory of elasticity: volume 7*, vol. 7 (Elsevier, 2012).
- [15] Gere, J. M. & Timoshenko, S. Mechanics of materials. ed. *Boston, MA: PWS* (1997).