

Supplementary Information

Scalable In-situ Fabrication of Multimodal Electronic Skin for Intelligent Robotics and Interactive Systems

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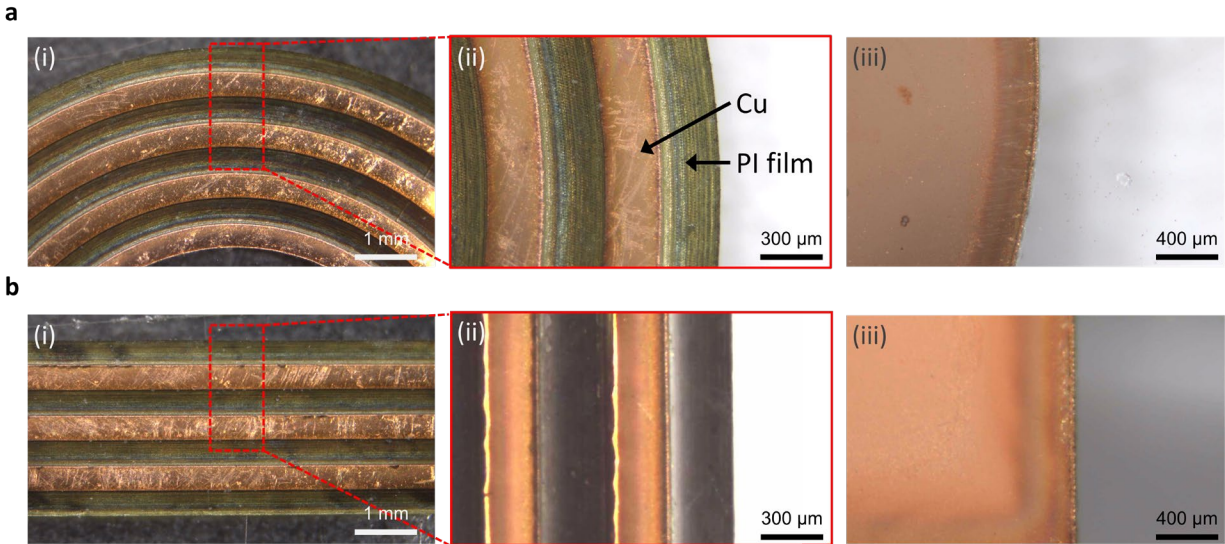
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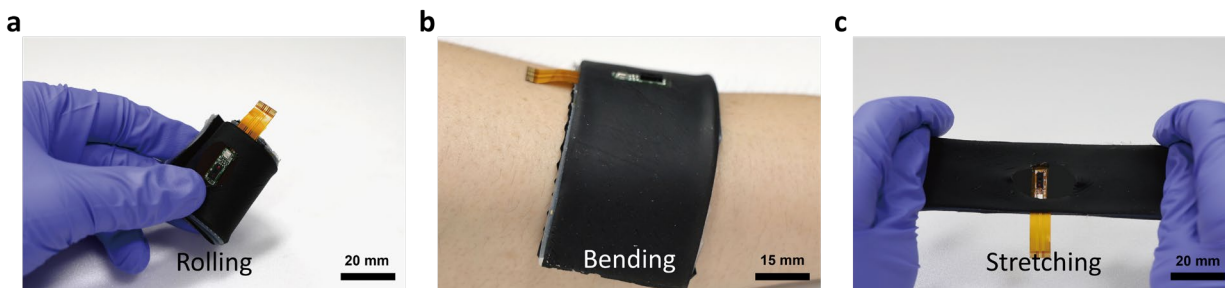
Keywords: Electronic skin (e-skin), multimodal sensing, rapid prototyping, in-situ fabrication, Human-machine interface

Reference	Mechanism	Modalities (Pressure/strain/others)	Customizability	Maskless Process	Cleanroom-free environment	E-skin characteristics
1	Piezoelectric	Pressure	X	X	X	intrinsically stretchable sensor array; Self-powered
2	Resistive	Pressure + Temperature	X	X	X	Used for pulse/breathing monitoring & spatial mapping
3	Electromagnetic	Pressure + Haptic Feedback	X	X	X	Wireless bidirectional touch communication
4	Resistive	Pressure + Temperature	X	X	X	Used in artery/swallowing monitoring & robotic grasping
5	Capacitive	Pressure + bending	X	X	X	Conformable, skin- mimicking
6	Piezoresistive	Pressure + Shear (3D Force)	X	X	O	3D force detection (Normal & Tangential); High sensitivity via porous structure
7	Capacitive	Stretch/pressure-sensitive	X	O	O	Stretchable strain and pressure sensing; used in gloves, insoles, robotic grasping
8	capacitive	Pressure + bending	X	O	O	Stretchable strain and pressure sensing; Used in Human Motion Monitoring and Swallowing Detection.
9	Capacitive	Pressure + bending	O	O	O	Textile e-skin; breathable, highly flexible
10	Iontronic capacitive	Pressure	O	O	O	Conformal onto 3D surfaces; high-resolution tactile maps
11	Capacitive	Pressure + shear + proximity	O	O	O	Highly flexible; attaches to robot fingers
12	Capacitive &Thermochromic	Pressure + Temperature	O	O	O	Visualized temperature sensing (Color change)
13	Resistive	Strain + Temperature + ECG	O	O	O	Multifunctional (strain/temp/ECG); In-situ fabrication
This work	Capacitive	Pressure + bending + Temperature + Proximity (8x8)	O	O	O	Soft, low-profile e-skin; integrated wiring + sensors in-situ; applied to robotics, pressure

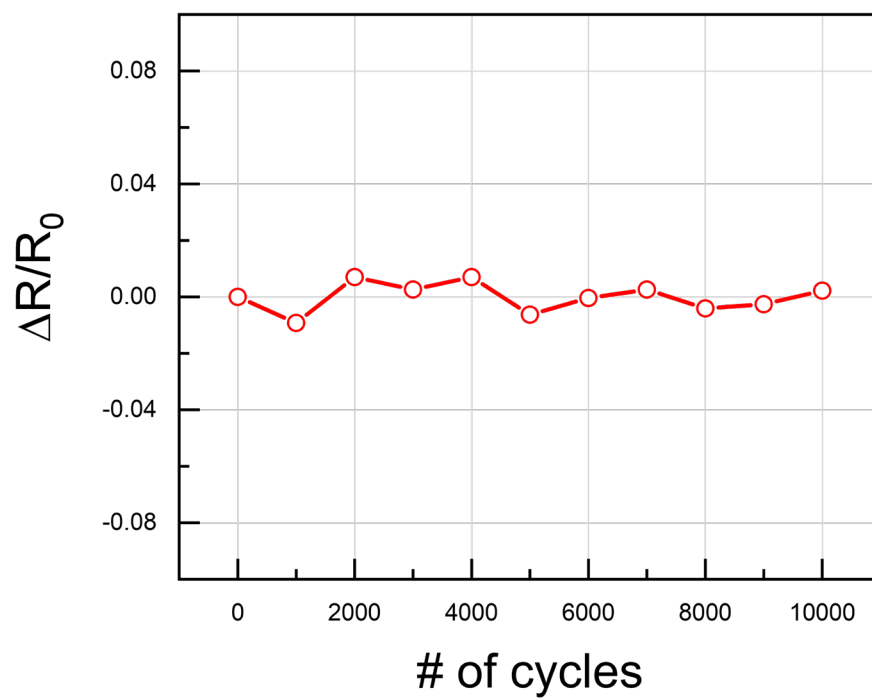
Supplementary Table 1: Comparison of key performance and manufacturing metrics determining suitability for fully soft, integrated sensing systems between state-of-the-art e-skin technologies and the soft-PCB-like platform developed in this study. The evaluation criteria include sensing mechanism, multimodal detection capability, design customizability, and fabrication accessibility defined by maskless and cleanroom-free processes.



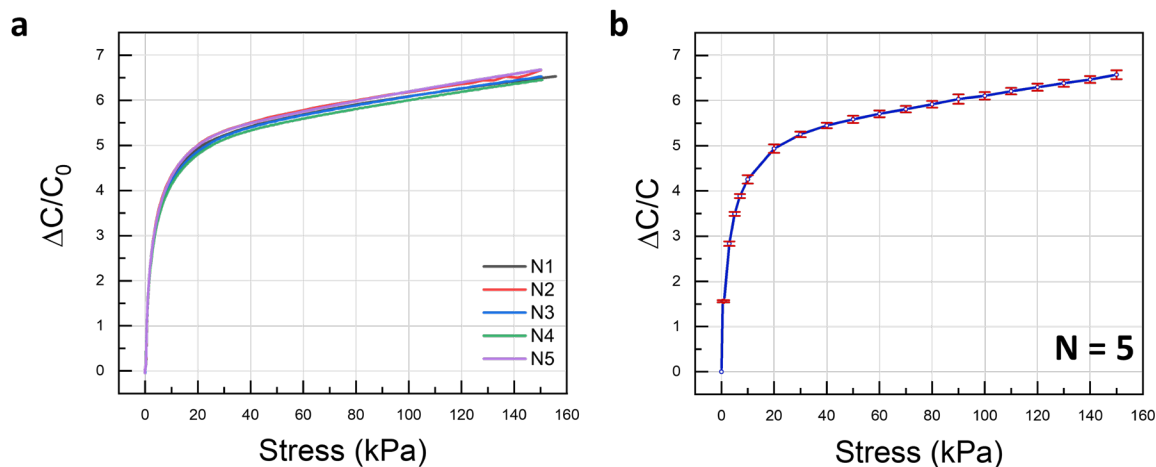
Supplementary Figure 1: Optical microscope images demonstrating the versatility of UV laser patterning on Cu/PI films. **a**, (i) Overview images showing patterned lines with curved geometries; (ii) Magnified views clearly distinguishing the copper (Cu) and polyimide (PI) layers, demonstrating precise material separation even in curved geometries; (iii) images highlighting the clean and sharp edges obtained by the full-depth cutting mode of the UV laser, despite the curved shape. **b**, (i) Overview images showing patterned lines with straight geometries; (ii) Magnified views clearly distinguishing the copper (Cu) and polyimide (PI) layers, demonstrating precise material separation in straight geometries; (iii) Images highlighting the clean and sharp edges obtained by the full-depth cutting mode of the UV laser, demonstrating high-quality, precise cuts in straight structures.



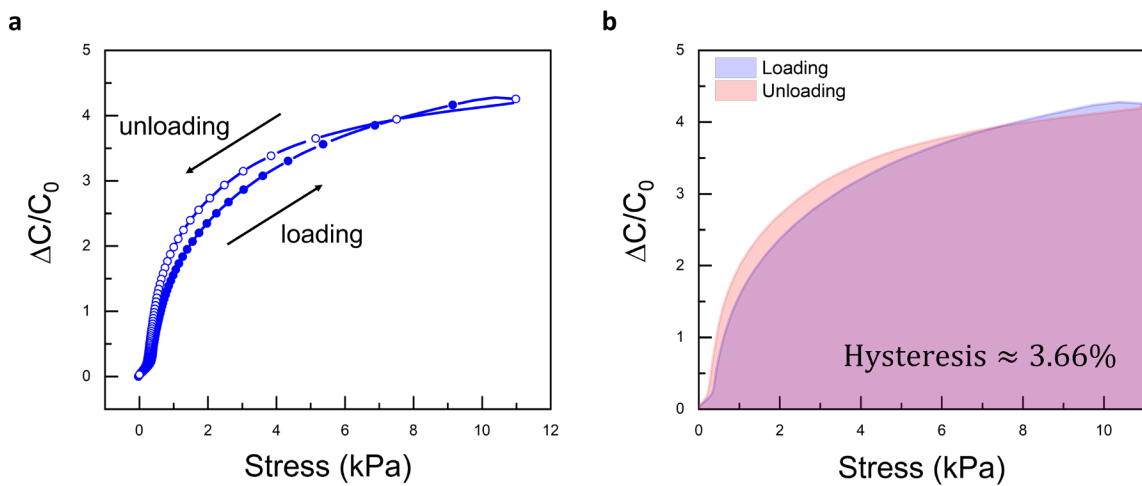
Supplementary Figure 2: The high elasticity of the porous elastomer film ensures that the sensor remains undamaged under physical deformations; rolling (a), bending (b), and stretching (c).



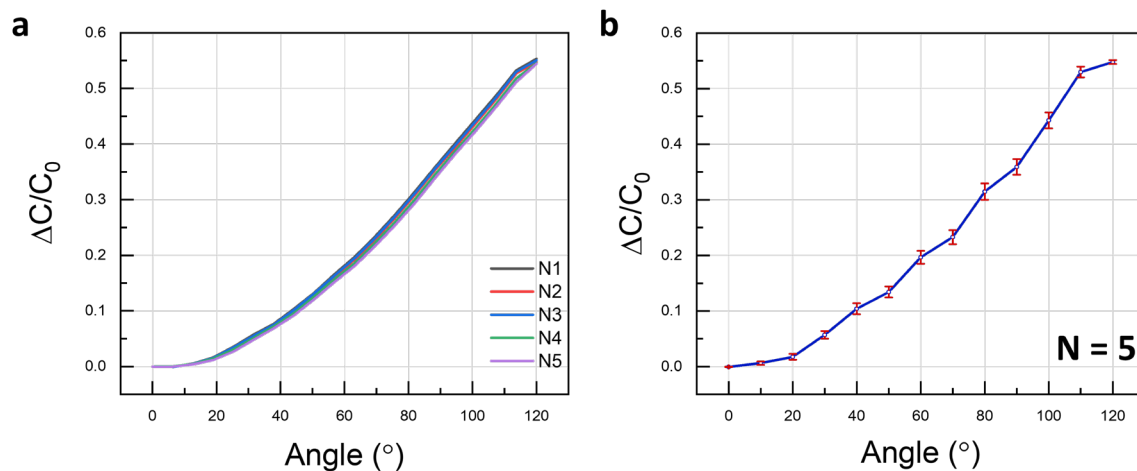
Supplementary Figure 3: After 10,000 strain cycles up to 120°, the resistance of the GND layer coated on the porous elastomer film surface changed by less than 1.2%.



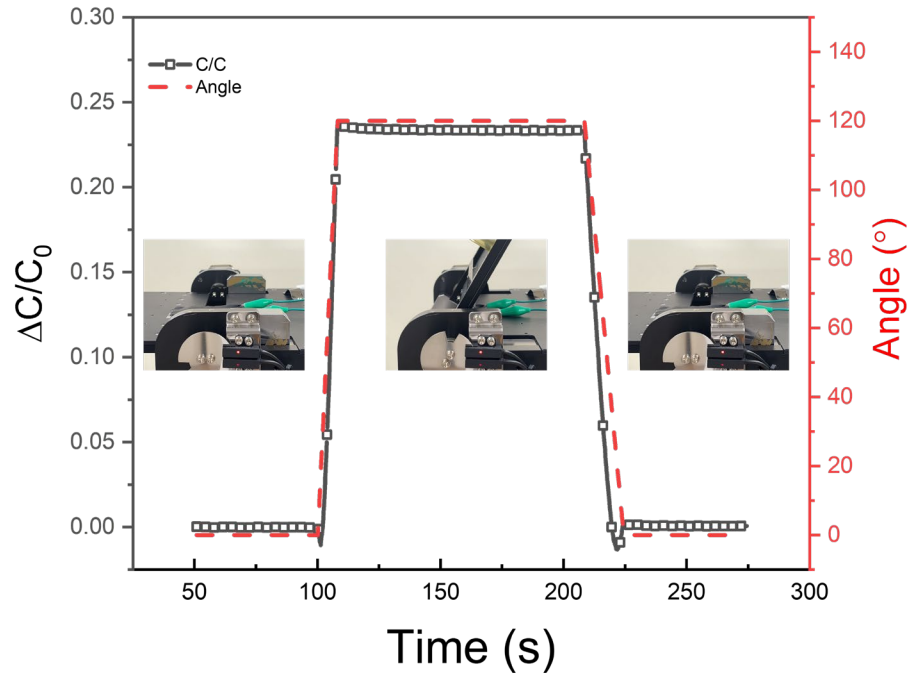
Supplementary Figure 4: Evaluation of the operational robustness of the pressure sensor. **Evaluation of the operational robustness of the pressure sensor.** **a**, Raw sensor response curves measured over five consecutive loading and unloading cycles. **b**, Average signal outputs and standard deviations recorded at applied pressures of 0.5, 1, 3, 5, 7 kPa, and from 10 to 150 kPa (in 10 kPa increments).



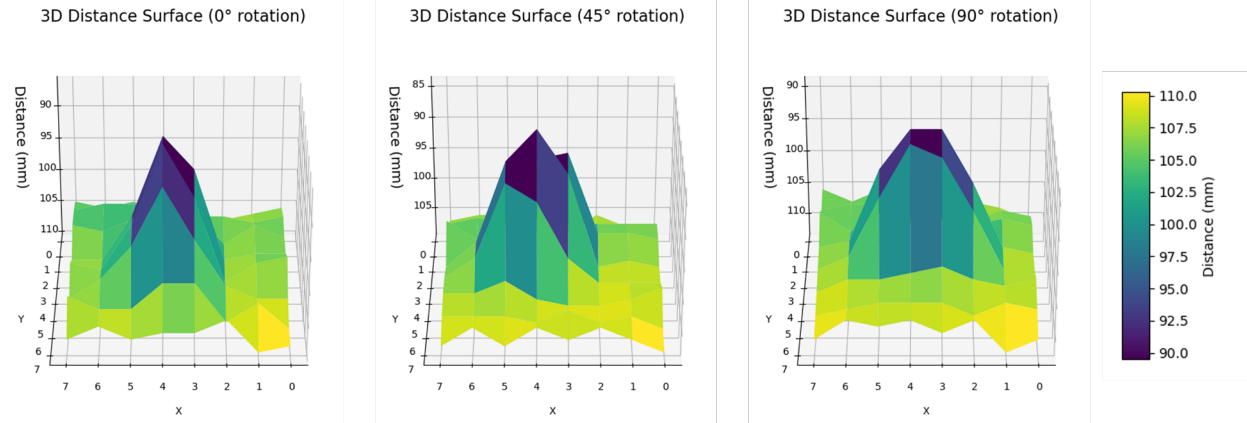
Supplementary Figure 5: Hysteresis behavior of the porous elastomer layer. a, Capacitance variation during loading and unloading cycles up to 10 kPa. **b,** Low hysteresis (3.66%) observed during loading and unloading cycles up to 10 kPa.



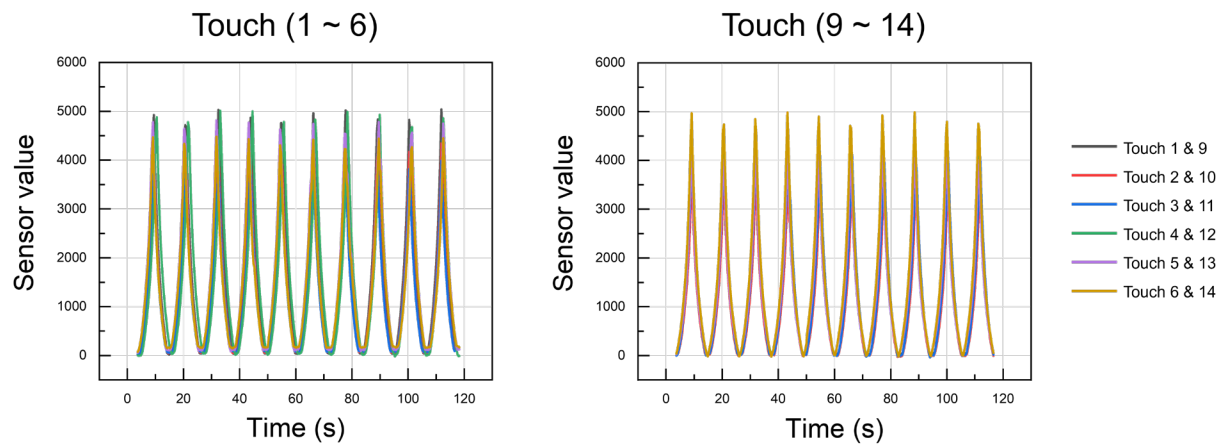
Supplementary Figure 6: Evaluation of the operational robustness of the pressure sensor. **Evaluation of the operational robustness of the pressure sensor.** **a**, Raw sensor response curves measured over five consecutive loading and unloading cycles. **b**, Average signal outputs and standard deviations recorded at applied pressures of 0.5, 1, 3, 5, 7 kPa, and from 10 to 150 kPa (in 10 kPa increments).



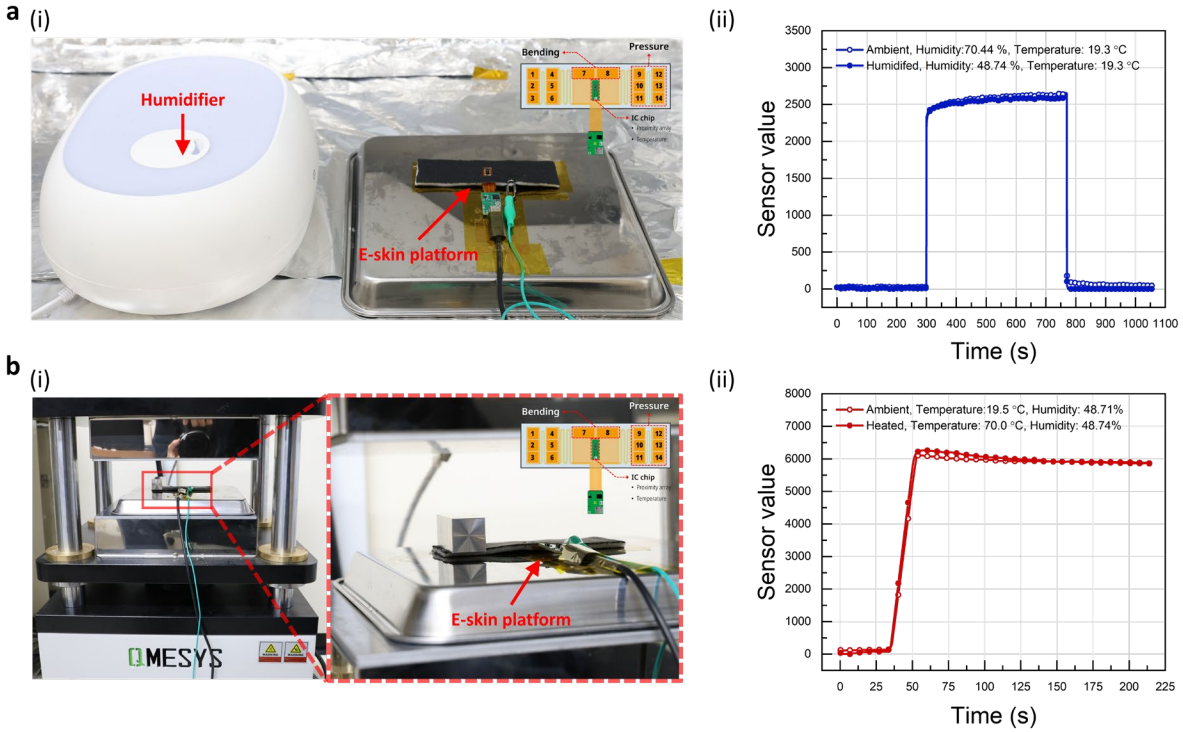
Supplementary Figure 7: Stable and consistent sensor response observed during loading of the multimodal e-skin sensor bent up to 120° for approximately 150 s.



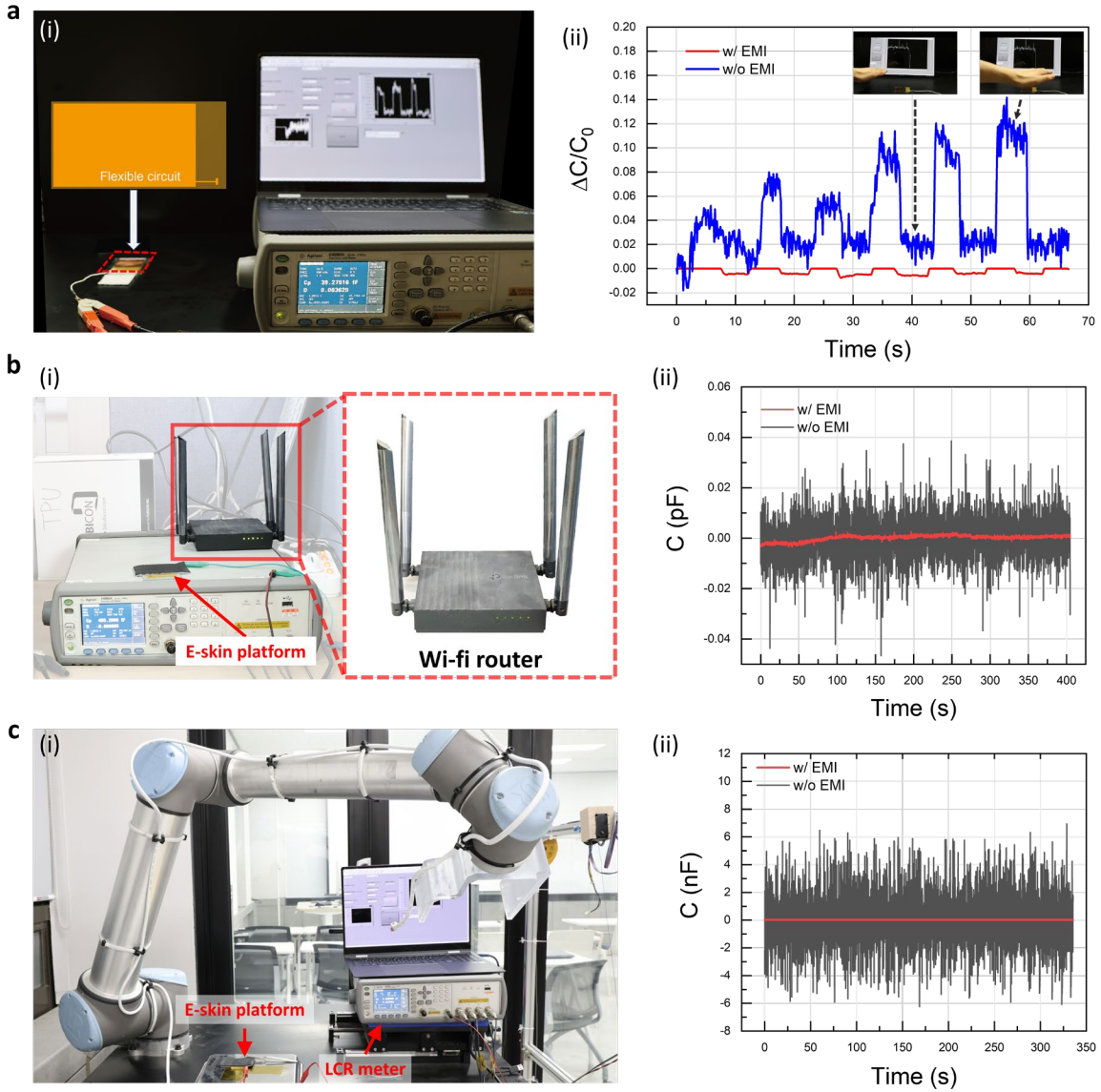
Supplementary Figure 8: The alignment of the target object can be determined from the various angles (0°, 45° and 90°) formed with the proximity array sensor.



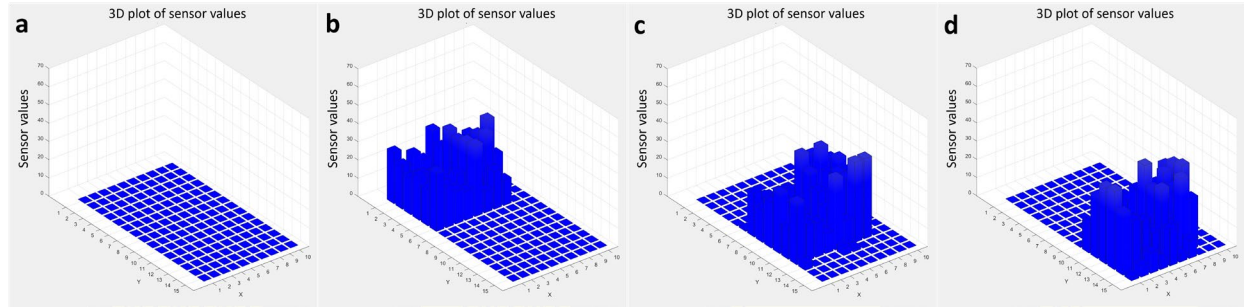
Supplementary Figure 9: It was confirmed that the pressure sensors attached to channels 1–6 and 9–14 produced stable outputs when subjected to ten repeated loadings up to 30 kPa.



Supplementary Figure 10: Verification of environmental stability and sensor crosstalk. a, (i) Overview of the experimental setup comparing the e-skin platform in a standard ambient environment and a high-humidity environment generated using a humidifier inside a fume hood. **(ii),** Comparison of the pressure sensor response (average of Ch. 1–6) under a loaded state. The sensor outputs measured in the high-humidity environment are maintained at levels nearly identical to those in the ambient state, confirming that the system exhibits stable performance with minimal interference from humidity. **b, (i)** Overview of the experimental setup utilizing a hydraulic press to compare sensor responses under ambient conditions and with a top plate heated to 70 °C. **(ii),** Analysis of pressure sensor readings under mechanical load. The results demonstrate that the pressure readings remain stable and consistent with the applied load even under heated conditions, showing no significant thermal drift. This confirms that the crosstalk effect between temperature and pressure is negligible.



Supplementary Figure 11: Experimental setup and sensor signal comparison demonstrating effective EMI shielding by the CNT-coated porous layer. **a**, (i) Overview of the experimental setup for EMI testing with approaching human body. (ii), Comparison of sensor signals measured from the flexible circuit integrated with and without the CNT-coated porous layer, demonstrating that the presence of the CNT-coated porous layer effectively reduces susceptibility to external environmental interference. **b**, (i) Overview of the experimental setup for EMI testing near a Wi-Fi router continuously emitting 5 GHz electromagnetic waves. (ii), SNR comparison showing that the shielding layer improved the SNR from 52 dB (unshielded) to 60 dB, confirming stable signal integrity against high-frequency noise. **c**, (i) Overview of the experimental setup adjacent to a robotic arm's electric motor, which generates strong magnetic fields and electrical sparks. (ii), SNR analysis demonstrating a significant enhancement from 52 dB to 70 dB with the CNT shielding layer, effectively mitigating environmental noise in practical interactive applications.



Supplementary Figure 12: Position-dependent characterization of the pressure-sensor array. **a**, Baseline output with no applied load. **b–d**, Array responses when a 30.0 mm $\times$ 50.0 mm loading cell is manually pressed at different locations on the array.

File Name: Supplementary Movie 1

Description: Demonstration of a cooking assistance scenario using the e-skin-integrated robotic gripper. The video shows the robotic gripper, equipped with the fabricated porous multimodal e-skin, securely grasping a target object and safely handing it over to a user. This demonstration highlights the sensor's capability to provide precise tactile feedback.

File Name: Supplementary Movie 2

Description: Interactive tactile sensing demonstration using a soft elastomer doll. This video illustrates the application of the e-skin on a soft, curved surface. It demonstrates real-time interaction capabilities where the sensor array attached to the doll detects physical contact and triggers corresponding feedback responses, verifying the device's conformability and sensitivity.

File Name: Supplementary Movie 3

Description: Real-time pressure mapping performance of the sensor array. The video demonstrates the spatial resolution and rapid response of the e-skin array through three distinct tests: single-point touch, simultaneous multi-point touch, and continuous line tracing.

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