
Original Research Article

Design and characterization of flexible electronic skin for robot grasping force detection

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Abstract: This study aims to develop and validate a flexible electronic skin for normal contact-force detection during robotic grasping. We fabricated a 4×4 piezoresistive array using a conductive hydrogel and evaluated it through static calibration, cyclic loading, curved-finger interference tests, array localization, and robotic grasping experiments. We designed a 4×4 flexible piezoresistive electronic skin based on conductive hydrogel for continuous contact-force detection, slippage recognition, and protection of fragile objects during robotic grasping. Verification covered device calibration, curved-surface interference, array positioning, and robotic grasping. Eight independent devices from two batches exhibited a stepped response in the 0–20 N range: Sensitivities of 0.05592 N⁻¹ and 0.01758 N⁻¹ in the 0–5 N and 5–20 N ranges, respectively, with an inversion RMSE of 0.468 N and a hysteresis error of 3.812% FS. Under a 5 N step stimulus, the system response and recovery times were 88.0 ms and 110.3 ms, respectively. After 10,000 cycles, the peak response changed by -1.882%, and baseline drift was 2.358% FS. The 4×4 array correctly localized all 48 point loads, with an average center-of-mass error of 0.391 mm. Robot testing covered 8 object types and 120 grasping operations. Overall relative steady-state force error was 3.752% ± 3.494%, and grasping success was 90.0%. Across 240 state events, recognition accuracy was 94.58%, and the F1 score for slippage recognition was 0.9167. Within the tested range, the electronic skin combined low-force sensitivity, curved-surface conformability, and array-based positioning. It supported open-loop grasping-force detection and slippage and overload alarms. Cross-object generalization and closed-loop control gains require further validation.

Keywords: flexible electronic skin; conductive hydrogel; piezoresistive sensing; grasping force detection; slippage detection; robotic grasping

1. Introduction

Robotic grasping requires reliable contact-force feedback to regulate clamping force, protect fragile objects, and maintain stable contact. Flexible electronic skin can conform to curved fingers while adding limited stiffness, making it suitable for distributed tactile sensing in compliant end-effectors.

Current flexible sensors use piezoresistive, capacitive, piezoelectric, triboelectric, and hydrogel-based mechanisms. Microstructured surfaces and conductive networks can improve low-load sensitivity, but curved-surface mounting, hysteresis, drift, packaging reliability, array readout, and cross-scenario calibration remain important challenges for practical grasping.

This work develops a 4×4 conductive-hydrogel piezoresistive electronic skin for normal contact-force detection during robotic grasping. The study integrates material selection, layered device design, signal conditioning, calibration, curved-finger mounting, and array-level grasping validation, with emphasis on force estimation, contact-state recognition, and slippage-related signal changes.

2. Overall design and operating principles

This study measures the normal contact force between a robotic finger and a grasped object. The grasping task defines the sensing, acquisition, and computation chain. The electronic skin covers the primary finger-contact areas and converts load into a stable electrical signal without substantially

increasing interface stiffness. The conditioning and acquisition module provides excitation, range matching, and analog-to-digital conversion. The calibration algorithm maps the normalized response to force. The robot controller records the force, evaluates contact status and signal quality, and supports decision-making or closed-loop control. A quality flag indicates whether the estimate is valid for control, whereas an invalid flag marks out-of-range, saturated, or drift-affected signals. This layered architecture maps material and device metrics to task metrics such as grasping-force error, response delay, and state recognition instead of relying on sensitivity alone^[1-2].

Figure 1 traces the force signal through the flexible sensing unit, analog conditioning, data acquisition, digital filtering, calibration, and compensation. The chain produces an estimated grasping force and a corresponding quality flag. The controller uses the estimate only when the output is within the calibrated range, the baseline is valid, and the channel is not saturated. If the output exceeds the range or abnormal drift occurs, the system retains the raw data and raises an invalid flag. This workflow avoids equating voltage change directly with grasping force and preserves traceability for comparison with an independent force gauge.

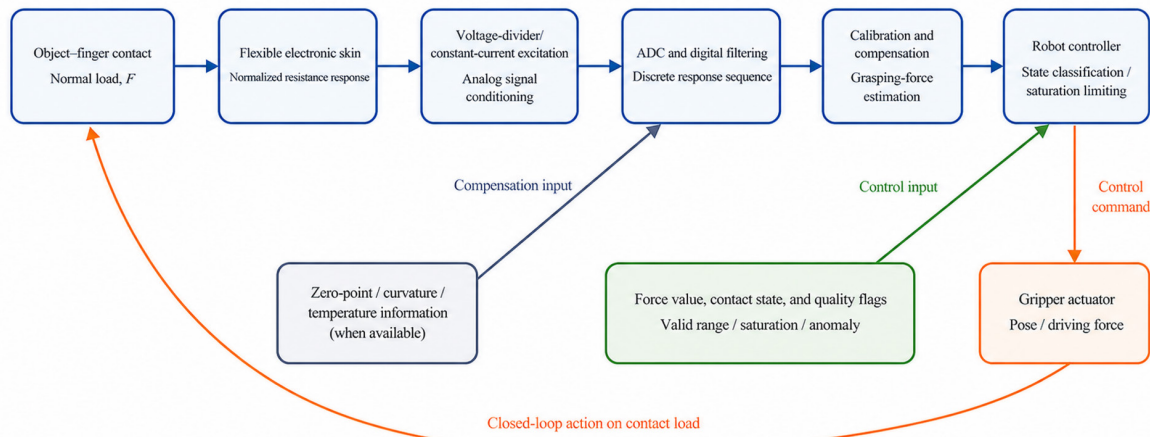


Figure 1. Overall architecture and data flow of the gripping force detection system for flexible electronic skin robots.

Table 1. Design specifications and validation metrics of the flexible electronic skin.

Design dimension	Target or constraint	Quantitative metric	Corresponding validation
Measured quantity	Normal grasping force at the robot finger-object interface	0–20 N	Static calibration and grasping comparison
Measurement accuracy	Supports grasping-force tracking and state classification	RMSE 0.468 N; resolution 0.020 N	Comparison with an independent reference force gauge
Sensitivity and linearity	Resolves low loads; calibratable over the operating range	0–5 N: 0.05592 N ⁻¹ ; 5–20 N: 0.01758 N ⁻¹ ; $R^2=0.998995$	Stepwise loading-unloading
Dynamic response	Does not constrain the robot control cycle	$t_r=88.0$ ms; $t_f=110.3$ ms	Step loading; 10%–90% definition
Sampling and bandwidth	Covers the effective tactile-signal bandwidth f_b	Static: 100 Hz; dynamic: 500 Hz	Synchronous acquisition and frequency-domain inspection
Compliance and dimensions	Conforms to the curved finger surface without impeding closure	Thickness 1.181 mm; minimum bending radius 20 mm	Dimensional measurement and curvature grouping
Stability	Reproducible output after repeated grasping	Hysteresis 3.812% FS; baseline drift 2.358% FS after 10,000 cycles	Cyclic and sustained-load tests
Installation constraints	The sensing area covers the contact surface; leads do not carry the primary strain	16 elements; 6 mm spacing; two-finger contact surface	Curved-surface installation and channel inspection

Shear force is not treated as an independent output in this section. Tangential loads during grasping are evaluated only as cross-sensitivity in the normal channel during later anti-interference or grasping experiments; this evidence does not support three-dimensional force measurement. A future prototype with independent shear-sensitive units would require separate structural decoupling, coordinate definitions, and multi-axis calibration matrices. Array-channel count should likewise follow contact-coverage and real-time readout requirements. Element layout and calibration on curved fingers should be established after installation to reduce errors when planar calibration is transferred to robotic operation^[3].

The sensing unit has a flexible layered structure comprising a protective/encapsulation layer, an upper flexible electrode, a conductive-hydrogel sensing layer, a lower flexible electrode, a flexible substrate, and an adhesion layer. Stress-relief zones at the electrode ends connect to external leads. The protective layer limits direct friction and moisture exchange. The flexible electrodes maintain contact during repeated bending, the conductive hydrogel converts force to an electrical response, and the substrate and adhesive layer provide positioning and conformal attachment to curved surfaces. Layer thickness and planar dimensions must be selected jointly from finger clearance, measurement range, and packaging constraints. Packaging must not restrict deformation of the sensitive layer. Microstructured or compressible surfaces can increase deformation and contact-area change at low loads, but compaction may introduce nonlinearity and saturation. Structural sensitization must therefore be designed for the specified measurement range^[1, 4].

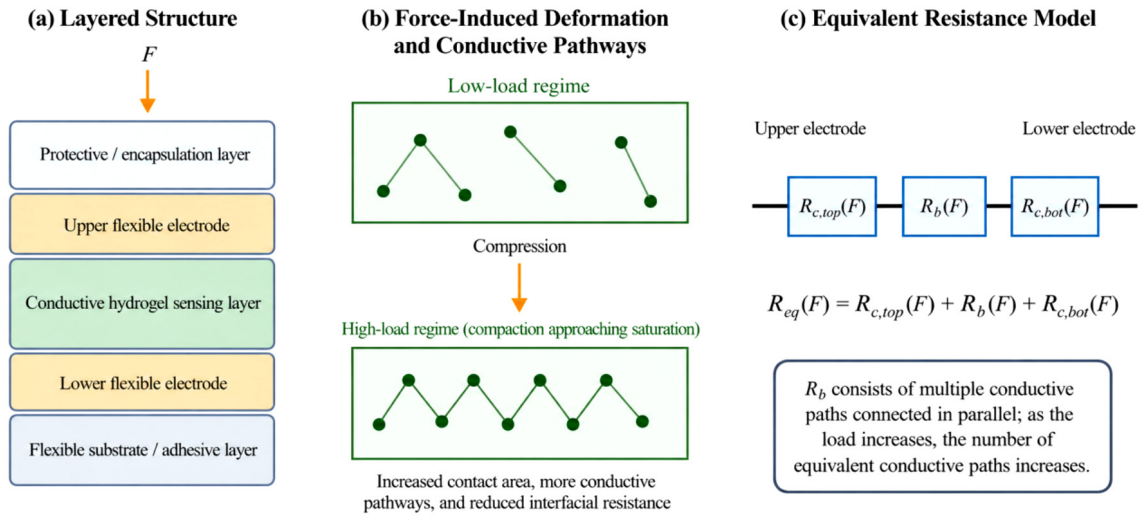


Figure 2. Layered structure, strain-induced deformation, and equivalent resistance mechanism of flexible electronic skin.

3. Materials, fabrication, and robotic integration

Material selection follows four criteria: Mechanical compatibility, electrical stability, process reproducibility, and interfacial compatibility. Conductive hydrogels combine low-modulus deformation with a continuous conductive medium and are therefore suitable as adhesive-type sensing layers. Their network structure, water content, and conductive components determine initial resistance, compressibility, and long-term drift. Dual-network and highly ductile hydrogels can improve crack resistance and cyclic load-bearing capacity by dissipating energy through limited network-segment sacrifice^[5]. Studies of ionic conductors and hydrogel electronic devices also show that conductive stability depends on encapsulation, interfacial adhesion, and control of water loss^[4, 6]. The sensitive material is therefore designed together with the electrodes, encapsulation, and curved-surface mounting rather than as an isolated film.

Figure 3 summarizes the preparation process. Polymer monomers/matrix, solvent, conductive components, crosslinking agents, and the initiator system are weighed according to the target initial resistance and mechanical properties; batch number, purity, and mass fraction are recorded. The mixture is then blended or dispersed at a controlled temperature and degassed by static settling, vacuum, or centrifugation. Casting, scraping, or printing sets the specified thickness, after which crosslinking or curing proceeds under predetermined time-temperature conditions. After demolding, sensitive-layer thickness,

effective area, and initial resistance are measured. Samples with through-bubbles, cracks, or substantial thickness deviations are discarded. Reviews of flexible sensors and hydrogel bioelectronics provide a basis for network design, interfacial integration, and device fabrication^[4, 6], but the formulations and process parameters reported here must follow the actual experimental records.

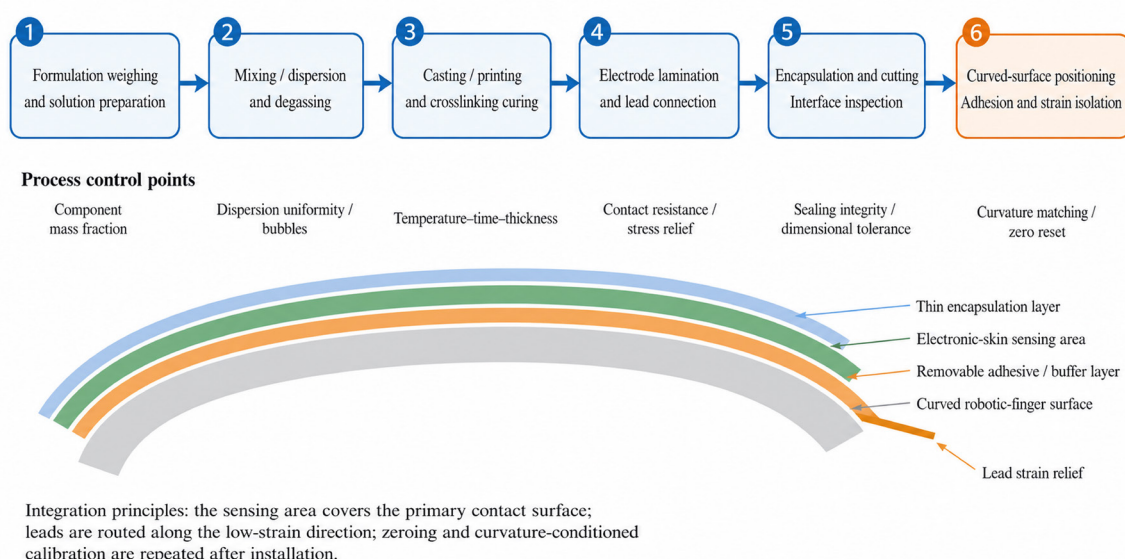


Figure 3. Process for fabricating electronic skin and method for integrating it onto the curved surface of a robotic finger.

4. Grasping-force detection and performance analysis

The array is read through sequential channel scanning, analog conditioning, analog-to-digital conversion, and digital filtering. Calibration maps the normalized resistance response to contact force, while baseline validity and saturation checks provide a quality flag. The measured response shows a stepped sensitivity over 0–20 N, with stable repeatability, limited hysteresis, and short response and recovery times. Cyclic loading confirms that the conductive network and encapsulated structure retain their function after extended operation. The 4×4 layout localizes point loads and provides spatial information for identifying contact position and load distribution during grasping. Changes in local force and signal quality can be used to distinguish initial contact, stable holding, and possible slippage. During testing, force estimates are accepted only when the channel remains within the calibrated range and the baseline is valid; abnormal drift or saturation is flagged for quality control. This procedure separates sensor response from controller decisions and supports comparison across repeated grasping trials.

5. Applications, limitations, conclusions, and outlook

When integrated on a robotic finger, the electronic skin supplies continuous force feedback for regulating clamping force, protecting fragile objects, and improving grasp stability. Array-level responses also support contact-state monitoring and early recognition of load redistribution associated with slippage. The present design mainly measures normal force; independent shear measurement, environmental durability, long-term water retention, channel crosstalk, and cross-scenario calibration require further improvement. Overall, the 4×4 conductive-hydrogel piezoresistive skin establishes a compact route from contact deformation to force estimation and demonstrates practical potential for robotic grasping. Future work should expand multidimensional sensing, optimize packaging and calibration, and combine tactile signals with data-driven recognition for adaptive closed-loop control.

References

- [1] Chung Wang, Chen Liu, Fangfang Shang, et al. Tactile sensing technology in bionic skin: A review[J]. Biosensors and Bioelectronics, 2023, 220:114882.

- [2] Zuqing Yuan, Guozhen Shen. Materials and device architecture towards a multimodal electronic skin[J]. *Materials Today*, 2023, 64:165–179.
- [3] Juntian Qu, Baijin Mao, Zhenkun Li, et al. Recent Progress in Advanced Tactile Sensing Technologies for Soft Grippers[J]. *Advanced Functional Materials*, 2023, 33(41):2306249.
- [4] Yin He, Xiaoxuan Xu, Shuang Xiao, et al. Research Progress and Application of Multimodal Flexible Sensors for Electronic Skin[J]. *ACS Sensors*, 2024, 9(5):2275–2293.
- [5] Jian Ping Gong, Yoshimi Katsuyama, Takayuki Kurokawa, Yoshihito Osada. Double-Network Hydrogels with Extremely High Mechanical Strength[J]. *Advanced Materials*, 2003, 15(14):1155–1158. DOI:10.1002/adma.200304907.
- [6] Hyunwoo Yuk, Baoyang Lu, Xuanhe Zhao. Hydrogel bioelectronics[J]. *Chemical Society Reviews*, 2019, 48:1642–1667. DOI:10.1039/C8CS00595H.