Centrosymmetric- and Axisymmetric-Patterned Flexible Tactile Sensor for Roughness and Slip Intelligent Recognition

Yafeng Liu, Shaowei Cui, Junhang Wei, Haibo Li, Jingyi Hu, Siyu Chen, Yin Chen, Yinji Ma, Shuo Wang,* and Xue Feng*

1. Introduction

Human skin is densely covered with mechanoreceptors that provide it the sense of touch.[1,2] Continuous tactile feedback from objects enables us to effectively handle diverse objects with fine dexterity.[3,4] Next-generation robots are being designed to function autonomously in complex and unstructured environments. In particular, based on the real-time measurement and differentiation of normal pressure and shear force, robots can be equipped with the capabilities of damage-free grasp within minimum force limits, as well as dexterous operation through surface roughness and slip information. Herein, a flexible tactile sensor with a small cylinder protrusion and four arc-shaped protrusions is developed. Due to its center symmetry and axisymmetry characteristics, the normal pressure and shear force can be decoupled from the complex stress without any interference from torsion. The flexible tactile sensor exhibits good linearity and superior cycling stability and is capable of determining the magnitude and direction of the applied force accurately. The flexible tactile sensor is comfortable to wear, and it is integrated onto the manipulator to realize various delicate and dexterous tasks, such as pressure detection, interaction with fragile objects, and roughness identification. Moreover, intelligent recognition of the sliding and stationary states can be achieved by decoding signals of sliding friction and static friction from the feedback information, leading to real time and precise adjustment of the grasping state of the manipulator.
manipulated object and the end of the manipulator are, however, usually damaged by overload when the feedback for surface roughness is unavailable.[12,13] Constrained by limited information, surface roughness discrimination is a bigger challenge than pressure detection for the development of tactile sensing, particularly in complex and unstructured environments.[14–16] In addition, future robots will be highly demanding, catering to delicate and precise tasks, such as holding a glass or inserting a key in a lock.[17] Robotics requires tactile sensors to obtain critical information (e.g., slip detection) to prevent objects from dropping.[18] Slip detection plays a central role in grip force adjustment, as well as in manipulation and tactile exploration, by providing information about the object properties.[19] Therefore, accessing accurate information related to sliding and incipient sliding will allow robots to automatically adjust the grasping force and perform appropriate actions.[20] However, it is still a challenge to develop a complex and flexible tactile sensor in order to get close to the surface roughness and slip detection performances of human skin, and the effective regulation of both force and precision grasps.[17]

Fortunately, many research groups have recently demonstrated a variety of flexible tactile sensors with high-sensitivity values.[21–26] Such flexible tactile sensors conform to irregular surfaces, and work as physical signal-oriented sensors for personal healthcare monitoring.[27–31] However, only the perception of normal pressure has been demonstrated in most of these reports.[32] Researchers have been developing tactile sensors to distinguish surface textures or slip detection by mimicking the touch capability of the human finger.[33,34] A flexible micro-hairied sensor consisting of nylon fibers is capable of sensing surface roughness after the active-touch exploration of surfaces.[35] In addition, inspired by the interlocked microstructures of human skin, one study has explored using piezoresistive interlocked microdome arrays for stress-direction-sensitive tactile sensors.[36] However, the surface roughness and slip detection performances were not integrated into a single device. Torque can also interfere with test results. Moreover, these can only qualitatively describe the state of tension, pressure, and bending, and cannot quantitatively determine the magnitude and direction of the shear force required by existing robots.[18,37–40] As a result, key information (e.g., static friction and sliding friction) cannot be decoded, making it difficult to realize the dexterous operation of robots through physical feedback and sensations that correspond to interactions with the environment.[41]

Through real-time measurement and decoding of complex stress, key information such as the dropping of an object can be obtained, contributing to a dexterous manipulator with natural mechanical movements, rich information feedback, and meaningful application scene implementation capabilities.[13,19,37,42] To meet the requirements of detecting complex mechanical stimuli, an artificial flexible tactile sensor is developed in this study, capable of perceiving normal pressure and shear force simultaneously. The flexible tactile sensor includes two polydimethylsiloxane (PDMS) films and one layer of metal. The upper layer is structured with a central symmetrical circular structure and four axisymmetric sector structures. The circular structure with a symmetrical center is insensitive to shear force, and can detect the normal pressure without any interference from the shear force. The four axisymmetric sector structures can detect the value and direction of the shear force without any interference from the torque. Moreover, the interference of torque is eliminated due to the symmetry of the central symmetrical circular and four axisymmetric sector structures in the torque direction. As a proof of concept, the flexible tactile sensor is combined into the manipulator to realize the operation of pulse wave detection, roughness recognition, shear force direction identification, and grasping and releasing objects. In addition, the flexible tactile sensor was demonstrated to carry out intelligent recognition of the sliding and stationary states by decoding the sliding friction and static friction signals when the robotic hand grasped the object.

2. Results and Discussion

Here, a flexible tactile sensor, including two PDMS films and one layer of metal, was prepared. As shown in Figure 1a, the fabrication process of the flexible tactile sensor is divided into three main parts: fabrication of the strain grid, the transfer printing process, and the microstructure formation process. The fabrication of the strain grid starts with spin casting an ultrathin polyimide (PI) film (≈10 μm) onto silicon wafers, which are coated with a layer of a sacrificial polymethylmethacrylate (PMMA) film. Subsequently, layers of 10 nm Cr and 100 nm Au were deposited on the surface of the cured PI film by electron beam evaporation, followed by traditional lithography and etching to design the strain grid structure. The PI film was etched into the same strain grid pattern using reactive ion etching (RIE). Then, Au/Cr/PI was picked up quickly with an elastic stamp and printed slowly onto the PDMS in a 2D planar state. The uncured PDMS was poured onto the mold, and the PDMS with meshed Au/Cr/PI was aligned with the mold pattern. After curing, the meshed Au/Cr/PI was encapsulated in PDMS. A flexible tactile sensor was obtained after demolding. The flexible tactile sensor is comfortable enough, which can be integrated onto the manipulator to decouple the normal pressure and shear force from the complex stress, and to realize various delicate and dexterous tasks.

The flexible tactile sensor is composed of three parts: a microstructure top part, one layer of strain grid, and a flat bottom part. The top part of microstructure (Figure S1, Supporting Information) is made of PDMS (Sylgard 184; thickness, 200 μm), with a small cylinder protrusion (diameter, 1.8 mm and height, 500 μm) and four arc-shaped bulges (inner/outer diameter, 2.5/4.6 mm and height, 500 μm). One layer of the strain grid exploits the resistance–strain effect of the metal foil, consisting of a supporting membrane of polyimide (PI ≈10 μm thick) and a metal film (Au ≈ 100 nm thick; Cr ≈ 10 nm thick) patterned lines (width, 20 μm) (Figure 1b and S2, Supporting Information). The conductive pattern adopts a circumferential arrangement structure, which is higher than the radial arrangement of the strain grid density, ensuring the sensitivity of the flexible tactile sensor. The pattern of the microstructure at the top part was aligned with that of the strain grating layer. The flat bottom part is a PDMS base (thickness, 500 μm). Figure 1c shows a photograph of the flexible tactile sensor placed on a glass rod with a diameter of 30 mm. The soft and deformable PDMS cover and base offer good flexibility, and they ensure that the flexible tactile sensor is electrically insulated. As shown in Figure 1d, the
small cylinder protrusion and four arc-shaped bulges are completely aligned with the meshed Au/Cr/PI of the strain grating.

The protrusion of the flexible tactile sensor always preferentially touches the grasped object. The small cylindrical protrusion in the middle was used to detect the normal pressure, and four arc-shaped protrusions were used to detect the shear force. The size of the entire sensor was less than 1 cm. To prevent the sensor from touching the grasped object, multiple flexible tactile sensor arrays can be integrated. When the flexible tactile sensor touches an object, pressure acts on the top protrusion, preferentially inducing strain in the strain-sensitive layer in the plane. The resistance of the metal grid changes induced by the strain; thus, the normal pressure was detected (Figure 2a). The theoretical response of the flexible tactile sensor to the normal pressure applied is given by

$$\frac{\Delta R}{R_0} = k \cdot F_p$$

where $k$ is the pressure sensitivity, and $F_p$ is the normal pressure applied.

When the flexible tactile sensor slides relative to the object, the deformation of the metal grid results in a variation in the resistance; thus, the shear force is detected. As shown in Figure 2b and S3, Supporting Information, the stress of arc-shaped protrusion 1 and arc-shaped protrusion 2 is caused by the shear force in the x-direction. The theoretical response of the flexible tactile sensor to the shear force applied is given by

$$\begin{align*}
\frac{\Delta R_1}{R_0} &= t_1 \cdot F_s \\
\frac{\Delta R_2}{R_0} &= t_2 \cdot F_s
\end{align*}$$

where $t_1$ is the shear force sensitivity of arc-shaped protrusion 1, $t_2$ is the shear force sensitivity of arc-shaped protrusion 2, and $F_s$ is the shear force applied.

As shown in the inset of Figure 2b, the stress of arc-shaped protrusion 4 is distributed in an antisymmetric direction along the y-axis. The left side is tensioned, and the right side is

---

Figure 1. a) Schematic illustrations of the fabrication process of the flexible tactile sensor. b) Strain grating structure of the flexible tactile sensor. c) Flexible tactile sensor placed on glass rod. d) Microstructure of the flexible tactile sensor.
compressed, and both these effects counterbalance each other. Therefore, arc-shaped protrusion 4 is insensitive to the shear force in the \( x \)-direction. The arc-shaped protrusion 3 is similar to the arc-shaped protrusion 4, resulting in insensitivity to the shear force in the \( x \)-direction. Similarly, arc-shaped protrusions 1 and 2 were insensitive to the shear force in the \( y \)-direction.

Thus, arc-shaped protrusions 1 and 2 can be used to detect the shear force in the \( x \)-direction, and the arc-shaped protrusions 3 and 4 can be used to detect the shear force in the \( y \)-direction.

When the normal pressure and shear force act on the flexible tactile sensor simultaneously, the response of the flexible tactile sensor is given by

\[
\frac{R_1 - R_2}{R_0} = k_1 \cdot F_P + t_1 \cdot F_S
\]

\[
\frac{R_1 - R_3}{R_0} = k_2 \cdot F_P + t_2 \cdot F_S
\]

The grating of the shear force is axisymmetric, so the strain response coefficient to pressure is the same. Thus, we can obtain \( R_{1,0} = R_{2,0} = R_0 \) and \( k_1 = k_2 \).

Meanwhile, the response coefficient of the shear force is different because of the noncentrosymmetric shear force grid. The theoretical response of the shear force grating to the applied shear force is given by

\[
\frac{R_1 - R_2}{R_0} = (t_1 - t_2) \cdot F_S = t \cdot F_S
\]

The small cylinder protrusion is a centrosymmetric graph, and the stress distribution under shear force is antisymmetric (upper inset of Figure 2b). The total stress distribution is zero after superposition; therefore, it is insensitive to the shear force.

The theoretical response of the strain grating of the flexible tactile sensor to the loading is given by

\[
\begin{align*}
\frac{R_1 - R_2}{R_0} &= k \cdot F_P \\
\frac{R_1 - R_3}{R_0} &= t \cdot F_S \cdot \vec{n}_x \\
\frac{R_1 - R_4}{R_0} &= t \cdot F_S \cdot \vec{n}_y
\end{align*}
\]

In the process of grasping an object, twisting may also occur. However, the influence of torsion on the stress distribution is rarely considered in the development of flexible sensors. As shown in Figure 2c, the stress distribution of the tactile sensor under torque in the \( z \) direction was simulated via the finite element analysis (FEA). The stress distribution of the arc-shaped protrusion 4 under torque in the \( z \) direction is antisymmetric (bottom inset of Figure 2c). The total stress distribution is zero after superposition; thus, it is insensitive to the torque in the \( z \) direction. The arc-shaped protrusions 1, 2, and 3 are similar to the arc-shaped protrusion 4, and show insensitivity to the torque in the \( z \) direction. In addition, there is no net effect of torque at the small cylinder protrusion due to the central symmetry. Therefore, the flexible tactile sensor eliminates the influence of torque, due to its ingenious structural design.

To investigate the piezoresistive behavior, the resistance change of the flexible tactile sensor under compression was monitored. An increasing displacement was slowly applied to the flexible tactile sensor, while the resistance of the flexible tactile sensor...
sensor and applied force were recorded simultaneously. The relative change in resistance (RCR, $\Delta R/R_0$) was calculated based on the initial measured resistance and real-time monitored resistance. As shown in Figure 3a, the RCR of the flexible tactile sensor under compression monotonically increased with the increase in pressure. The flexible tactile sensor exhibited good linearity ($R^2 = 0.998$) over a relatively large measurable range (0–1.2 N). The sensitivity ($\Delta R/(R_0\Delta F)$) of the flexible tactile sensor was calculated as 2.65 N$^{-1}$, based on the RCR–pressure curve obtained. The tactile sensor based on PDMS has a low elastic modulus, resulting in a relatively narrow measurement range (0–1.2 N). As shown in Figure S4 and S5, Supporting Information, the response of the flexible tactile sensor is nonlinear under high-pressure conditions. Moreover, the metal film sensor would undergo an internal fracture with a further increase in pressure, leading to a flexible tactile sensor failure. In addition, the measurement range of the sensor increased as the modulus of the PDMS increased. Meanwhile, the maximum value for force detection can be improved by integrating multiple flexible tactile sensor arrays to withstand external loads. As shown in the inset of Figure 3a, the resistance remains almost unchanged with the increase in shear force, which is attributed to the axisymmetric nature of the small cylinder in the radial direction. The antisymmetric stresses formed under the shear force counteracted each other. Therefore, the resistance is insensitive to the shear force, which is consistent with the finite-element simulation results (Figure 2b).

The RCR response of the flexible tactile sensor to the cyclic compressive loading was investigated. As shown in Figure 3b, the RCR response curves under different peak pressures were almost identical, except for the RCR magnitude. It is indicated that the flexible tactile sensor has excellent response and stability.

**Figure 3.** Response of the flexible tactile sensor to compressive loading: a) RCR-pressure curve; the inset shows a reduced RCR range; b) RCR response of the flexible tactile sensor to cyclic compression loading-unloading under different peak strains; c) RCR response to cyclic compression loading-unloading under different frequencies; d) response time and recovery time of the flexible tactile sensor; e) reliability after 5000 cycles with a peak pressure of 0.3 N at 0.1 Hz; f) $R_2$ response of the flexible tactile sensor to shear force loading; g) $R_1$ and $R_2$ response and decoupling of the flexible tactile sensor to shear force loading; h) Decoupling of $R_1$–$R_2$ and $R_3$–$R_4$ response to shear force loading with a direction of 15°; and i) comparison of shear force direction from the calculation and the test results.
In addition, the effect of the loading frequency on the response of the flexible tactile sensor was investigated. As shown in Figure 3c, there was no apparent signal delay observed within the different loading frequencies, indicating the rapid response of the sensor. The amplitude of the RCR at high frequencies was similar to that at low frequencies, which reveals that the response of the flexible tactile sensor is almost independent of frequency. To obtain the response time of the flexible tactile sensor, a table tennis ball was dropped on the flexible tactile sensor and bounced back immediately. A rise time of less than 60 ms was detected, which illustrates that the sensor was fast in its response (Figure 3d). The recovery time was \( \approx 0.09 \) s, which is slightly larger than the response time. Furthermore, the reliability of the flexible tactile sensor was evaluated. After 5000 load–unload cycles, a slight increase (0.13\%) in the RCR amplitude was observed (Figure 3e). It indicated that the flexible tactile sensor is reliable for long-term application.

In addition, it is more important that a flexible tactile sensor can be used to detect shear forces. Figure S6, Supporting Information, shows the testing method for the shear force. Figure 3f shows the ratio of the measured resistance to its initial resistance obtained when a shear force was applied in the x direction. The RCR of the flexible tactile sensor under shear monotonically decreased with an increase in shear force. The sensor exhibited good linearity \( (R^2 = 0.979) \) over a relatively large measurable range (0–1 N). The sensitivity \( (\Delta R/(R_0 \Delta F)) \) of the flexible tactile sensor was calculated as 0.3 N\(^{-1}\), based on the RCR–pressure curve obtained. The response test results of the two strain gratings (\( R_1 \) and \( R_2 \)) in the x axis direction are shown in Figure 3g. The RCR of \( R_1 \) under shear monotonically increases with the increase in shear force, whereas the RCR of \( R_2 \) under shear monotonically decreases with the increase in shear force. The effect of pressure is eliminated by means of shear monotonically decreases with the increase in shear force. The standard deviation (12.6) at 45° is greater than that of 0° (4.6°), indicating that the volatility of 45° is greater than that of 0°.

Robotic experiments were carried out to demonstrate the use of the flexible tactile sensor for 1) perception of environmental signals and 2) tasks requiring high dexterity, such as sliding intelligent recognition. The flexible tactile sensor is equipped with a robotic fingertip to evaluate its sensing ability to identify a pulse. The softness of the flexible tactile sensor ensured its intimate contact with the skin. As shown in Figure 4a, a real-time pulse was recorded with the flexible tactile sensor, and the pulse rate and depth were identified well through the frequency and magnitude of the monitored RCR. The average blood pulse was calculated as 65 beats per minute. It is consistent with the typical blood pulse rate of a healthy adult. Moreover, both the incident and reflected waves in one blood pulse were observed, which is significant for cardiovascular disease diagnosis.

It is generally difficult for previous e-skins to identify the surface roughness of objects. A major advantage of the flexible tactile sensor manufactured here is that it is very effective in distinguishing surface roughness. To demonstrate this advantage, the flexible tactile sensor was moved by a robotic fingertip across various surfaces smoothly and steadily. When the flexible tactile sensor slides across the surface of an object, its RCR response is recorded. For comparison, two plates with different surface topographies were tested. The plates had a wavy surface structure, and the wave shape of plate A was denser than that of plane B. Plate A had 14 grooves with an interval of 1.4 mm and a depth of 0.7 mm, and plate B had five grooves, with an interval of 4 mm and a depth of 2 mm. When the flexible tactile sensor slides across the surface of an object, resistance changes are caused by microstructural deformation. As shown in Figure 4b, the surface textures of the plates were well traced by the RCR signal of the flexible tactile sensor. For plate A, similar to the shape of the plate surface, the RCR response curve has a waveform with 14 peaks. For plate B, waveforms with five peaks were observed, which can be identified well from the monitored RCR curve. In addition, the interval of the grooves in plates A and B can be counted, as shown in Figure 4c, by the RCR curves. The intervals of the grooves in plates A and B are observed to be \( \approx 1.4 \) and 4 mm, respectively, which are similar to the actual sizes. Thus, the surface roughness of an object, represented here by the interval and number of grooves in plates A and B, can be well identified from the monitored RCR curves.

While grasping objects, the shear force between the manipulator and the objects always occurs in arbitrary directions. The flexible tactile sensor fabricated here can detect the magnitude and direction of the shear force, which can be used to evaluate the state of the grasping objects. The flexible sensor was integrated onto the manipulator to grasp the kiwifruit. The stress state of the flexible tactile sensor changes with the rotation of the manipulator, causing a change in resistance, which enables the direction of the shear force to be detected (Figure S7 and Movie S1, Supporting Information). As shown in Figure 4d,
the direction of the shear force was 45° at the beginning of grasping. The responses of R1–R2 and R3–R4 increased simultaneously, and the values were basically the same. The amplitude of R3–R4 decreased to 0 when the direction of the shear force decreased from 45° to 0°. When the direction of the shear force changes to −45°, the amplitude of R3–R4 became negative. Through the calculation of the resistance response based on (8), the direction of the shear force can be obtained as shown in Figure 4e. The angle of the shear force changes from 45° to −45°, which is consistent with the actual angle change. At the same time, it can be observed that there is a certain error between the measured shear force direction and the actual direction for the following reasons: the influence of environmental factors (e.g., inertial force) in the process of dynamic rotation, the error caused by the uneven surface of the kiwifruit, and the measurement error of the flexible tactile sensor itself.

It is difficult to control the manipulators to avoid damage to soft or fragile objects from overload. As shown in Figure 5a, when a manipulator grasps an orange without a flexible tactile sensor, the orange is easily damaged due to overload. The dynamic process of orange grasping and breaking is shown in Movie S2, Supporting Information. Figure 5b,c shows the
delicate and precise grasp experiment of the manipulator combined with the flexible tactile sensor. As shown in Figure 5b, Movie S3, Supporting Information, when the manipulator grasps an orange with a flexible tactile sensor, it is easy for the orange to slide if the grasping force is too small, resulting in failure. As shown in Figure 5d, the response of the flexible tactile sensor increased instantaneously when the manipulator grasped the orange. As the manipulator is lifted up gradually, the orange slips with the manipulator, and the flexible tactile sensor response decreases gradually. The explanation for this phenomenon is that when relative sliding occurs between the object and the flexible tactile sensor, the state of the force changes from static
friction to dynamic friction, and the amplitude of the friction decreases (Figure 5e). This change in the motion state can be detected by the flexible tactile sensor. The friction force detected by the flexible tactile sensor is transmitted to the “Python” software for processing. The manipulator can control an object accurately according to the feedback of the flexible tactile sensor. As shown in Figure 5c, when the manipulator grasps an orange, the latter slides easily if the grasping force is too small. The response of the flexible tactile sensor is reduced and fed back to the manipulator controller, and the manipulator increases the grasping force. The grasping state was constantly adjusted according to the magnitude of the feedback force. The dynamic processes of manipulator grasping, sliding, and adjusting are shown in Figure 5f and Movie S4, Supporting Information. When the manipulator grasps the orange, the flexible sensor responds and delivers feedback to the manipulator so that the manipulator will pick up the orange. When the manipulator moves upward, it slides if the grasping force is too small. At this moment, the response detected by the flexible sensor decreases and is fed back to the manipulator control end. Subsequently, the manipulator increases the grasping force and constantly adjusts the grasping tension according to the feedback of the flexible sensor, resulting in a damage-free grasp of the orange.

3. Conclusion
To meet the requirements for detecting complex mechanical stimuli, we developed an artificial flexible tactile sensor that can be used to perceive the magnitude and direction of normal pressure and shear force, and realize sensing feedback and intelligent recognition. The upper layer is structured with a central symmetrical circular structure and four axisymmetric sector structures. The circular structure can detect the normal pressure and avoid interference from the shear force. The four axisymmetric sector structures can detect the value and direction of the shear force and eliminate the interference from the shear force. The four axisymmetric sector structures can detect the value and direction of the shear force and eliminate the interference from the shear force. The shear force and eliminate the interference from the shear force.

4. Experiment Section

Fabrication of Flexible Tactile Sensor: The flexible tactile sensor consists of three parts: a PDMS (Sylgard-184) cover, a strain-sensitive membrane, and a PDMS base. The PDMS cover and base were fabricated by molding. A mixture of PDMS liquid (10:1 with curing agent) was degassed in a vacuum chamber for 10 min, cast into the corresponding mold, and cured at a temperature of 80 °C for 60 min. After demolding, the PDMS base was completed. The fabrication of the sensitive membrane starts with the preparation of different material membranes on a silicon wafer, including PMMA/PI/Cr/Au (500 nm/10 nm/10 nm/100 nm). PMMA (M130002, MicroChem, USA), serving as a sacrificial layer, was spin coated on a silicon wafer at 3000 rpm for 30 s and cured at 180 °C for 20 min. Then, a film of PI (ZKPI-3051IB, POME, CHN), which functions as the support layer, was spin coated over the PMMA at 5000 rpm for 60 s and cured at 80 °C for 15 min, 120 °C for 25 min, 150 °C for 30 min, and 180 °C for 1 h. The layers of 10 nm Cr and 100 nm Au were deposited onto the surface of the cured PI film using electron beam evaporation, and the deposition rate of the metal layer was controlled at ~0.1 nm/s. The Au/Cr layer was photolithographed and etched into the designed mesh patterns. The PI film was patterned to the same shapes by RIE masked by Au (power, 80 W; pressure, 250 mTorr; O2, 30) for 5000 s. Then, Au/Cr/PI was picked up quickly with an elastic stamp and printed slowly onto the PDMS base in a 2D planar state. The PDMS liquid was spin coated on the mold pattern at 500 rpm for 30 s and cured at 120 °C for 5 min. The PDMS with meshed Au/Cr/PI was aligned with the mold pattern. After curing at 80 °C for 60 min, the meshed Au/Cr/PI was encapsulated in the PDMS. A flexible tactile sensor was obtained after demolding.

Characterizations: To investigate the response of the flexible tactile sensor to mechanical stimuli, it was fixed on the three-point bending fixture of a universal testing machine (DMA Q800, USA), whereas each electrode of the flexible tactile sensor was connected to the electrode of a high-resolution digital multimeter (Keysight 34465A). The relative change in the resistance (RCR, ΔR/R0) was calculated based on the initial resistance measured and real-time resistance monitored. Based on the RCR-strain curves, the sensitivity (ΔR/R0ΔF) was calculated. FEA of the stress state of the structure was carried out with ANSYS 15.0. The element type used was solid45, and the PDMS base was fully constrained.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
The authors are grateful for the financial support provided by the National Natural Science Foundation of China (grant nos. U20A6001, 11625207, 12002190, and 11921002), and the China Postdoctoral Science Foundation (2020M670305).

Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.
Keywords
complex stresses, flexible tactile sensors, intelligent recognition, shear forces

Received: April 19, 2021
Revised: July 28, 2021
Published online: September 15, 2021

[1] S. Bauer, Nat. Mater. 2013, 12, 871.
[2] R. S. Johansson, J. R. Flanagan, Nat. Rev. Neurosci. 2009, 10, 345.
[3] C. G. Núñez, W. T. Navaraj, E. O. Polat, R. Dahiya, Adv. Funct. Mater. 2017, 27, 1606287.
[4] S. Zhao, J. Li, D. Cao, G. Zhang, J. Li, K. Li, Y. Yang, W. Wang, Y. Jin, R. Sun, C. P. Wong, ACS Appl. Mater. Interfaces 2017, 9, 12147.
[5] T. Li, J. Zou, F. Xing, M. Zhang, X. Cao, N. Wang, Z. L. Wang, ACS Nano 2017, 11, 3950.
[6] S. Sundaram, Science 2020, 370, 768.
[7] Z. Han, Z. Cheng, Y. Chen, B. Li, Z. Liang, H. Li, Y. Ma, X. Feng, Nanoscale 2019, 11, 5942.
[8] W. Tang, Y. Zhou, H. Zhu, H. Yang, Appl. Surf. Sci. 2013, 273, 199.
[9] Y. Zhengkun, Z. Yilei, Neurocomputing 2017, 244, 102.
[10] Z. Yi, Y. Zhang, J. Peters, Sens. Actuators, Part A, Phys. 2017, 255, 46.
[11] J. Feng, Q. Jiang, Sens. Actuators, Part A, Phys. 2019, 287, 143.
[12] S. Sundaram, Sci. Robotics 2020, 5, 1502.
[13] G. Li, S. Liu, L. Wang, R. Zhu, Sci. Adv. 2020, 5, 8134.
[14] G. Liang, Y. Wang, D. Mei, K. Xi, Z. Chen, J. Micromech. Microeng. 2015, 24, 1510.
[15] C. Pang, G. Y. Lee, T. I. Kim, S. M. Kim, H. N. Kim, S. H. Ahn, K. Y. Suh, Nat. Mater. 2012, 11, 795.
[16] H. Chang, S. Kim, S. Jin, S. W. Lee, G. T. Yang, K. Y. Lee, H. Yi, ACS Appl. Mater. Interfaces 2018, 10, 1067.
[17] C. M. Boutry, M. Negre, M. Jorda, O. Vardoulis, A. Chortos, O. Khatib, Z. Bao, Sci. Adv. 2018, 3, eaau6914.
[18] J. Park, M. Kim, Y. Lee, H. Sang Lee, H. Ko, Sci. Adv. 2015, 1, e1500661.
[19] M. T. Francomano, D. Accoto, E. Guglielmelli, IEEE Sens. J. 2013, 13, 2489.
[20] J. Li, S. Dong, E. Adelson, IEEE Int. Conf. on Robotics Automation 2018, 5, 7772.
[21] H. Bai, S. Li, J. Barreiros, Y. Tu, C. R. Pollock, R. F. Shepherd, Science 2020, 370, 848.
[22] Z. Liang, J. Cheng, Q. Zhao, X. Zhao, Z. Han, Y. Chen, Y. Ma, X. Feng, Adv. Mater. Technol. 2019, 4, 1900317.
[23] P. Pan, Z. Bian, X. Song, X. Zhou, J. Appl. Mech. 2020, 87, 101009.
[24] K. I. Jang, H. U. Chung, S. Xu, C. H. Lee, H. Luan, J. Jeong, H. Cheng, G. T. Kim, S. Y. Han, J. W. Lee, J. Kim, M. Cho, F. Miao, Y. Yang, H. N. Jung, M. Flavin, H. Liu, G. W. Kong, K. J. Yu, S. I. Rhee, J. Chung, B. Kim, J. W. Kwak, M. H. Yun, J. Y. Kim, Y. M. Song, U. Paik, Y. Zhang, Y. Huang, J. A. Rogers, Nat. Commun. 2015, 6, 6566.
[25] A. Atalay, V. Sanchez, O. Atalay, D. M. Vogt, F. Haufe, R. J. Wood, C. J. Walsh, Adv. Mater. Technol. 2017, 2.
[26] O. Ozioko, P. Karipoth, P. Escobedo, M. Ntagios, A. Pullanchiyodan, R. Dahiya, Adv. Intell. Syst. 2021, 3, 1900145.
[27] Y. Ma, Y. Zhang, S. Cai, Z. Han, X. Liu, F. Wang, Y. Cao, Z. Wang, H. Li, Y. Chen, X. Feng, Adv. Mater. 2020, 32, e1902062.
[28] Z. Han, H. Li, J. Xiao, H. Song, B. Li, S. Cai, Y. Chen, Y. Ma, X. Feng, ACS Appl. Mater. Interfaces 2019, 11, 33370.
[29] F. Zhu, H. Xiao, H. Li, Y. Huang, Y. Ma, J. Appl. Mech. 2019, 86, 034501.
[30] S. Nie, M. Cai, C. Wang, J. Song, J. Appl. Mech. 2020, 87.
[31] Y. Ma, H. Li, S. Chen, Y. Liu, Y. Meng, J. Cheng, X. Feng, Adv. Intell. Syst. 2020, https://doi.org/10.1002/aisy.202001082000108.
[32] T. Sekine, M. Abe, K. Muraki, S. Tachibana, Y.-F. Wang, J. Hong, Y. Takeda, D. Kumaki, S. Tokito, Adv. Intell. Syst. 2020, 2, 2000179.
[33] L. Qin, Z. Yi, Y. Zhang, Sens. Actuators, Part A, Phys. 2018, 269, 483.
[34] H. Souri, H. Banerjee, A. Jusufi, N. Radacsi, A. A. Stokes, I. Park, M. Sitti, M. Amjadi, Adv. Intell. Syst. 2020, 2, 2000039.
[35] Y.-F. Liu, P. Huang, Y.-Q. Li, Q. Liu, J.-K. Tao, D.-J. Xiong, N. Hu, C. Yan, H. Wang, S.-Y. Fu, J. Mater. Chem. A 2019, 7, 1889.
[36] J. Park, Y. Lee, J. Hong, Y. Lee, M. Ha, Y. Jung, H. Lim, S. Y. Kim, H. Ko, ACS Nano 2014, 8, 12020.
[37] Q. Li, L. Natale, R. Haschke, A. Cherubini, A.-V. Ho, H. Ritter, Int. J. Humanoid Robotics 2018, 15, 1802001.
[38] Y. F. Liu, Y. F. Fu, Y. Q. Li, P. Huang, C. H. Xu, N. Hu, S. Y. Fu, J. Mater. Chem. B 2018, 6, 896.
[39] Y. F. Liu, Q. Liu, J. F. Long, F. L. Yi, Y. Q. Li, X. H. Lei, P. Huang, B. Du, N. Hu, S. Y. Fu, ACS Appl. Mater. Interfaces 2020, 12, 49866.
[40] J. Kwiatkowski, D. Cockburn, V. Duchaine, Int. Conf. Intell. Robots Syst. 2017, 9, 286.
[41] J. Yin, R. Hinchet, H. Shea, C. Majidi, Adv. Funct. Mater. 2020, https://doi.org/10.1002/adfm.2020074282007428.
[42] C. Majidi, Sci. Robotics 2020, 5, 0894.